MASTER THESIS

Design of an Innovative Siltation Removal System for Rolling Gates

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This thesis proved to be a challenging project from start to finish. Not only was the subject difficult, the project started and ended in the COVID-19 pandemic. In the beginning I thought the impact of the pandemic on my thesis would not be that significant, unfortunately I was wrong. That's why I'm grateful for all the people around me who helped me through this difficult process.

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In addition, I'm grateful for all the help of the experts. During my research I have spoken to numerous experts and not only was this interesting, it was crucial to complete my thesis. I have had conversations up to two hours talking about siltation of rolling gates and every minute was useful. I appreciate all the time and effort you put into my research.

Kelwin Koets,

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Abstract

The Netherlands has an impressive infrastructure to manage the country's relationship with water, e.g. dikes, bridges and locks. A crucial aspect of a lock is the gate, which opens and closes the lock. An option is the use of rolling gates. Rolling gates move perpendicular to the length of the lock and are a proven solution commonly used for wide locks (width > 40 m). However, a disadvantage of rolling gates is the susceptibility to siltation. Siltation is the accumulation of sediments (e.g. silt, sand and mud) at locations where the accumulation is disadvantageous. Dredging operations are used to remove the siltation, however such operations are time consuming, expensive and could even be dangerous. Meaning, a feasible alternative is desired.

Thus, the main objective of this research was to design an effective siltation removal system for rolling gates. The siltation of rolling gates is a grey area, literature is extremely limited and the subject is difficult to investigate. As a result, an effort is made to include experts from start to finish in the design process. Experts provide knowledge, experience, insight and more which is essential for this research.

The first step was to create a better understanding of the siltation problem of rolling gates, for which a literature study and expert interviews are used. Subsequently, the acquired information is used to realise a focus for the design. Additionally, more focussed interviews and a site visit to a rolling gate are performed. All information combined leads to the foundation of the design and eventually to the generation of twelve concepts. The concepts are subsequently exposed to an extensive concept selection process, from coarse to refined. The final steps of the selection process are concept scoring *stage 1* and *stage 2*, in which experts are actively involved. *Stage 1* resulted in two remaining concepts. The two concepts are validated with extensive prototyping in a home garage (due to restrictions as COVID-19) and the results are presented to the experts for concept scoring *stage 2*, leading to the final concept.

The experts proved to be crucial from the start since literature is extremely limited. The key findings from the interviews are that the siltation of rolling gates is mainly divided into four different areas. The context differs per area (e.g. components, geometry and waterflow) and an universal solution for a siltation removal system for rolling gates is difficult to achieve. As a result, the design is focused on siltation removal from the gate recesses of rolling gates.

The prototyping is used to validate the remaining concept 1 and concept 2. Concept 1 uses waterjets to remove the siltation and concept 2 uses a scoop. The quantitative data of concept scoring *stage 2* shows concept 1 has an average score of 74% and concept 2 of 60% (relative to a perfect score). In addition, qualitative data in the form of notes from the experts is essential. A main concern of concept 1 is what happens to the siltation after concept 1 successfully removes the siltation out of the recess. However, vessels could disperse the siltation further and early tests (and notes from the experts) seem promising regarding aiming the jets sideways to improve concept 1 even further. Thus, concept 1 is confidently chosen as the final concept. The concept uses stair climber wheels to walk over the edge, removing the need for cranes. As a result, the concept is easy to use, mobile and effective in removing the siltation.

In conclusion, the proposed method is successful in the design of a siltation removal system to remove the siltation from the gate recesses. The experts are essential in the design process of this research and provide valuable information regarding ideas, concerns, improvements and more. Without the experts, this research would not be possible. To further improve the final concept, future tests should focus on aiming the waterjets sideways, as well as tests with fine and compacted siltation. Furthermore, to better understand the effect of the experts on the design process a comparative study should be performed between the proposed method and a method without experts in similar conditions, e.g. on a case study.

Contents

1 Introduction

The Netherlands is well known for the country's relationship with water. Since a significant amount of the Netherlands is below sea level, a constant defence against The North Sea is required. In addition, The Netherlands is crossed by several large rivers e.g. the Lek, Rhine and Meuse. As a result, The Netherlands is connected to a network of European waterways which is primarily used for inland navigation. The complete network includes a total of 40000 km of waterways linked between 18 countries and is responsible for 550 million tons of cargo per year [1].

To further emphasize the importance of waterways in The Netherlands: inland waterways account for 40% of the transport performance and create, combined with Belgium, the most dense network of inland waterways in Europe [1]. In addition, the largest sea port of Europe (Port of Rotterdam) is connected to the North Sea and the large rivers of The Netherlands and is responsible for 450 metric ton cargo in 2014 [2]. Hence, inland water navigation is of high importance for The Netherlands.

Infrastructure is required to realise a functioning network of inland water navigation. The lock is an important aspect of the infrastructure. Multiple types of locks are used in The Netherlands (e.g. storm surge barriers and dewatering gates), however navigation locks are of interest for this thesis. The main function of navigation locks is to provide passage for vessels between two different levels of water [3]. For instance, a navigation lock could be placed within a canal to overcome a height difference or as a barrier between the sea and a canal.

Numerous navigation locks are used in The Netherlands. A substantial stakeholder involved with the navigation locks is the Directorate-General for Public Works and Water Management, or Rijkswaterstaat (RWS) in Dutch. In total RWS is responsible for maintenance and management of 131 navigation locks [4]. Different types of navigation locks are used. For instance, small locks with mitre gates placed in local canals or immense locks with rolling gates suitable for cruise ships. An example is the construction of the largest sea lock worldwide in IJmuiden by RWS and OpenIJ (to be completed in 2022).

1.1. Rolling gates in navigation locks

As mentioned, different types of navigation locks are used. In addition to the size, a clear distinction is the type of gates used in the lock. A standard navigation lock is equipped with two sets of gates with the lock chamber in between. For the type of gates numerous options are available, e.g. mitre gates, lifting gates and rolling gates.

The rolling gate is commonly used for large locks with a substantial width, e.g. the IJmuiden sea lock. The movement of the rolling gate during opening and closing is perpendicular to the longitudinal axis of the lock (thus perpendicular to the travel direction of the vessels). The gate is fixated on a set of undercarriages, which guide the gate along rails. The rails are located within a sill at the bottom of the lock. With the use of a driving mechanism, the gate is able to move along the rails to open and close.

An example of rolling gates is shown in Figure 1 (left). The figure shows the Kieldrecht lock [5]. Instead of two gates in total, the Kieldrecht lock is equipped with additional gates on both sides. The example perfectly illustrates the difference between a closed and an open gate. To open the gate, the gate is retracted into the civil structure and stored in the gate chamber. Meaning, the rails should continue into the gate chamber, which is illustrated in Figure 1 (right).

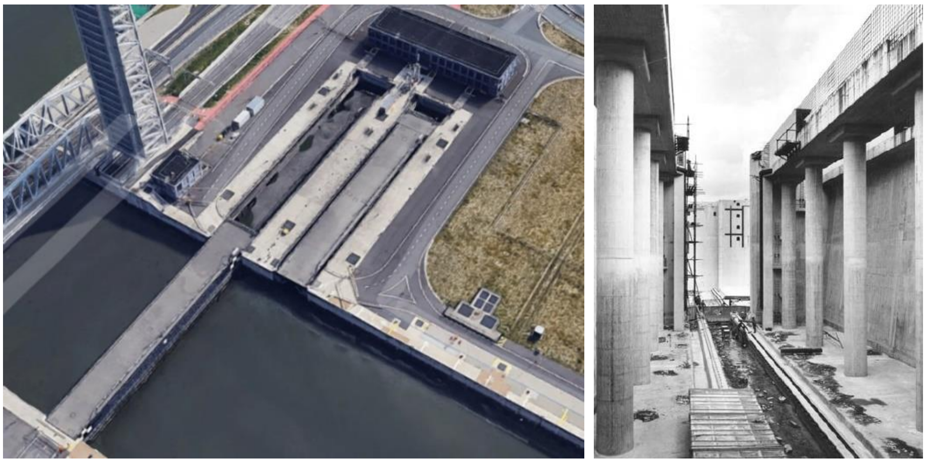


Figure 1. Kieldrecht lock with a closed and open gate respectively (left) [5], gate chamber of a rolling gate in the marine lock in Terneuzen (right) [3].

Rolling gates are the near unanimous choice for lock chambers with a width larger than 40 meter due to several advantages [6]. For instance, a rolling gate is able to function in a situation where the high water level alternates between both sides of the lock, which is the case for tidal locks. However, rolling gates are large and complex structures with numerous open spaces in a harsh environment. As a result, a disadvantage of rolling gates is the exposure to siltation.

1.2. Siltation: definition

To understand the term siltation, the explanation should start with soil. Soil is realised, primarily, by the weathering of rock [7]. Examples of weathering are temperature effects, wind, impact and rain. Rock is broken down by different types of weathering to small particles, which create soil. As a result, soil is composed of different particles. To define soil, the different particles are categorized by size and the most common particle sizes are defined as clay, sand and silt. Important to note is the classification by size, not by mineral constituent. Meaning, different types of sand could have different mineral constituents (e.g. silica) and still be classified as sand due to the particle size [7].

Different classification standards are used. Assallay et al. [8] define (based on the MIT/British standard) silt from 0.002 mm to 0.060 mm and sand from 0.060 mm to 2 mm. An additional standard is the Unified Soil Classification System [9], which states the following ranges: clay < 0.002 mm, silt 0.002 mm to 0.075mm, sand 0.075 mm to 4.75 mm and gravel 4.75 mm to 100 mm. Noticeable are the minor differences between standards and often the used standard is based on preference or country [7].

The particle descriptions could be used to define a soil texture [7]. For instance, soil with a certain percentage of clay, silt and sand could be called loam and, with different percentages, clay loam. The different soil textures could be man made, e.g. the soil for a house plant, or the result of natural deposition. Natural soil deposition is highly influenced by the mechanism of particle transport, e.g. gravity, water, ice or wind.

Water is an important mechanism of particle transport, particles are suspended in water and deposited at different locations, which is the basis for sedimentation [7]. However, sedimentation could result in problems such as siltation. The term siltation is regarded as common knowledge in scientific sources and thus not extensively explained. However, from context from various sources [6, 7, 10, 11] siltation is defined as: *accumulation of silt at e.g. the bottom of a river, harbour, lake or different locations at which the silt is disadvantageous*.

To elaborate, the term siltation is not solely used for accumulation of silt. In The Netherlands the translation of silt is “slib”. The term “slib” is used by experts (deducted from the interviews in section 2.4) to describe the accumulation of different types of sediment. For instance, sand, mud, clay, silt and more. Not solely silt. Thus, for the remainder of the thesis *the term siltation is used to describe accumulated sediments at locations at which the accumulated sediments are disadvantageous*. An example, removing siltation means: *removing the accumulated sediments*. Furthermore, the term silt could (if not defined specifically) refer to various sediments. Note: the term siltation does not include debris, e.g. tires, ropes and more.

1.3. Problem definition

The starting point for the research is a recent project at Witteveen+Bos, an engineering and consultancy firm active mainly in the civil sector. Siltation of a rolling gate proved to be a significant challenge in the design process, resulting in a relevant topic. The occurrence of siltation of rolling gates is a known problem [3, 6] and results in issues with the operation of the gate. However, detailed information regarding the siltation of rolling gates is limited.

A rolling gate is a complex structure and numerous factors could influence the siltation problem of rolling gates. For instance, the water around the rolling gate is constantly moving and particles could deposit anywhere. Meaning, the location of components, the type of water in the lock, the dimensions of the gate and more could possibly all affect the siltation problem.

Eventually, the siltation needs to be removed. The most common method to remove siltation in general is dredging. Dredging is used for e.g. channels, lakes, harbours, rivers, coast lines and navigation locks. However, dredging is linked to several disadvantages. Dredging is a costly and time consuming operation and could include the use of dredging ships, heavy machinery, divers and more [7]. As a result, siltation removal of rolling gates could take a significant amount of time and even is dangerous in certain situations. Meaning a feasible alternative is desired.

1.4. Research objective

Thus, the objective of this research is to design an effective siltation removal system for rolling gates, for which the first step is to create a better understanding of the siltation problem of rolling gates. Which leads to the main research question:

How could a siltation removal system be designed for effective removal of siltation of rolling gates in The Netherlands and Belgium?

The main research question is supported by several sub research questions. The sub research questions focus on aspects which affect the design, e.g. factors which influence siltation, the effects of siltation on rolling gates and the current methods of siltation removal. Furthermore, how valuable prototyping could still be achieved within restrictions is explored as well as the use of experts in the design process. Leading to the following sub questions:

What are influencing factors on siltation that could have an impact on the design?
What are the effects of siltation on rolling gates?
Which measures against siltation of rolling gates are known and how effective are these?
What sort of mechanism can achieve siltation removal?
How could the use of experts benefit the design process?

1.5. Method

Numerous design methods are available, all with variations in the steps, focus, tools and more. For instance, the well known Design thinking is heavily focussed on the user. While other methods, e.g. methodical design [12], focusses less on the user and is more dependent on the designer/design team. In certain design cases the situation could be especially *ill defined*, complex, vague, or even unexplored. In such situations the use of experts could be extremely useful.

Experts are utilised in a wide range of disciplines in multiple ways, e.g. experts are used for consults or in the decision making process. An example is the Analytic Hierarchy Process (AHP) [13], which uses the judgement of experts for the decision making process, e.g. for objectively choosing concepts. However, the AHP is primarily focussed on creating priority scales and more useful for the later phases in the design process. While the early phase could benefit greatly from experts as well.

The circumstances of this research are especially difficult due to several reasons: the siltation problem of rolling gates is a grey area, the literature is *extremely limited* and the subject is difficult to research. For instance, navigation locks are immense structures (mostly inaccessible to public) with most components underwater in a dangerous environment. As a result, this research is particularly suitable for the use of experts. Experts have advanced knowledge, experience, insight and more which could help to define and better understand the subject. Furthermore, the experts could provide input for improvements and concerns, which is useful for the design process.

Thus, the use of experts could be beneficial for the entire design process. However, to the knowledge of the author no method is available which involves experts from *start to finish* in the design process. As a result, an effort is made to involve experts, actively and passively, in the entire design process to increase e.g. the understanding of the problem and objectivity in the concept selection process. A flow chart of the proposed method is shown in Figure 2 (*at the end of this section*) and could be used for similar situations. Blue in the flowchart indicates active involvement of experts (e.g. interviews or the experts are asked to perform a task). The steps of the flow chart are briefly discussed below.

As mentioned, the main objective of this research is to design an effective siltation removal system, for which the first step is to create a better understanding of the siltation problem of rolling gates. Thus, the first mission is to investigate siltation of rolling gates. Initially, a literature study and expert interviews are performed to define the influencing factors on siltation, locations of siltation, resulting issues of siltation and methods of siltation removal. Which is subsequently used to define the focus of the design.

The next step is to set-up the programme of requirements, for which the acquired information is used in combination with additional information (in this research several norms and information gathered during a site visit). Furthermore, needs are extracted from the expert interviews and additional focused expert interviews. The needs are used as an additional control for the requirements: to check if the needs are represented in the programme of requirements.

Subsequently, a function analysis is performed to determine the main and sub functions in a function diagram. During concept generation solutions to the subfunctions are generated and combined in a morphological map. Next the morphological map is used to create the concepts, resulting in 12 concepts.

The following step is to choose between the high number of concepts during concept selection. Four steps are used, from coarse to refined. A diverse panel of experts plays a significant role in concept selection. The first step is concept selection based on discussion and intuition within the design team. Involving the experts with such a high number of concepts will not result in an effective process (time,

complexity, communication etc). The discussion reduces the number of concepts from 12 to 8. Subsequently, concept screening is used to reduce the concepts from 8 to 4. The experts are not actively involved in concept screening since the number of concepts remains high at the start. However, the experts should be kept in mind since the selection criteria used for concept screening are used for concept scoring as well. The selection criteria are the primary needs, which are extracted from the expert interviews. The unweighted selection criteria are used for concept screening, while simultaneously the diverse panel of experts determines the weight factors of the selection criteria for the concept scoring.
In concept scoring stage 1 (S1) the diverse panel of experts is actively involved. The data from concept scoring (S1) is analysed and two concepts remain. During each step of the concept selection process the concepts are altered and improved. Meaning, the two remaining concepts are close together and additional information is required to choose a final concept. *Note: the number of remaining concepts after each step could vary per project.*

Prototype testing is used for concept validation. The prototype tests mainly provide information regarding the main features of the concepts, the selection criteria and notes from the experts. Due to several restrictions (*the entire research started and ended in the COVID-19 pandemic)*, the tests are performed in a home garage. Thus, considering which tests provide valuable information and if the tests could be realised within the restrictions is essential.

Finally, the results of the prototype tests are carefully presented to the diverse panel of experts. The information should be purely objective, e.g. no disadvantages and advantages or recommendations for improvements. The experts use the information for concept scoring stage 2 (S2), leading to the final concept. Choosing the final concept is the end of this thesis, *the detailed design is out of scope.*

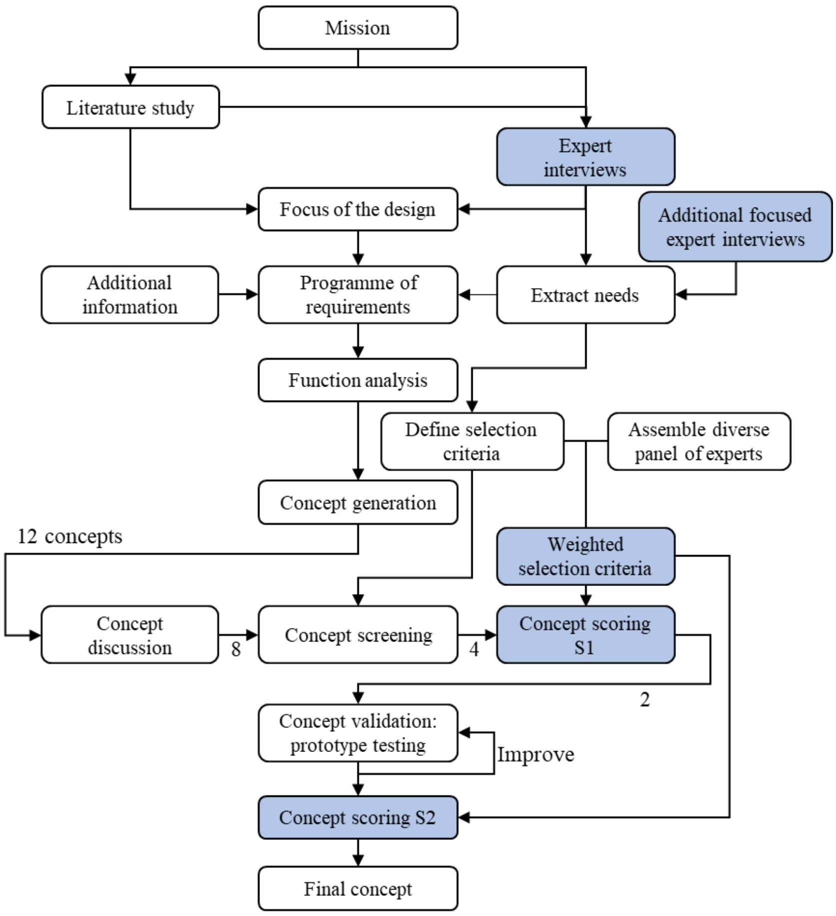


Figure 2. Flowchart of the proposed method involving experts.

2 Analysis

The following chapter discusses the analysis phase of this research. The first two sections provide context regarding navigation locks and rolling gates. Subsequently, to create a better understanding of the siltation problem of rolling gates a literature study and expert interviews are performed. The influences on siltation, locations of siltation, effects of siltation on rolling gates, measures against siltation and more is investigated. The expert interviews provide in depth information, which is subsequently used to determine the focus of the design. Finally, the analysis phase is concluded with setting up the programme of requirements and a function diagram, which are essential for the next phase.

2.1. Context: navigation lock

As mentioned, inland navigation is of great importance for The Netherlands. To realise a functional network of inland navigation, a complex infrastructure is required. One of the components is a *navigation lock*, referred to as a *lock* in the remainder of the thesis. Even though the lock has been used for multiple centuries in The Netherlands, the main function remains the same: *provide passage for vessels between two different levels of water* [3], e.g. due to tidal differences. In addition to the main function, the lock fulfils the following functions [3]:

1. **Water retention:** the lock is used to retain water, independent of the conditions. An example are the locks in the Afsluitdijk [14], which provide protection against the North Sea while exposed to e.g. storms or tidal differences. A lock could provide *one* or *two sided water retention*. With *one sided retention* the high water level is one side and will not change (e.g. a canal with a height difference). With *two sided retention*, the high water level alternates between the difference sides of the lock. An example is a sea lock, due to tidal differences.
2. **Water management:** the lock is used to limit water loss and to discharge or take in a certain volume. In certain situations the water loss should be limited, e.g. in transitions from polluted to non polluted water or from salt to fresh water. Pumps could be used to pump the water back to the high water side and limit the water loss. The discharge or intake of a certain volume is related to e.g. a sudden rise in water level. For instance, a severe (local) rain storm could result in the rise of an inland canal and the lock is used to discharge the water and prevent flooding.

The main operating principle of a lock is shown in Figure 3 and explained in several steps [3] with the relevant components:

- **Figure 3 A**: a vessel approaches from the low water side (downstream) with the purpose to enter the high water side (upstream). Gate 1 is open and the water level in the lock chamber (area denoted by 3) is equal to the downstream level, meaning the vessel could enter the lock chamber.
- **Figure 3 B**: in the lock chamber, the vessel is moored to the walls for safe operation conditions. Subsequently, lock gate 1 is closed to seal the lock chamber. To rise the water level, openings in lock gate 2 are opened. As a result, water from upstream fills the lock chamber until an equilibrium is reached.
- **Figure 3 C**: once the water level in the lock chamber is equal to the upstream level, gate 2 is opened. The mooring is removed from the vessel and the vessel could leave the lock chamber. To travel from upstream to downstream, the order of operation is reversed.

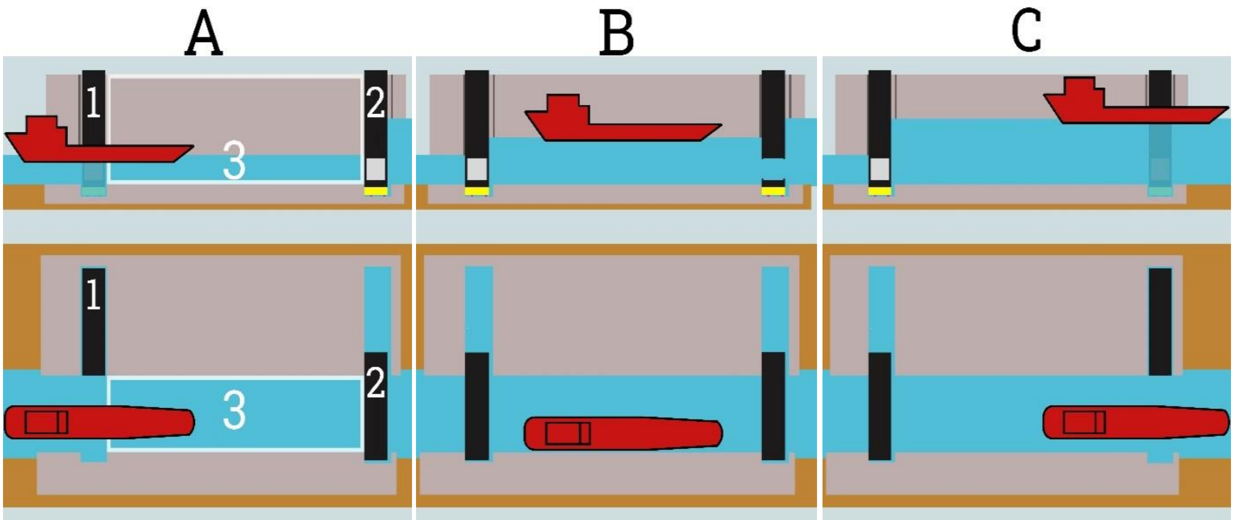


Figure 3. A: the vessel enters the lock chamber, B: filling of the lock chamber and C: the vessel leaves the lock chamber.

2.2. Context: rolling gates

To provide context for the rolling gate, the following section discusses the working principle, main components and advantages/disadvantages of a rolling gate. For additional reading, detailed information regarding the components is found in *Appendix A: additional information rolling gates*. Most of the following information has been retrieved from Design of Locks [3].

To visualize the working principle of a rolling gate, the main components are illustrated schematically in Figure 4 (left). A rolling gate moves perpendicular to the longitudinal axis of the lock to open or close the lock. For a functioning lock at least two rolling gates are required, one on each side of the lock chamber. Additional gates could be present, e.g. in the middle to divide the lock chamber or backup gates as shown in the introduction for the Kieldrecht lock (Figure 1). To open the lock, the rolling gate recesses into the gate chamber. As a result, the gate will not obscure the navigation channel. Furthermore, the gate chamber could be transformed into a dry dock to perform maintenance on the gate. To close the lock, the rolling gate rolls across the lock chamber to the opposing side. At the opposing side, a gate recess is present in which the gate locks. Subsequently, a sealing is created between the gate, the gate recess, the sill and the gate chamber. With the rolling gate in locked position, water levelling is engaged by opening of the gate openings.

For the rolling movement the gate uses a rail and undercarriages. The structure of the gate is placed upon one or more undercarriages, which are normally equipped with wheels to roll along rails. The rails are fixated on a sill, which is slightly recessed (e.g. 0.7 m) in the bottom of the lock. To create the rolling movement a driving mechanism is used. Commonly the driving mechanism is a combination of cable drums, cables and a motor connected to the gate by a top carriage. The top carriage is connected to the gate and, similar to the undercarriage, rolls along rails. However, the rails for the top carriage are above water level.

For further visualization, the schematic illustration could be compared to the real life example of the Panama gates in Figure 4 (right). *Note: in Figure 4 (right) the gate chamber is referred to as the large recess and the gate recess as the small recess. Both definitions are used in literature, however this thesis will solely use gate chamber and gate recess*

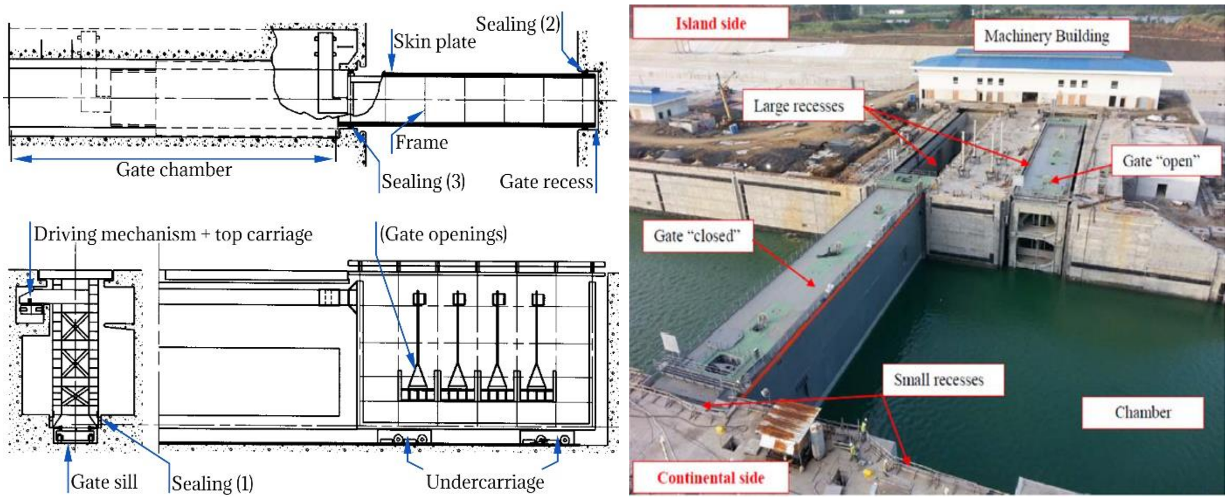


Figure 4. Overview horizontal rolling gate with levelling openings (left) [3] and Panama gates and machinery building (right) [6].

One of the main reasons rolling gates are preferred for wide locks is that no rotation is required around a hinge. The rolling gate rolls through the water, in contrast to a mitre gate. A mitre gate rotates around a hinge and with increasing width the hydraulic resistance increases significantly compared to a rolling gate [6]. Due to the suitability for wide locks, rolling gates are often used in sea locks e.g. the IJmuiden locks. Sea locks are exposed to tidal differences, meaning (as discussed in section 2.1) the lock should provide two sided retention, which is one of the advantages of a rolling gate.

Additional *advantages* are [6]: 1. due to the rolling motion no obstruction in height (thus vessel height is not limited), 2. a road could be realised on top of the rolling gates as an alternative for a bridge, 3. a relative short opening and closing time and 4. a relative simple and reliable driving mechanism (low risk).

However, some *disadvantages* are [6]: 1. numerous moving parts underwater (increased maintenance), 2. rolling gates are susceptible to siltation, 3. a massive concrete construction is required for rolling gates and 4. in case of a vessel collision in closed position, the gate could get stuck (blocking the lock).

To conclude, rolling gates are a proven and commonly used solution with advantages and disadvantages. However, as stated by PIANC [6] each installation of a rolling gate is extremely specific and all aspects should be considered carefully.

2.3. Siltation: on location

With the context of locks and rolling gates clear, the next step is create a better understanding of the siltation problem of rolling gates. The definition of siltation has been introduced in section 1.2 and is required to comprehend the siltation problem of rolling gates. However, siltation of rolling gates is an extremely specific topic and literature is limited. The approach is to review literature with analogies to locks, which could be found in siltation of harbours. Locks are often combined with harbours and thus exposed to similar conditions. An example is the Port of Antwerp, which includes several locks [15].

Harbour siltation has been an issue since the existence of harbours and is linked to the dormant conditions created by the sheltering function of harbours [10]. Difficulties often arise for vessels due to siltation at the entrance zone of a harbour. Several factors appear to be related to the degree of siltation: the design of the harbour entrance and the environmental and physical conditions. The different types of flow (connected to fluid density) are especially important. The types of flow could be specified as

[10]: 1. fresh water flow (e.g. in canals or rivers), 2. brackish water flow (mix of salt and fresh water, e.g. in estuaries or tidal rivers) and 3. salt water flow (e.g. at locations close to sea).

The type of water proves to have a significant effect on the siltation. Nasner [16] performed an analysis to quantify the effect of different environmental conditions on the siltation. The research showed a significant difference in siltation between the types of water. In fresh water, siltation appeared to be a factor 5 less when compared to brackish and salt water.

The maximum siltation is generally found in a specific zone, the turbidity maximum (TM) [10]. Stratified flows in combination with a salt water wedge are a known occurrence in the tidal zone of rivers. The location where the edge of the salt water wedge is moving back and forth is known as the TM. In the TM fluid layers of sediment are formed in slack tides (unstressed water conditions) as a result of deposition. Thus, harbours located within the TM are prone to the layers of sediment, which enter the basins.

The TM is also present in estuaries, defined as the estuarine turbidity maximum (ETM). The ETM is well known to increase siltation in harbours [11]. Harbours are often situated within estuaries due to the sheltered conditions and connections to inland waterways. An example of such a harbour is the Botlek Harbour in Port of Rotterdam, 20 km from the North Sea (inland). The yearly siltation is significantly larger than all more inland basins combined [11]. The research of de Nijs et al. [11] concluded the high siltation in Botlek Harbour is mainly caused by salinity-induced density gradients. As a result, suspended particle matter is available for exchange between the harbour and the tidal river.

To account for siltation in harbours, different measures are used. An example is a current deflecting wall (CDW) for the Deurganckdok in Antwerp, discussed in the research of van Maren et al. [15] and shown in Figure 5.

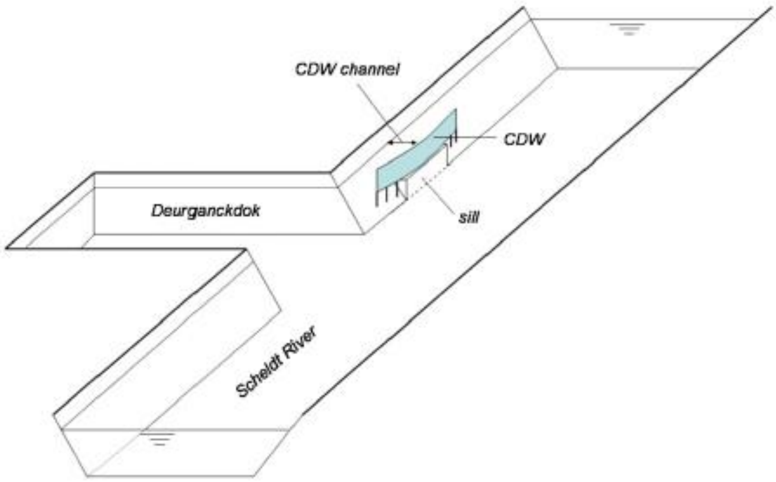


Figure 5. Sketch of the Current Deflecting Wall near the Deurganckdok (not to scale). The CDW consists of a guiding wall placed on a sill in its middle and is supported by piles in the upstream and downstream direction. The CDW channel is the channel in-between the guiding wall and the nearby river bank [15].

The Deurganckdok is located in the Port of Antwerp with an open connection to the Scheldt river. The open connection is different from the additional docks, which are connected to the Scheldt river with locks. As a result, high siltation rates are expected. Which is realistic since the TM of the Scheldt river is near the Deurganckdok.

The main mechanisms of a CDW to reduce siltation are: 1. decrease the power of exchange flows (e.g. the salinity-induced density currents) and 2. redirect the turbid bottom water around the entrance of the dock. The research of van Maren et al. [15] estimate a decrease in siltation of 18% due to the CDW. Van Rijn [10] provides a clear overview of additional measures to reduce siltation in harbours. For instance: a silt curtain, the discussed CDW, optimize the geometry of the entrance, realise a sill at the entrance and select a suitable location for a new site (e.g. not within the TM). However, no measure completely eliminates the siltation.

As mentioned, literature on the siltation of rolling gates is limited. A report by PIANC [6], which specifically focusses on movable bridges and rolling gates, barely discusses siltation. The report mentions the susceptibility of rolling gates to siltation and debris. Siltation could occur at the bottom, on the rails and undercarriage. Furthermore, during closing of the gate siltation could be sucked into the gate chamber. Subsequently, the siltation settles and accumulates in the gate chamber.

Two measures against siltation of the locks in Port of Antwerp are briefly mentioned: 1. a venturi system and 2. mixers. The two systems are used to prevent siltation from settling during movement and are illustrated in Figure 6 respectively. The mixers are used to remove silt from the buoyancy tanks and the venturi system is used to transport silt from the undercarriage and rails [6]. However, no additional details on the working principle or the effects are discussed.

Figure 6. Venturi system inlet detail (left) [6] and Internal gate structure and mixer for debris and sediment control (right).

The interesting findings are the increase of siltation in salt and brackish water (relative to fresh water) and in the (E)TM. The increase of siltation in such conditions could mean siltation removal should be performed more frequently. Furthermore, siltation seems to occur in different locations of a rolling gate, which could mean the context differs per location. Expert interviews are the next step and could benefit from the findings. For instance, focus the interviews on locks in estuaries (e.g. the Western Scheldt and Eastern Scheldt) or along the coast line.

2.4. Expert interviews

As mentioned, siltation of rolling gates is an extremely specific subject and relevant literature is limited. Thus, to further investigate the siltation of rolling gates, expert interviews are used. The experts could provide information regarding the siltation problem which is not found in the literature. The information is crucial to understand the siltation problem, e.g. where does siltation occur, what are the difficulties, how is siltation currently removed, what are the effects of siltation and more. Subsequently, the information could be used for the design of the siltation removal system.

In total six interviews are performed regarding different navigation locks with rolling gates. An overview of the locks is provided in Figure 7 and the diverse assembly of interviewees is shown in Table 1. The following sections discuss the interviews in detail with the important findings.

The transcripts of all interviews from this thesis (as well as follow up questions) are found in *Appendix B: interviews,* organized per expert.

Figure 7. Overview of the navigation locks discussed in the interviews.

Table 1. Locks with corresponding interviewees.

Lock	Interviewee
1. Terneuzen lock	Expert 1 – Civil Adviser
2. New Lock IJmuiden	Expert 2 – Maintenance Manager
3. Krammer locks	Expert 3 – Technical Adviser
4. Northern lock IJmuiden	Expert 4 – Asset Manager
5. Meppelerdiep lock	Expert 5 – Advisor Water management
	Expert 6 – Object expert
6. Port of Antwerp	Expert 7 – Maintenance Specialist

2.4.1. Terneuzen locks [17]

The Terneuzen lock complex is situated between the Western Scheldt (estuary) and the Ghent-Terneuzen canal, which is connected to the Port of Ghent. Due to the brackish water the Western Scheldt is prone to significant silt and thus siltation is a relevant problem in the Terneuzen locks. The exact composition of the siltation is dependent on numerous factors, e.g. the weather and the season, and thus difficult to define. However, at the bottom sand is dominant and could become solid, meaning extensive cleaning operations are required.

The main location of the siltation problem is within the gate chamber. In open position (gate recessed into the gate chamber) several meters remain between the end of the gate and the end of the gate chamber and thus the area is prone to siltation. Eventually, the gate is not be able to recess into the gate chamber completely. The siltation could reach up to 4-5 meter at the end of the gate recess and decrease to 1 meter near the lock chamber. Meaning, measures are required to remove the siltation to prevent failure of the gate. In the past (around 1980) proactive measures have been used: 1. a pump at the back of the gate chamber and 2. a water pipe at the end of the gate chamber. The pump was used to suck away the siltation and discard the siltation into the sewer. However, the effects were limited and in current times discarding the siltation in the sewer is not permitted. The water pipe was used to blow the siltation from the gate chamber into the lock chamber. The operating costs were significant and the effects were once again limited. As a result, both measures were terminated.

Meaning a reactive measure is required. Currently a dredging operation is used in intervals of six months to clean the gate recess. The interval has been determined in the past and is not based on data. The interval was sufficient in the past, however at the moment several gates require an increase in dredging frequency. A proposal by *expert 1* is to measure the operating loads of the gate and set a maximum. In case the operating loads exceed the maximum, dredging is required. Currently the siltation is dredged with a dragline crane, meaning the siltation is scooped from the gate chamber and discarded into trucks.

However in certain situations the siltation could harden and the dragline crane is not sufficient. For instance, the middle gate was once out of service due to maintenance for several months. Subsequently to the maintenance the gate was unable to move (the siltation had hardened) and a team of divers was required with pumps and high pressure washers to remove the siltation. Thus, regular dredging is required to prevent hardening. Additionally, movement is essential. *Expert 1* mentions siltation becomes a problem if a gate has not been moved for several days. As a result, the protocol is to open and close each gate at least once every 12 hours.

The main described siltation problem is present in the West lock. The lock complex is divided into three different locks: the middle lock, East lock and West lock. In addition, a new project is under construction: the new lock Terneuzen. The West lock is equipped with five rolling gates, illustrated in Figure 8 [18]. The gates are labelled A to E. Gate A is located at the Western Scheldt side and gate E is located at the canal side.

Figure 8. West lock Terneuzen [18].

A trend is noticeable in the difference of siltation per gate. Per advise of *expert 1* the removed siltation has been measured for April 2020. The results are shown in Table 2. The amount of siltation is decreased from gate A (estuary side) to gate E (canal side), which is corresponding with the discussed literature in section 2.3. The trend could be used for future solutions, e.g. a less extensive siltation removal system is required on gate E than on gate A.

Table 2. Additional data regarding removed siltation in Westlock Terneuzen [17].

Gate	Amount of siltation (mixed with water) [m^3]
West lock gate A	312
West lock gate B	200
West lock gate C	176
West lock gate D	128
West lock gate E	128
Total	944
Total siltation without water (estimated)	750

2.4.2. New lock IJmuiden [19]

The New lock IJmuiden is a project which will be completed in 2021/2022 in the IJmuiden lock complex. The New lock will be realised between the existing Northern lock and Middle lock and once completed the New lock will be the largest sea lock worldwide. The IJmuiden lock complex is situated between the North sea and the North Sea Canal, which is the canal to Amsterdam. Due to the location the lock is exposed to salt water (North Sea) and brackish water (North Sea Canal), thus siltation could be an issue. Since the lock is not completed, no operational experience is available.

The design of the largest sea lock worldwide is an immense complex project with numerous issues and siltation was not the top priority during the tender period. However, several measures are implemented against siltation in the design: 1. a maintenance regime, 2. waterjets and 3. a silt reservoir.

The lock is not completed, meaning the main location of the siltation problem is not known. During the design contact was made with the Kaiserschleuse in Germany and the Northern lock in IJmuiden. The Kaiserschleuse had issues with the rails due to siltation, the Northern lock had siltation issues in the gate chamber. As a result, the maintenance regime (1) is implemented. The gate chamber will be dredged 1-2x annually. The dredging frequency is lower in the Northern lock, thus the siltation is more compact and difficult to remove. By dredging 1-2x annually in the New Lock, the prediction is the siltation could be blown away or sucked up by a pump. A crane will be placed on top of the gate or the gate chamber, which lowers a dredge pump. The dredging is realised while the gate is closed, to clean the complete gate chamber. *Expert 2* argues the approach of regular dredging could eventually reduce costs. Furthermore the complete lock chamber is dredged 2x annually with a dredging vessel.

In addition a waterjet system (2) is installed on the undercarriage. The waterjet blows in front of the wheels. The waterjets solely blow during the closing motion, as the gate is leaving the gate chamber. During the closing motion the waterjets will not blow, even though siltation could occur in the closing motion. For the waterjets a pump is incorporated in the gate and power is provided by the gate.

The last measure is a silt reservoir (3). The reservoir is located at the gate recess and is 1.5-2 meter deeper than the rails. The reservoir is a simple slot/hole in the bottom. During the closing motion the waterjets (2) blow the silt in front of the wheels and the silt is blown and pushed into the reservoir towards the end of the closing motion.

As mentioned, the siltation was not the main priority during the design. Furthermore, the knowledge was limited. Contact with several parties (Northern lock, divers of RWS and divers from an external party) lead to a recommendation of 2/3x annual dredging of the gate chambers. However, experts mention the maintenance frequency should be even higher to prevent the siltation from hardening. As a result, the idea was to implement an ingenious system.

The system would include bulkheads attached to the gate to create a principle similar to a piston. In theory, the siltation would be agitated during movement of the gate and removed from the gate chamber in combination with the water. However, the New lock has an extreme high availability, 18 hours down time annually. Additional downtime results in a fine of €160000/hour. Since the system would have additional components with risk of failure, and thus additional downtime, the decision was made to remove the system.

To conclude, siltation will occur and measures have been taken. However, experience with the operational lock is required to confirm if the siltation problem is more significant or less significant than expected.

2.4.3. Krammer locks [20]

The Krammer locks is a lock complex situated between the Eastern Scheldt and the Zoom lake. The Eastern Scheldt is salt water, the Zoom lake sweet water and siltation is certainly an issue. The main location of siltation is at the end of the gate chamber and sand is dominant. To remove siltation the following measures are used: 1. a scraper, 2. a siltation reservoir and 3. dredging.

The scraper (1) and siltation reservoir (2) could be seen as a combination and are similar to the waterjet and siltation reservoir in the New lock IJmuiden (section 2.4.2). The scraper is a U or H-beam attached to the front undercarriage, 2-3 cm above the rails. During the closing motion the scraper pushes the siltation ahead of the gate. Near the gate recess a siltation reservoir is realised in which the silt is pushed. The reservoir is approximately 0.5 m deep and located between the rails. The scraper is located above the rails, meaning siltation between the rails is not be pushed away. However, siltation on the rails has never been an issue at the Krammer locks. Since the Krammer locks are used by numerous large vessels each day, which create significant turbulence, the siltation reservoir is prevented from filling up completely. Furthermore, the turbulence from the vessels removes siltation from the sill.

Nevertheless, dredging (3) is required to remove siltation. Once a year, usually in week 40-50, a dredging operation is used to clean the gate chamber and the siltation reservoir. The gate chamber is the main issue, siltation accumulates in the gate chamber and could only be removed by dredging. As mentioned, sand is dominant and the dredging frequency of 1x annually is sufficient to prevent the siltation from hardening. However, if the frequency is reduced problems arise.

For dredging divers (~3), a barge, a crane and dredge pumps (~2) are used. The divers are submerged with the pumps and suck away the siltation, which is stored on the barge. The crane is used to move the divers and pumps. The costs are approximately: €700-1000 per day for the barge, €250 per hour for a diver, €250 per hour for a crane and additional costs for the pumps. A dredging operation per gate (thus one gate chamber and one siltation reservoir) is around 1.5-2 days. Meaning, the dredging cost are €13050-18000 annually per gate..

Once the dredging is complete, no additional control is performed. RWS will not measure the amount of siltation left. Furthermore, the composition of the removed siltation is not tested. In addition to the siltation, growth of sea life (e.g. oysters and clams) is a problem. Actually, the main function of the scraper is to remove sea life and additional debris. However, the growth of sea life is not within the scope of this thesis.

2.4.4. Northern lock [21]

The Northern lock IJmuiden is located in the IJmuiden lock complex, similar to the New lock IJmuiden in section 2.4.2. Thus the locks have similar conditions, salt and brackish water. However, in contrast to the New lock the Northern lock is operational and information based on experience is available.

Siltation is mainly an issue at the end of the gate chamber. Siltation eventually leads to failure. Sensors on the gate are used as a tool to control the opening and closing of the gate. Eventually, the siltation prevents the gate from opening to the end position and the sensors register a failure. An emergency solution is to relocate the sensor (approximately 50 cm) to eliminate the failure. However, the gate chamber requires cleaning on short notice to prevent further issues.

Several measures are used in the Northern lock: 1. a scraper, 2. siltation reservoirs, 3. water jets, 4. a portable pump and 5. dredging.

The scraper (1) and siltation reservoirs (2) are similar to the system at the Krammer locks (section 2.4.3), however at the Northern lock the scraper is a solid beam and the siltation reservoirs are different. The rails of the Northern lock are situated on a mount (protruded from the lock bottom) and siltation reservoirs are located all along the rails, on both sides, approximately 50 cm below the rails. Thus the siltation is pushed into the reservoirs.

In addition, waterjets (3) have been added to the undercarriage. The waterjets were not incorporated in the original design. The waterjets are used to prevent siltation from settling on the rails, which is successful. However, the siltation is blown in both the siltation reservoirs and the gate chamber. Which contributes to the siltation in the gate chamber.

In the past a portable pump (4) was used. The pump would be lowered into the gate chamber by a crane and moved around the gate chamber to suck up the siltation. In closed position of the gate, the pump would be able to clean for a significant amount of time. In open position of the gate, the pump would be stored at the end of the gate chamber (in open position 6 meter remains between the end of the gate and the end of the gate chamber). However, the pump would get clogged frequently and require cleaning and maintenance. As a result the pump was not profitable and eventually discarded.

As a result, dredging (5) is used to clean the gate chambers. Normally, a regular dredging interval should be used. However, the maintenance regime is not upheld due to contract issues. Consequently, no regular dredging is performed and the siltation hardens and eventually become solid. To remove the hardened siltation a pump is not sufficient. Divers with high pressure washers are required to loosen the siltation and subsequently the siltation could be sucked up. The intensive cleaning operation increases the costs to approximately €60000 per gate.

Due to the brackish and salt water significant siltation is present, normally the siltation is a combination of sand and grit. The siltation could increase the loads on the driving mechanism, which could lead to increased wear and eventually failure and motor revision. Meaning the cleaning of siltation is of high importance, especially to prevent hardening.

2.4.5. Meppelerdiep lock [22]

The Meppelerdiep lock is a relative new lock completed in 2017. The Meppelerdiep lock was transformed from flood lock to navigation lock with rolling gates. The lock could be seen as a divider between the Lake IJsel and the water surrounding Meppel. All surrounding water of the Meppelerdiep Lock is fresh water, however siltation remains an issue. In normal conditions no differential head is present. Meaning, the lock is solely used in certain conditions which result in a differential head (e.g. storm on the Lake IJsel). As a result, the lock is used approximately 26 days annually. When not in use, the gates are in open position and recessed in the gate chamber.

Three systems are used against siltation: 1. a siltation reservoir, 2. a scraper, 3. waterjets, and 4. dredging. The systems are shown in Figure 9.

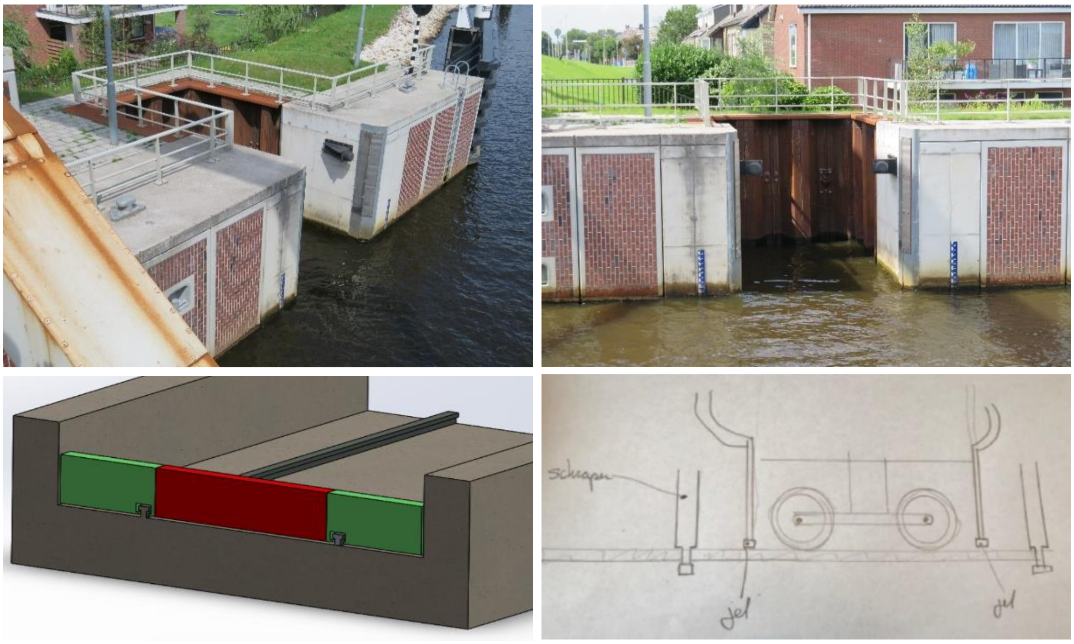


Figure 9. Siltation reservoir at the gate recess (top), sketch of the scraper (bottom left) [22] and sketch of the waterjet system (bottom right) [22].

The systems are used simultaneously to remove siltation from the rails and the working principle is similar to the systems in the Northern lock IJmuiden (section 2.4.4). The main differences are the location of the siltation reservoir (1) and the shape of the scraper (2). Instead of a beam above the rails, the scraper is contoured around the rails and sill: the scraper scrapes out the complete sill. The siltation reservoir is placed at the gate recess, however adaptions have been made to the gate recess. Normally a gate recess is shallow. For instance, a normal gate recess would stop at the black stops in Figure 9 (top). Evidently, the gate recess at the Meppelerdiep Lock has been expanded. The siltation reservoir is realized in the expansion with an approximate dimension of 5x5x5 meter. The depth of 5 meter is measured from the bottom of the lock.

The gates are equipped with two undercarriages each and 4 waterjets (3) are used per undercarriage: two in front of the wheels and two behind the wheels. The waterjets blow during closing and opening of the gate. The combination of the systems is successful and siltation is removed from the rails and collected in the siltation reservoir. However, the systems contribute to the main location of siltation.

The main location of siltation is within the siltation reservoir. Even though the main function of the siltation reservoir is to collect siltation, the reservoir fills up too quickly. The prediction was that the siltation reservoir requires dredging 1x annually. However, the siltation reservoir is dredged 4x annually and thus the costs are increased significantly. The closing time of the gate is measured. Meaning, if the normal closing time is 40 seconds and the time increases significantly dredging is required.

The siltation is generally a combination of peat, fractions of wood and mud and will not harden. Which is probably induced by the regular dredging. Dredging (4) is realised with an excavator, divers and a barge. The excavator digs up the siltation and places the siltation on the barge. Once the excavator operator concludes the dredging is completed, the divers inspect the bottom to confirm. However, due to agitated siltation and muddy water the vision is minimal. Meaning siltation could remain in the reservoir. The total cost of the dredging operations (4x annually for both gates) are €100000.

Currently no further siltation issues are present. However, the lock is new and *expert 6* argues the situation should be monitored for changes.

2.4.6. Port of Antwerp [23]

The Port of Antwerp is the largest port in Belgium and second largest in Europe. In total 24 rolling gates are used. Furthermore, the Kieldrecht lock is located in the Port of Antwerp. The Kieldrecht lock is currently the largest sea lock worldwide, until the New lock IJmuiden is completed. The Port of Antwerp is located at the Scheldt river, which is connected to the Western Scheldt (estuary) in the Netherlands. The water conditions are brackish and sweet, depending on the tidal conditions. Furthermore the Port of Antwerp is located near the TM of the Scheldt river [15], thus siltation is certainly an issue.

The interview with *expert 7* was extensive and the siltation could be divided into three different sections: 1. on top of the buoyancy tanks, 2. in the gate chamber and 3. in the gate recess. In advance to the description per section, the two major measures against siltation are discussed: 1. mixers and 2. airlifts.

The mixers (1) are briefly mentioned in section 2.3 (show in Figure 6 right), however the interview with *expert 7* provided additional information. The location of the mixers on the gates is illustrated in Figure 10 (left). The mixers are comparable to the propeller of a ship. The mixers create a water flow by use of electricity. The costs of the mixers are €175000 in a set of two, with a design life of approximately 15 years. In total 4 are installed per gate (thus €350000). Furthermore, operational costs of €500 annually are required per gate (excluding electricity).

The airlift (2) is illustrated in Figure 6 (left) in section 2.3 and the working principle in Figure 10 (right). The working principle is based on the venturi effect. Pressurized air is blown into an inlet (light blue arrow) and due to the venturi effect, siltation is sucked up at the bottom (spotted dark blue arrow). Subsequently the siltation flows through tubes and eventually is blown out of the tubes. Each gate is equipped with 16 tubes, which are divided into sets of 4. Meaning, a set of 4 is connected to one shared inlet. Each set of 4 tubes is situated on a corner of the gate. The entrance of the tubes is at the bottom of the lock (to reach the siltation) and the exit is slightly below the buoyancy tanks. To operate the airlift a mobile compressor is required, which is placed on top of the gate by truck. The compressor is switched manually from set to set. All gates in Port of Antwerp are equipped with the airlift system, leading to significant costs. The installation costs are €250000 per gate and the design life is approximately 20 years. The operational costs are €2600 annually per gate. *Note: the airlift is able to suck up "loose" siltation, not compacted and hardened siltation.*

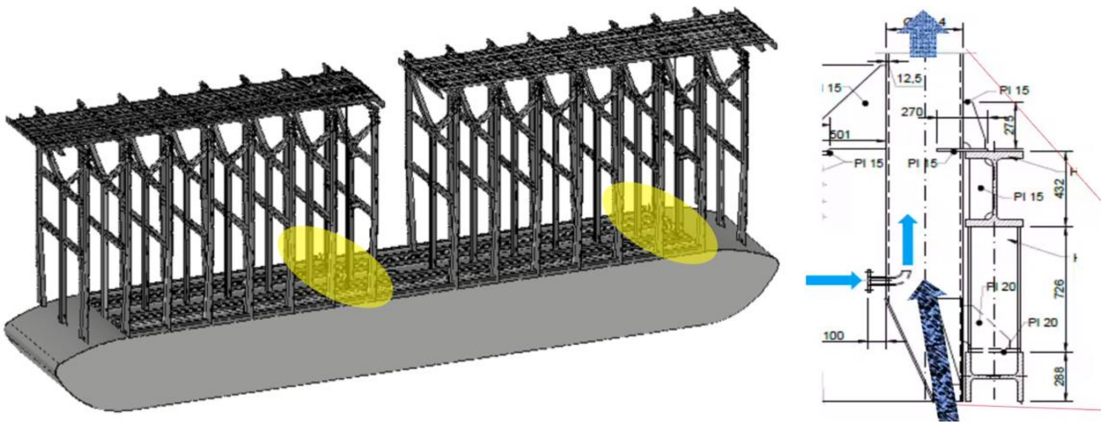


Figure 10. Location of the mixers (in sets of two) on the buoyancy tanks (left) and the airlift working principle (right) [23] [not to be copied without permission of Port of Antwerp].

1. On top of the buoyancy tanks

Siltation on top of the buoyancy tanks appears to be a major issue. All gates in Port of Antwerp are equipped with buoyancy tanks due to the weight of the gates. The buoyancy tanks are located approximately in the (vertical) middle of the gate and along the complete length. In Figure 10 (left) the top part of a gate is shown, including the buoyancy tank. The bottom part (framing) and the skin plating is not shown. Since the gates in Port of Antwerp are open at the front, water flows through the gate during operation. As a result, siltation occurs on top of the buoyancy tanks. Due to siltation, the weight on top of the buoyancy tanks increases, which increases the loads on the driving mechanism and carriages. The required power is increased and eventually the gates might not be able to open and close properly. No major failures have occurred in Port of Antwerp except two incidents with fracture, which are believed to be related to siltation. However, in Zeebrugge (Sea port) failure of an undercarriage was directly related to increased weight due to siltation. The siltation is shown in Figure 11.

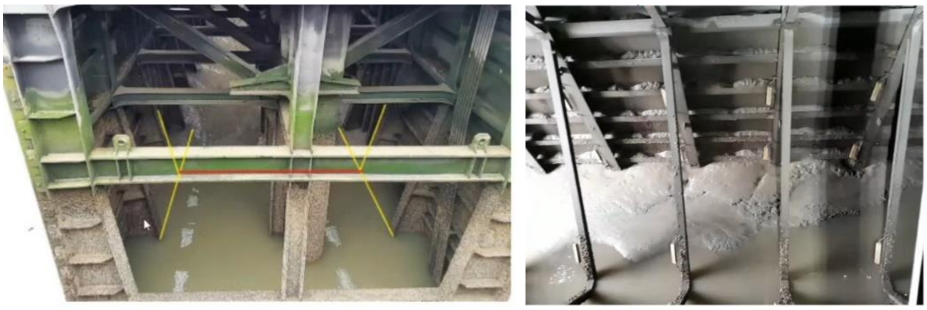


Figure 11. Siltation on top of the buoyancy tanks [23][not to be copied without permission of Port of Antwerp].

To counter the siltation, installation of the mixers (1) started in 1990. The mixers are installed in the (horizontal) middle and at the end of the gate in sets of two, illustrated in Figure 10 (left). The mixers have been installed on all gates except three. To install the mixers the gate should be above water, which should be combined with major maintenance and thus requires extensive planning.

Each lock in Port of Antwerp is equipped with four gates: two at the side of the Scheldt river and two at the side of the dock. The gates are numbered 1-2-3-4, with gate 1 at the Scheldt side and gate 4 at the dock side. Evidently, the siltation at the dock side is significant less than at the Scheldt side. As a result, the mixers on the gates at the dock side are not utilized.

An important contribution to the siltation problem is movement of the gates. The inner gates (2 and 3) are mainly backup gates and are normally not used. Less movement results in more siltation. Thus, the protocol is to open and close all gates a minimum of 1x per 12 hours. The success of the mixers and movement is based on weight measurements. As mentioned, the weight increases due to siltation. The weight is measured and compared with the "normal" weight (without siltation) to conclude if the siltation is removed. Based on the measurements, the effects are positive: the siltation on the buoyancy tanks is under control. However, the used load cells are not ideal for the measurements. Thus, the success could only be completely confirmed once the gates are above water.

2. The gate chamber

Once a gate is in open position, recessed in the gate chamber, several meters remain between the gate and the gate chamber. An additional modus is available, called the ultimate open position in which the gate is brought back further. The ultimate open position could be used in case the front undercarriage needs maintenance. The gate is moved in ultimate open position and the front undercarriage is picked up. To achieve such an operation, the gate chamber is emptied of water and siltation is removed. However, siltation at the end of the gate chamber is not a major issue: siltation is removed manually from the gate chamber once every 10-15 years. The manual operation is realised with excavators and bulldozers.

The siltation in the gate chamber is "controlled". To control the siltation the mixers (1) and airlift (2) are combined. The gate is placed in the open position and the airlifts (at the back corners) are engaged to suck the siltation from the end of the gate chamber to the top of the buoyancy tanks. Subsequently, the siltation is transported by the flow of the mixers to the front of the gate. In front of the gate the siltation is removed by turbulence of vessels. The process is repeated several times until the gate is able to reach the ultimate open position.

In theory, the method should be done regularly. However, due to the labour intensive operation with the mobile compressor no regular interval is achieved. In addition, the results of the method are unclear since no visual confirmation is possible. Nevertheless, since the manual cleaning operation is merely required once every 10-15 years the method with the mixers and airlifts is believed to have a positive effect.

3. The gate recess

The siltation in the gate recess remains the *main issue*. In front of the wheels of the undercarriage ploughs are installed, illustrated in Figure 12. The ploughs push silt forwards during the closing motion, towards the gate recess, causing siltation of the gate recess over time. As a result, the required power for the gate movement increases, until a limit is reached and the gate is not able to close properly. Occasionally the gate is able to close by going back and forth, however the siltation is compacted further. In the past a waterjet system was used on the undercarriage, which was removed 30 years ago. The system was too vulnerable with permanently submerged pumps and motors.

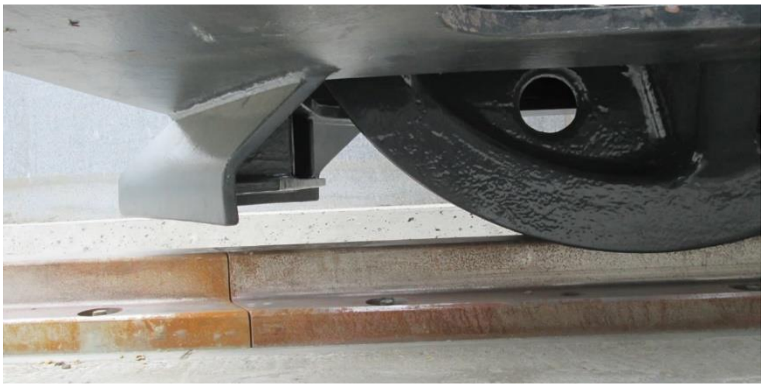


Figure 12. Plough in front of the wheels [23][not to be copied without permission of Port of Antwerp].

The airlifts (2) were used to clean the gate recess, similar to the gate chamber, however the effect was not sufficient. To remove the siltation in the gate recess a dredging operation with divers is required. The divers use pressure washers to blow away the siltation. The operation is done 4x annually per gate recess with a cost of €1250 per gate recess per operation. Meaning the total costs for the Kieldrecht lock (4 gates) would result in €20000 annually. The proposal is to eliminate the divers and use a crane (due to safety issues), however no suitable crane has been found.

As shown in Figure 12, the ploughs are not sufficient to remove all siltation from the rails. Meaning siltation remains between the rails and could eventually harden. However, no problems arise from the siltation between the rails and thus no further measures are used. *Expert 7* would prefer a siltation reservoir near the gate recess to collect the siltation, similar to the New lock IJmuiden or Krammer locks. The siltation reservoir might reduce the dredging frequency.

Movement

The main advise of *expert 7* is to open and close the gates frequently, even backup gates. As mentioned, the protocol is to open and close each gate a minimum of 1x per 12 hours. In addition to the weight measurements (discussed in 1. On top of the buoyancy tanks), a test was performed to the investigate the correlation between siltation and movement. The results are shown in Figure 13

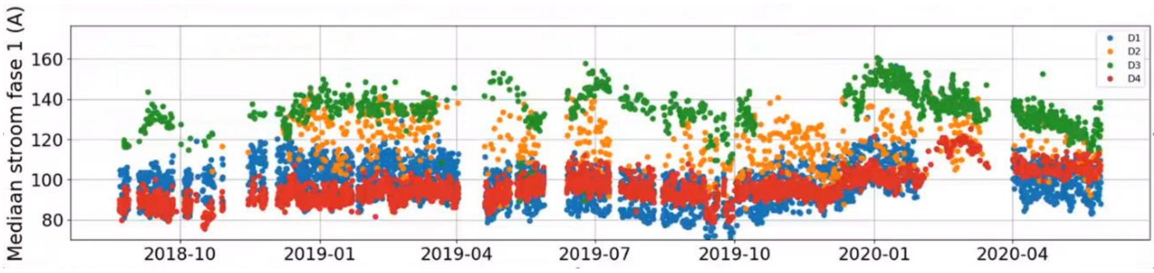


Figure 13. Results of movement test [23][not to be copied without permission of Port of Antwerp].

The test subject was gate 3 (green dots) in 2020-01. Gate 3 is the back-up gate of the Kieldrecht lock, meaning the gate is not used in standard conditions. Furthermore, the gate is not equipped with mixers. Instead of 1 movement per 12 hours, the frequency was increased to 8-9x per 12 hours. Noticeable is the decrease in drive current from approximately 160 A to 120 A. The results are interpreted as a reduction of siltation on top of the buoyancy tanks. Since the siltation is reduced, the weight is reduced and thus the drive current is decreasing. However, no final conclusions could be made without visual confirmation.

Expert 7 has over 10 years of experience in the Port of Antwerp and the siltation issue remains a grey area without certainties. A variety of issues is known and no solution is perfect. Therefore experience is of high importance and methods should be questioned and tested. The advantage of the Port of Antwerp is the ability to compare a number of gates and furthermore discuss with colleagues. Practical knowledge and experience is of high importance.

2.4.7. Conclusion expert interviews

Siltation of rolling gates proved to be a challenging subject. Literature is limited and even experts describe the subject as a grey area. Interviews were conducted with experts involved with rolling gates. The interviews provided valuable information on the main locations of siltation, the effects of siltation and existing measures against siltation.

The problematic locations of siltation are: 1. the gate recess, 2. the gate chamber, 3. the rails/sill and 4. on top of buoyancy tanks. The main effect of siltation is difficulty during closing and opening of the gates. For instance, the closing time is delayed or the gate will not close correctly, resulting in delay or failures. As confirmed by the interviews, dredging could be seen as the main "solution" for siltation. Meaning, dredging is used to successfully remove siltation with a variety of methods. However, dredging is accompanied by high costs which depend on e.g. used equipment, methods and complexity. Furthermore, dredging is a reactive "solution" and thus required frequently. However, the main issue is that dredging is a time consuming process in which the lock could not be used. The frequency differ per situation and could increase to four times annually. Furthermore, several additional measures against siltation have been discussed: 1. integrated pumps, 2. waterpipes, 3. waterjets, 4. siltation reservoirs, 5. scrapers/ploughs, 6. portable pumps, 7. mixers, 8. airlifts and 9. a regular movement regime.

Different measures are used on different locations and the results vary. Certain measures are applied in multiple locks, e.g. the waterjets or scrapers, while other measures are specific to one lock, e.g. the mixers. No defined method appears to be present in choosing measures against siltation between the different locks. However, one aspect which is equal in all locks is *the separation of the siltation problem per location*. The context is different per location (e.g. waterflow, geometry of the location, presence of additional features and more) and no measure could be applied to all locations without alterations in the design. Thus, to design a feasible siltation removal system *the design should focus on one problematic location of siltation.*

Deducted from the interviews, siltation of the *gate recess* (1) and *gate chamber* (2) remain the significant issues. Siltation on the rails/sill (3) is controlled with e.g. water jets and scrapers. Furthermore, siltation on top of the buoyancy tanks (4) is specific to Port of Antwerp and "under control" with the mixers (7) and regular movement (9). Meaning a choice should be made between siltation in the gate recess or siltation in the gate chamber.

After consideration, ***siltation of the gate recess*** (1) is chosen as the problematic location of siltation. The main reason is the presence of additional features in the gate chamber compared to the gate recess. For instance, the driving mechanism, rails, maintenance clearance and dry dock features are incorporated into the gate chamber. In comparison, the gate recess is a relative small slot in the lock wall devoid of additional features. The gate recess could be described as a "blank canvas", which is more feasible in this stage of the research.

2.5. Siltation of the gate recesses in Port of Antwerp

As discussed in the previous section, the design of the siltation removal system focuses on siltation of the gate recess. Two suitable situations remain from the interviews regarding siltation of the gate recess: 1. the Meppelerdiep lock and 2. Port of Antwerp. Subsequent to additional review of both situations and follow up questions [22, 23], the decision is made the focus of the design is *to remove the siltation from the gate recesses in Port of Antwerp***.** The decision is based on three factors:

1. Port of Antwerp is exposed to brackish water, which is connected to increased siltation according to literature (section 2.3), while Meppelerdiep lock is exposed to sweet water.
2. The locks in Port of Antwerp are used daily (the Meppelerdiep lock approximately 26 days annually) and thus more representative for other locks.
3. The gate recesses in Port of Antwerp could be described as a standard design found in other locks with rolling gates as well, while the gate recesses of the Meppelerdiep lock are deepened significantly and have incorporated a deep siltation reservoir. Meaning, incorporation of the siltation removal system designed for the Port of Antwerp to other locks is more suitable then a system designed for the Meppelerdiep lock.

According to *expert 7* [23] Port of Antwerp has a total of 24 rolling gates divided over six locks with an equal layout. The overall dimensions of the locks and components vary, for instance the Kieldrecht lock is the largest, however the overall design is equal. Thus, all gate recesses are equal in shape.

Siltation of the gate recesses in Port of Antwerp has been discussed in section 2.4.6. A follow-up interview was conducted with *expert 7* regarding the gate recess in specific [24] for additional information. The core information is discussed below.

Depth charts were made, which indicate siltation in the proximity of the sills and gate recesses. In addition, detailed echo pictures were made, which visualize the siltation from the depth chart. The echo picture is illustrated in Figure 14 (left) and shows siltation in several areas. For instance, located between or next to the sills. *Expert 7* mentions siltation in such areas will not result in issues. The problematic siltation is visualized in Figure 14 (right), encircled in yellow. The siltation occurs at the bottom of the gate recess. Eventually, the gate recess is full and the gate will not close properly, meaning the lock is not able to function as required.

Subsequently, divers are used to remove the siltation from the gate recess with pressure washers. Layers of 1.5-2 meter of siltation could occur, resulting in difficult and dangerous working conditions for the divers. However, the main issue is with regard to time. The gate is not allowed to move with divers present, thus the lock is out of function during cleaning. Each month eight hours of downtime is reserved per lock for maintenance, which is mostly used for the cleaning of the gate recesses by the divers. As a result, the pressure on additional maintenance tasks (which require downtime of the lock as well) is increased. Ideally, the divers would blow away all the siltation, which takes approximately eight hours per gate recess. However, due to the time restrictions this is not feasible. Meaning, the siltation is not properly removed from the gate recesses.

Figure 14. Echo picture of siltation in "non-problematic area's" (left), echo picture of siltation of the gate recesses in Port of Antwerp (right) [24][not to be copied without permission of Port of Antwerp].

As described, divers are used to remove the siltation, while in reality the divers *transport* the siltation. Meaning, the term *siltation removal* has two meanings. Currently, the siltation is *transported*. Divers use pressure washers to blow away siltation, which deposits in new areas. In addition, siltation could actually be *removed*. Siltation could be brought up to the surface and discarded, which is similarly done with potential small debris (e.g. pieces of wood) the divers encounter. As *expert 7* mentioned, there are areas in which the siltation will not result in issues; the main point is that the gate recess is clear of siltation. Therefore, transporting siltation from the gate recess to different areas in the lock could be seen as a solution according to *expert 7*. Thus, for the remainder of the thesis the term *siltation removal* could mean complete removal from the recess or transportation of siltation from the recess to other areas in the lock.

2.6. Programme of requirements

The siltation removal system will be designed to remove siltation from the gate recesses in Port of Antwerp, which has been discussed in detail. The next step in the design process is to state the programme of requirements. To realise suitable requirements, the system should be considered in the context of the gate recess. For instance, location of the system, accessibility of the system and desired effects of the system.

To state the programme of requirements several elements are used, e.g. the reviewed literature, norms used for locks, the expert interviews, expert needs and a site visit (Meppelerdiep lock). Furthermore, two additional interviews were conducted with *expert 7* [25] and *expert 8* [26] regarding potential requirements. Expert 8 is a contact at a diving company and the transcribed interview is shown in *Appendix B7: interview expert 8*. Regarding the experts needs, a step is used based on an element of

Quality Function Deployment [27]. To retrieve the experts needs from the interviews, a combination of certain guidelines by Ulrich and Eppinger [28] and experience with Design Thinking is used. It is important to identify latent needs as well. Subsequently, the needs are used as an additional control for the requirements. The additional control is to check if the needs are represented in the programme of requirements.

As mentioned in section 2.5, the decision to focus the design on siltation of the gate recesses in Port of Antwerp is based on three factors. Two factors include the connection to other locks, which is of great importance. To increase the added value of the system, the system should be applicable to similar locks in the future as well. Thus, the requirements reflect a system designed for the Port of Antwerp, while not excluding the future applicability to similar locks.

System requirements:

1. The system should be applicable to existing locks.
   Locks have a design life of 100 years and thus new locks are uncommon. Meaning the applicability is limited. Furthermore, a system applicable to existing locks could in general be applied to new locks as well.
2. The system should be suitable for gate recesses with a length of 6 – 11 meters, a height up to 1 meter and a width up to 1.5 meter (see Figure 15).
   Dimensions of gate recesses vary between locks and to increase the applicability a range is used. The described range includes all gate recesses in Port of Antwerp and numerous gate recesses in The Netherlands e.g. New lock IJmuiden (largest), Krammer locks, Northern lock and Terneuzen locks.
3. The system should be able to clear the siltation in the gate recess, denoted in Figure 15 by the green volume.

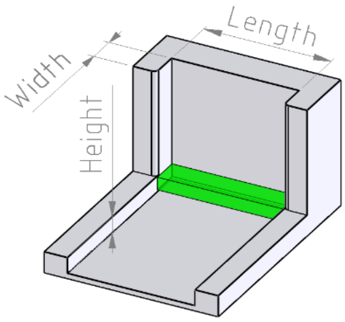


Figure 15. Recess dimensions and the to be cleared volume (green).

4. The system should 4.1) not obstruct the working principle of the rolling gate, 4.2) be able to perform a siltation removal operation under 60 minutes per gate recess.
   The most used gates of Port of Antwerp move approximately 12x per 12 hours, meaning a siltation removal operation under 60 minutes should not result in delay of the lock. The 60 minutes does not include activities which have no effect on the working principle of the gate, e.g. unloading components on shore.
5. The system should be suitable for lock chambers up to 27 meters of height.
   If applicable, the system should be able to reach the gate recess from shore. Meaning, from the top of the lock chamber to the bottom, which is 27 meters maximum (Kieldrecht lock).
6. Silt removal by the system should not be disrupted by debris up to 500 mm (leading dimension of the object).
   Removal of debris is an additional subject and not within the scope of this project, however the system should be able to perform siltation removal with the presence of relative small and frequently found debris.
7. Maintenance of the system *which will interrupt operation of the lock* should not exceed 8 hours per year per lock chamber.
   In Port of Antwerp each lock is allowed to be out of function 8 hours per month for maintenance. To focus on additional maintenance tasks, maintenance on the system should be kept to a minimum. Note: maintenance of the system which could be performed while the lock is functional is less critical and thus no quantitative requirement has been stated.
8. The system should require a maximum of 80 kW.
   The system presumably requires a source of power. In case no power is available at the lock a mobile power source is required, meaning the mobile power source will be the limiting factor.

The limit of a mobile power source (e.g. generator or compressor) is determined to be 80 kW. Note: mobile means transportable on a trailer with a Dutch BE license.

9. The system should be able to function without the use of divers.

User requirements:

10. The system should not be used if ice is formed on the water in the lock chamber.
11. The system should be operatable by a maximum of 2 persons.

Safety requirements:

12. The system should be waterproof, meaning water will not affect the functioning of the system.
13. The system should not prevent vessels from entering and leaving the lock chamber.
    Requirement 13 is to assure the system operates without resulting in delay of the lock as well to prevent collisions with vessels.
14. The system should not protrude the lock bottom in rest position.
    Lock chambers are required to withstand collisions with e.g. an anchor [29]. *Components which would protrude the lock bottom in rest position (e.g. a pump placed on the bottom) are invisible from shore and vessels and thus vulnerable to such extreme collision conditions. Furthermore, protruding components in rest position would be a risk during dredging operations of the lock chamber.*
15. The system should not directly produce and secrete waste material (e.g. chemicals, plastics and more).
    Waste materials produced and secreted by the system could enter the water in the lock chamber and eventually the surrounding waters, which could result in water pollution.

Durability requirements:

16. The system should have a design life of: a) 50 years for fixed mechanical components, b) 25 years for replaceable mechanical components. c) 25 years for electrical installations and d) 15 years for the control system.
    The design life is according to NEN 6786-1 [30] *and NEN-EN 1990+A1+A1/C2:2019* [31] *and is used if applicable.*
17. The system should be designed with no cavities to entrap water.
    To eliminate water entrapment, cavities could either be removed or designed to release the entrapped water. For instance, place a U-beam open side up or add holes to release the water.

Wishes:

1. The system should minimize permanently submerged components.
   The system operate in a hostile environment with water, meaning corrosion and maintenance are of importance. Above water components minimize corrosion and increase maintainability.
2. The system should be robust.
   In addition to water the system is exposed to e.g. currents, vessels, concrete structures, operators and more. Meaning, the system should be robust to endure unexpected situations.
3. The system should be easily replaceable.
   In case the system is damaged beyond repair (by e.g. a collision) replacement should be quick and accessible.
4. The system should be simple to operate.
5. Maintenance of the system should be able to be performed during normal functioning of the lock.
6. The weight of singular mobile components or assemblies should be minimized

Reduced weight means the components could be moved with lower capacity cranes, which means smaller vehicles and thus increased mobility. Mobile refers to components or assemblies which need to be loaded in and out of the water, or on to vehicles, during each siltation removal operation.

2.7. Function analysis

The function analysis is used to determine the main and subfunctions, which are combined with solutions in the next phase. To perform a function analysis a variety of methods are available. The method proposed by Ulrich and Eppinger in Product Design and Development [28] is used. The method makes use of a *functional decomposition* by dividing the *main function* into *subfunctions*. The main function and subfunctions are connected in a logical order and visualized in a *function diagram*.

The method could be described in a few steps. First the system is considered as a black box operated by energy, material and information flows. The flows could be transformed, transported, stored, separated or combined within the black box. The next step is to determine the *main function* of the system. As mentioned in section 2.6, the system should be able to remove the siltation from the gate recesses. Which leads to the *main function*:

Remove siltation

The subfunctions are used to describe what elements of the system might do to fulfil the main function. By solving the subfunctions, the main function is implemented. As mentioned, the main function and subfunctions are combined in a *function diagram* and connected in a logical order. To start, the order could be based on the energy, material and information flows. However, Ulrich and Eppinger state no method is "the single correct" method in creating a functional decomposition or function diagram. Meaning the order could furthermore be in time, a "how to" basis or many more. The process is to create several function diagrams and refine until satisfactory. The final function diagram is shown in Figure 16. The order could be seen from "internal" (core methods to loosen and transport siltation) to "external" (how to connect the system to e.g. the surroundings and reach the recess). The subfunctions are: 1. loosen siltation, 2. transport siltation, 3. actuate system, 4. place system, 5. integrate system and 6. reach recess.

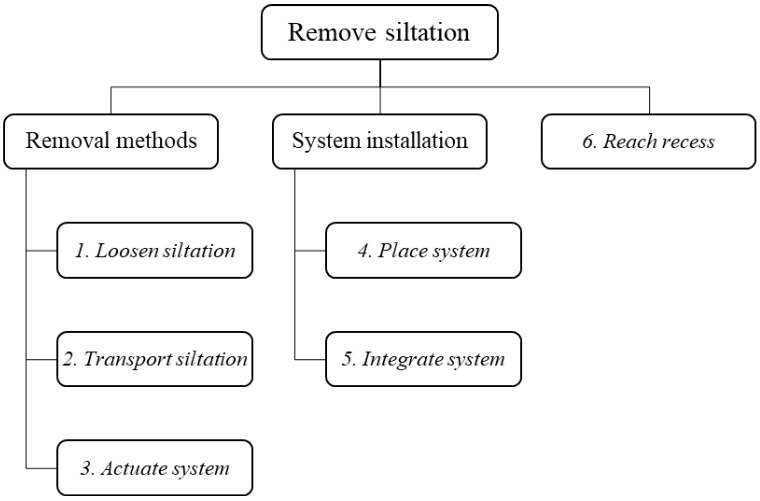


Figure 16. Function diagram innovative siltation removal system.

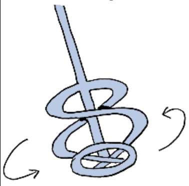
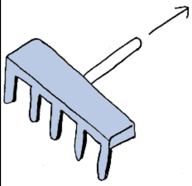
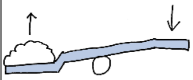
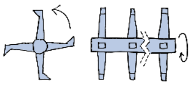
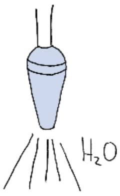
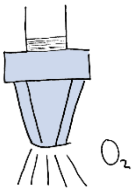
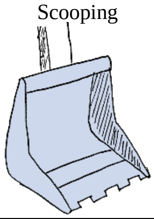
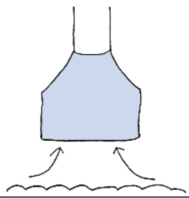
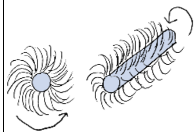
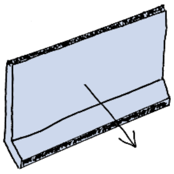
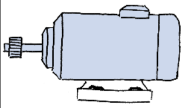
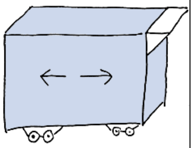
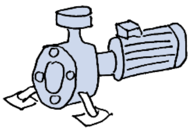
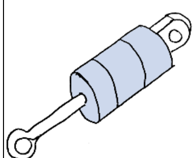
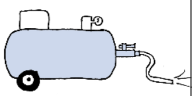
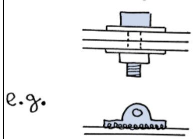
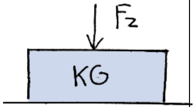
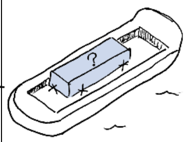
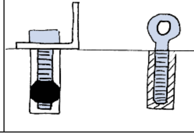
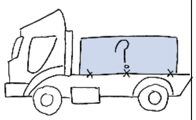
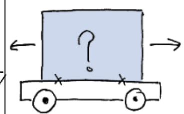
3 Concept generation

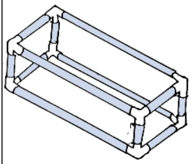
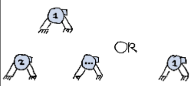
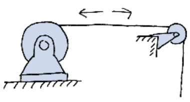
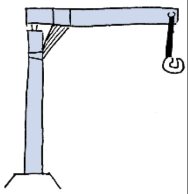
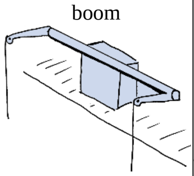
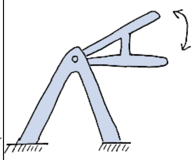
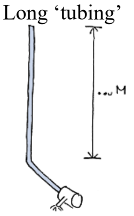
The analysis phase is complete and all the information leads to the next step, concept generation. Ideation is realised and concepts are designed based on the requirements and function analysis. The first step is to create solutions with the help of a morphological map. Subsequently, the solutions are used to create concepts. During concept generation creativity is essential, ideas could form in numerous ways.

3.1. Morphological map

The morphological map is crucial in the design of the concepts. In section 2.7 the functions of the innovative siltation removal system are identified. In the following section, solutions to the subfunctions are generated. Numerous methods could be used to generate solutions. For instance, brainstorming, idea doodling and brain writing are effective methods. In addition, inspiration could be found in different applications or even a different field of industry. Generation and sketching of ideas in large quantities is beneficial to explore the solution space [28]. The solutions are summarized in the morphological map in Table 3.

Table 3. Morphological map innovative siltation removal system.

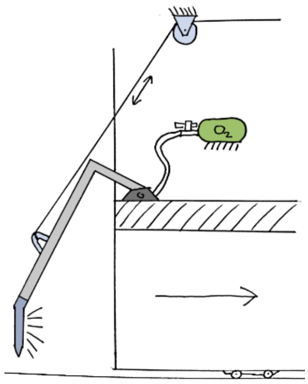
	A	B	C	D	E	F
1. Loosen siltation	Mixer 	Rake 	Seesaw 	Vibration 	Scraping wheel 	None
2. Transport siltation	Water nozzles 	Air nozzles 	Scooping 	Suction 	Sweeper 	Plough 
3. Actuate system	Motor 	Gate movement 	Pump 	Hydraulics 	Compressor 	
4. Place system	Mechanically connected to gate 	Fixated by weight 	Fixated to boat deck 	Mechanically connected to concrete 	Fixated to truck bed 	Placed on wheels 

5. Integrate system	Frame 	None - loose component(s) 				
6. Reach recess	Guided winching 	Crane 	Window washing boom 	Hinging frame 	Long ‘tubing’ 	None

3.2. Concepts

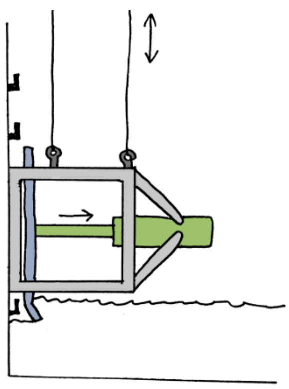
Twelve concepts are designed with the use of the morphological map, by choosing one or more solutions per subfunction. To stimulate the process a name or theme is chosen in advance for each concept. The following section states the concepts with a brief description and sketch to visualize the concept. In addition, the elements chosen from the morphological map (Table 3) are stated for each concept.

A. Ingenious



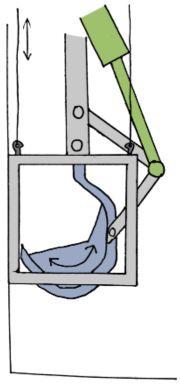
A hinging frame is connected to the inside of the gate with a rake attached. During closing of the gate, the rake hinges into the gate recess by releasing a winching system. Furthermore, the rake is equipped with airholes aimed towards the lock chamber. As a result, the system loosens the siltation with the rake and simultaneously transport the silt out of the recess with compressed air. Once the rake is cleared from the recess, the rake is pulled back into the gate by activating the winching system. [1B. 2B, 3B+E, 4A, 5A, 6A+D].

B. Brute force



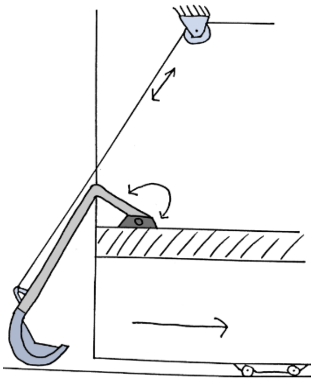
The concept consists of a frame equipped with hydraulic cylinders attached to a plough. The frame is lowered into the recess by a crane (e.g. crane on a small truck) to a certain depth. Once lowered, the frame is hooked on to anchor points connected to the vertical wall of the gate recess. Subsequently, the hydraulic cylinder is activated and the plough pushes out the siltation. The anchor points are located on different depths, meaning the system is able to push the siltation out in layered steps until the bottom is reached. The plough protrudes the bottom of the frame to assure not the complete frame needs to be submerged in the siltation for the system to work. In addition, the plough is V-shaped to push the siltation sideways, out of the sill. [1F, 2F, 3D, 4D, 5A, 6B].

C. Quick



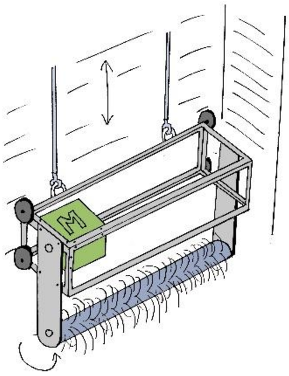
The working principle of concept quick is similar to an excavator, a scoop is used to transport the siltation out of the recess. The scooping blade is attached to a frame. The blade is operated with simple hydraulic cylinders. Once the cylinders are activated, the blade scoops towards the gate recess wall. As a result, the wall is used as a stopping block for the siltation and the siltation is forced into the scoop. The frame is attached to cranes on a (small) truck with cables. Once the siltation is within the scoop, the scoop is raised and placed on the truck. Subsequently, the siltation could be discarded (e.g. in the lock chamber). [1F, 2C, 3D, 4E, 5A, 6B]. For a sketch of the placement on a truck, see *J. Mobile*.

D. Embedded



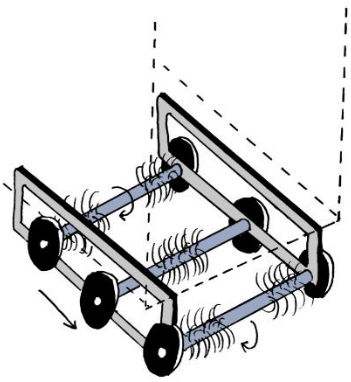
A hinging frame is connected to inside of the gate with a scooping blade attached. During opening of the gate, the blade hinges towards the bottom by releasing a winching system. The blade enters the siltation and pulls siltation from the gate recess during the opening motion of the gate. In the lock chamber the scooping blade hinges back into the gate, by activating the winching system, and release the siltation. Subsequently, the siltation is further dispersed by vessel movement. [1F, 2C, 3B, 4A, 5A, 6D+A].

E. Simple



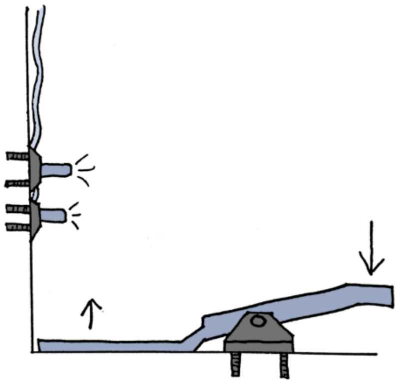
The simple geometry and vertical walls of the recess are utilized in concept simple. To transport the siltation, a sweeper is used. A sweeper is installed across the length of a simple frame and driven by a motor (similar to swimming pool cleaners). Attached to the frame are guidance wheels to ride along the vertical walls of the recess. To load the system, the frame "walks" over the edge of the recess from shore and is lowered towards the bottom. At the bottom, the sweeper is activated to clean the recess. A simple winching system (e.g. attached to shore or a car/truck) is used to lower and raise the system.[1F, 2C, 3D, 4F, 5A, 6B].

F. Invisible



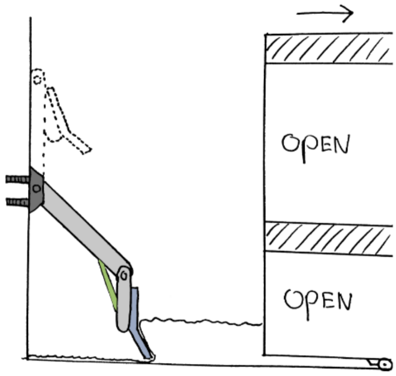
Multiple sweepers are attached underneath the gate (at the front) and rotate by movement of the gate (the wheels makes contact with the sill). During closing of the gate, the sweepers rotate backwards and transport siltation into the lock chamber. During the first meters of opening of the gate, the sweepers are blocked (no rotation) to assure no siltation is transported back into the recess. Subsequent to the first meters, the sweepers are unblocked and siltation underneath the gate due to the cleaning of the recess is transported into the open sill/lock chamber. The sweepers are combined in a frame and installed in a pattern to stimulate siltation transport between the sweepers. [1F, 2E, 3B, 4A+F, 5A, 6F].

G. Submerged



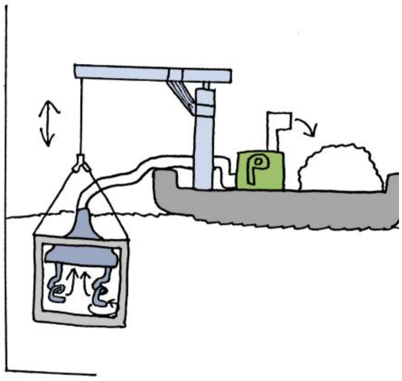
A seesaw is connected to the bottom of the gate recess. In rest position and during closing of the gate, the lower side of the seesaw rests on the bottom of the recess. During opening of the gate (thus the gate leaves the recess), the gate activates the seesaw by motion of the gate. The seesaw loosens the settled siltation in the recess. Subsequently, water nozzles are used to transport the siltation from the gate recess to the lock chamber. The water nozzles are placed separately near the bottom of the gate recess. [1C, 2A, 3B+C, 4D, 5A+B, 6E].

H. Advanced.



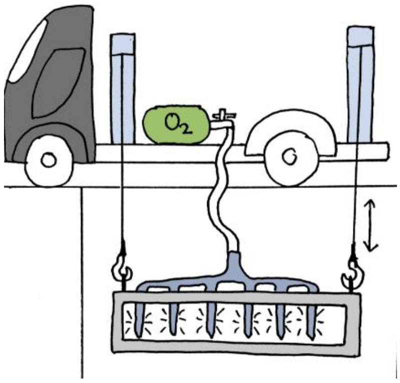
The advanced concept utilizes the open front side of the gate. A hinging frame is connected to the vertical wall of the gate recess. During closing of the gate, the system is stored at a height at which the front of the gate is open and preferably above water level. During opening of the gate, the system extends the frame to the bottom of the recess with several hydraulic cylinders and force a plough into the siltation. Subsequently, the hydraulic cylinders are used to push the siltation out of the recess. Similar to *concept G. brute force*, the plough is V-shaped to push the siltation out of the recess and simultaneously sideways out of the sill. [1F, 2F, 3D, 4D, 5A, 6D].

I. Complete removal



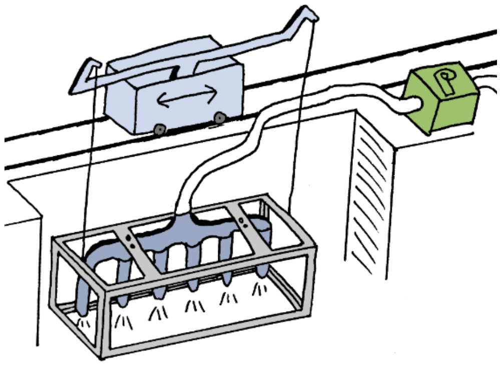
A combination of mixers and suction is used. The mixers loosen the siltation, which is subsequently sucked up. The mixers are combined in a rectangular frame with suction heads above. Cranes are be fixated to a boat deck and load the frame in and out of the water. The sucked up siltation could be stored on the boat and discarded subsequent to cleaning, resulting in complete removal from the lock. In case complete removal is excessive and not required, the siltation could be redirected from the ship to other locations in the lock chamber. [1A, 2D, 3A+C, 4C, 5A, 6B].

J. Mobile



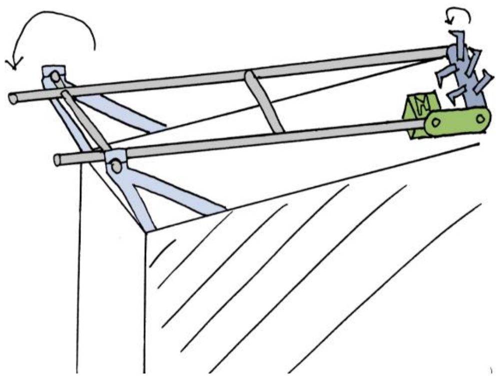
All components of the system are placed on a (small) truck to create a mobile system. A rectangular frame is used with various air nozzles attached to the frame. The air nozzles are powered by a compressor, located on the truck, to blow away the siltation. To lower and raise the system, cranes on the truck are used. The truck is used to move the system from recess to recess and furthermore sideways in a recess. [1F, 2B, 3E, 4E, 5A, 6B+E].

K. Exchangeable



Water nozzles are attached to a rectangular frame and the frame is subsequently connected to a window washing boom. The boom is placed on wheels, on a track. The track is located in front of the gate recess (perpendicular to the gate) and continued along the shore line (approximately twice the length of the gate recess). To use the system, the window washing boom is rolled in front of the gate recess and the frame with water nozzles is lowered to clean the recess (blow away the siltation). Once the cleaning operation is complete, the frame is raised and the window washing boom is rolled to the side. The frame could be coupled and decoupled to different window washing booms at different recesses. [1F, 2A, 3C, 4G, 5A, 6C+E].

L. Long



A scraping wheel is combined with a scooping mechanism for simultaneous loosening and transport of the siltation. A rotating wheel is equipped with multiple scooping blades, which enter the siltation. A hinging frame is connected on top of the gate (permanently) in which a frame with the scooping wheel could be placed. Once a cleaning operation is required at a recess, the frame with the scooping wheel is installed and ready for use. During the opening of the gate the scooping wheel is hinged towards the recess to start the cleaning operation. Subsequent to cleaning, a winching system is used to retrieve the system. [1E, 2C, 3A, 4A, 5A, 6A+D].

4 Concept selection

With the generation of twelve concepts the challenge is to choose between all options, which leads to concept selection. Concept selection is an iterative process in which a number of concepts are evaluated against selection criteria. During the evaluation the weaknesses and strengths of the concepts are compared, eventually leading to the selection of the winning concept(s) to further investigate, develop or test [28]. Section 4.1 discusses the methods, e.g. why a method is chosen and how the method is applied. Subsequently, section 4.2 discusses the results of each step of the concept selection process.

4.1. Concept selection steps

Concept selection is a process for which numerous methods are available, e.g. Pros and Cons, Multivoting, Intuition, Pugh matrix, Quality Function Deployment (QFD), Analytic Hierarchy Process (AHP) and many more. Kremer provides a thorough overview of concept selection methods (CSM) [32]. However, there is not a method which is universally agreed upon to be the standard solution.

The use of experts for the concept selection process (CSP) could be beneficial. In addition to knowledge, experience and intuition on the subject the experts have an additional advantage: objectivity. A designer (or design team) could fixate on a certain concept, removing objectivity in the concept selection process. Thus, a diverse panel of experts is used consisting of the following members:

Expert 3	Technical advisor
Expert 6	Object expert
Expert 7	Maintenance specialist
Expert 9	Senior Engineer bridges and locks 1
Expert 10	Senior Engineer bridges and locks 2

The use of a panel of experts means certain aspects during the CSP need to be considered, e.g. communication, ease of use and available time. For instance, due to the COVID-19 pandemic contact with the experts at different organisations is restricted to e-mail and phone/video calls, which influences the ability to explain or assist with the methods. Furthermore, the help of the experts is voluntarily and should be completed in a reasonable time span.

The decision is made to use four different steps for the CSP: 1. concept selection based on discussion and intuition [28], 2. concept screening [28, 33], 3. concept scoring [12, 28] stage 1 (S1) and 4. concept scoring stage 2 (S2). The approach starts coarse and becomes more refined with each step. The following sections discuss the separate steps, e.g. why a method is chosen and how a method is applied.

4.1.1. Concept selection based on discussion an intuition

The first selection is based on discussion and intuition within the "design team" (author and supervisors). The method is suitable to filter the high number of concepts, to achieve a more realistic selection process for the more detailed selection methods (concepts screening and scoring).

During the discussion members of the team argue regarding the feasibility of the concepts, advantages, disadvantages, potential alterations and more. As a result, concepts are discarded, continued or altered. The results of concept selection based on discussion and initiation are discussed in section 4.2.1.

4.1.2. Concept screening

The next step is concept screening with a screening matrix. Concept screening [28] is a method based on *Pugh concept selection* by Stuart Pugh [33]. The method utilizes a table in which the concepts are compared against a reference concept on selection criteria. Thorough quantitative evaluations are complex in a preliminary phase and, according to Pugh, could even be misleading. Thus, the screening matrix uses a relative coarse grading system to compare the concepts. The advantage of concept screening in this phase is the structured approach, in combination with the ability to improve concepts and quickly reduce the number of concepts.

Due to the coarse ranking system, the screening matrix is suitable for a group discussion in which arguments could be exchanged and explained. However, the experts are not yet involved. The experts are not familiar with the concepts, meaning to accurately inform the experts regarding the high number of concepts extensive time and documentation is required. Furthermore, a discussion with all experts and the design team could result in a unrealistically long and overwhelming process. The actual discussion of the screening matrix already resulted in a session of two hours with solely the "design team" (student and supervisors, which are familiar with the complete design process). Thus, involvement of the experts is more suitable for the next step: concept scoring.

However, the screening matrix uses selection criteria, which are used for the concept scoring as well. Concept scoring is the step in which the experts are involved, thus setting up the selection criteria should be done with the experts in mind. Selection criteria could be e.g. requirements or specifications. However, this could result in a long and intimidating list. Furthermore, a long list of criteria could result in confusion and increase the difficulty of giving honest answers. Selection criteria which are more forward and clear are more suitable, leading to the decision to use the needs of the experts.

As mentioned in section 2.6, the needs and latent needs were collected from the interviews. The next step is to categorize the needs into primary and secondary needs. For instance, the system can be easily inspected and easily cleaned are two secondary needs, which are grouped underneath the primary need: maintainability. The primary needs are used as the selection criteria and are shown in Table 4. The grouping is shown in *Appendix C2: selection criteria.*

Table 4. Selection criteria based on the primary experts needs.

Selection criteria	Meaning
1. Non-interference of lock function	- The ability of the system to not interfere with normal functioning of the lock. In other words: use of the lock can continue.
2. Ease of use	- The simplicity with which the system can be used to remove the siltation.
3. Maintainability	- The ability of a system to be maintained or repaired to a state where the system can perform the required function.
4. Ability to remove siltation	- The effectiveness of the system in removing siltation from the gate recess.
5. Ease of construction	- The simplicity of the construction of the system.
6. Mobility	- The ability of the system to be transported.
7. Reliability	- The ability of the system to perform the required function sufficiently over time.
8. Costs	- The costs of the system (not the operational costs).

With the selection criteria clear, the remaining task is to choose a reference concept. As mentioned, the concepts are compared to a reference concept, which could be e.g. a competitors product, benchmark, assembly of subsystems or one of the concepts in the screening matrix. Concept *B. brute force* is chosen as the reference product due to the representation of the middle ground. For instance, complex features, however not the most complex concept.

The steps to summarize the concept screening method are: 1. construct the matrix, 2. rate the concepts with [-] and [+] for worse or better than the reference concept on each criterion, 3. create a ranking of the concepts based on the sum of [-] and [+], 4. improve concepts if possible, e.g. combine concepts or remove features and 5. select one or more concepts to continue. The results of concept screening are discussed in section 4.2.2.

4.1.3. Concept scoring

For the final two steps concept scoring [12, 28] is used. The previous selection methods are relative coarse, while concept scoring provides a more refined method. Since the number of the concepts is reduced, the concepts have been through several iterations, are better defined and closer together, concept scoring is a suitable step to actively involve the experts in the concept selection. Concept scoring provides refinement to differentiate between the concepts, while the method remains clear, straightforward to communicate and direct.

Similar to concept screening, concept scoring utilizes a matrix. The criteria for the matrix were discussed in section 4.1.2. However, the concept scoring matrix is equipped with an additional feature: weighting factors.

A simple example: criteria X is deemed more important than criteria Y and provided with a weight factor of two, while criteria Y is provided with a weight factor of one. If both criteria are scored equal, criteria X will have more impact on the overall score. Which could help differentiate between concepts. To choose the weighting factors numerous methods are available. Ulrich and Eppinger [28] suggest subjective assigning of the factors by the design team, while the Analytical Hierarchy Process of Saaty [13] uses a more complex pairwise comparison. The chosen method is a pairwise comparison matrix used in Methodical Design [12]. Equal to concept scoring, the method is clear, straightforward to communicate and direct.

The weight factors are determined in advance to the concept scoring. An example of a completed pairwise comparison matrix by one of the experts is shown in Figure 17.

Compared to → / Importance of ↓	Non-interference of lock function	Ease of use	Maintainability	Ability to remove siltation	Ease of construction	Mobility	Reliability	Costs	Score	Weight [%]
Non-interference of lock function		1	1	1	1	1	1	1	7	25
Ease of use	0		0	1	1	0	1	0	3	11
Maintainability	0	1		0	1	0	1	1	4	14
Ability to remove siltation	0	0	1		1	1	1	1	5	18
Ease of construction	0	0	0	0		0	1	1	2	7
Mobility	0	1	1	0	1		0	0	3	11
Reliability	0	0	0	0	0	1		1	2	7
Costs	0	1	0	0	0	1	0		2	7
								Total score	28	

Figure 17. Pairwise comparison matrix for weighting factors.

The matrix compares the horizontal criteria to the vertical criteria. If the horizontal criteria is deemed more important, an one is noted. If the vertical criteria is deemed more important, a zero is noted. Solely the blue fields are filled in, the white fields are the mirrored values. The scores are summed, resulting in a weight factor in percentages. The percentages of all experts are collected and the average values are the final weight factors.

The actual assigning of the weight factors, based on the scores, could be done with different approaches according to Siers [12]. For instance, the higher scoring criteria could be grouped and given a weight factor of three, while the lower scoring criteria are grouped and given a weight factor of one. However, such an approach groups scores which are not identical and removes resolution from the weight factors. Thus, an approach with percentages is chosen.

Once the weight factors are known, the concept scoring could be started. The weight factors are not shown to the experts during the concept scoring to maintain objectivity. If the weight factors are shown, scores could be altered (intentional or unintentional) for e.g. criteria with a high weight factor to choose a favoured concept.

The concept sketches + descriptions (the results from concept screening in section 4.2.2) and objective of the concepts are presented to the experts, accompanied by a concept scoring matrix and instructions on how to fill in the matrix. Important is to gather all information in one file (*Excel file*), realise clear and short explanations and provide oversight. An example of a filled in concept scoring matrix is shown in Figure 18. Furthermore, the steps to summarize the concept scoring are: 1. construct the matrix, 2. rate the concepts from 1 (lowest score) to 4 (highest score) on each criterion, 3. create a ranking of the concepts based on the total score 4. improve concepts if possible, e.g. combine concepts or remove features and 5. select one or more concepts to continue.

Concept scoring		**Concept 1: Mobile**		**Concept 2: Quick**		**Concept 3: Simple**		**Concept 4: Exchangable**		
Selection criteria	Weight [%]	Score	Weighted score	Score	Weighted score	Score	Weighted score	Score	Weighted score	Ideal score
Non-interference of lock function	21	4	0.86	4	0.86	4	0.86	4	0.86	0.86
Ease of use	12	3	0.36	3	0.36	2	0.24	1	0.12	0.49
Maintainability	14	2	0.29	3	0.43	1	0.14	1	0.14	0.57
Ability to remove siltation	18	3	0.54	2	0.36	2	0.36	3	0.54	0.71
Ease of construction	6	3	0.17	3	0.17	1	0.06	1	0.06	0.23
Mobility	7	3	0.21	3	0.21	3	0.21	2	0.14	0.29
Reliability	15	2	0.30	3	0.45	1	0.15	1	0.15	0.60
Costs	6	3	0.19	3	0.19	2	0.13	1	0.06	0.26
	Total score	2.92		3.04		2.15		2.07		4.00
	Percentage	73		76		54		52		
	Rank	2		1		3		4		

Figure 18. Concept scoring matrix.

The blue cells in Figure 18 are not shown to the experts, meaning the weight factors and total score of the concepts are unknown to the experts. Furthermore, the green cells are the only cells which could be selected and filled in. The green cells solely accept a score of 1 to 4, to prevent mistakes with typing. The score of 1 to 4 is intentional to remove a middle ground, opposite to a score of e.g. 1 to 5. The total score of a concept is the sum of the weighted scores. Furthermore, a large cell underneath the scoring matrix is provided in which the experts are asked for notes, e.g. possible improvements, concerns and recommendations.

As mentioned, the concept scoring is performed in two steps: concept scoring stage 1 (S1) and concept scoring stage 2 (S2). The method for S2 is equal to S1. The weight factors are already known from S1, the information (concept objectives, scoring matrix and instructions on how to fill in the matrix) are gathered in one *Excel file* and the scoring matrix from Figure 18 is used with the same steps. However, there is a difference. For S1 the concept descriptions + sketches (the results from concept screening in section 4.2.2) are used, while for S2 different information is used.

S1 is performed in advance to prototyping and S2 subsequent to prototyping. S1 aims to choose the most promising concepts for the prototyping phase and S2 to choose the final concept based on objective information created by the prototyping. Thus, instead off the concepts descriptions + sketches, prototyping results are sent to the experts for S2. The results of concept scoring S1 and S2 are discussed in section 4.2.3 and chapter 6 respectively.

The details of which information is sent to the experts (*and how the information should be presented*) is discussed in section 5.8, subsequent to the prototyping.

4.2. Results concept selection

Section 4.1 discussed the steps of the concept selection process. The following sections discuss the results of the separate steps in order (except the results of concept scoring S2, which is discussed in chapter 6). The results of each previous step are used for the following step. For instance, if alterations are made to a concept, the altered concept is used for the next step.

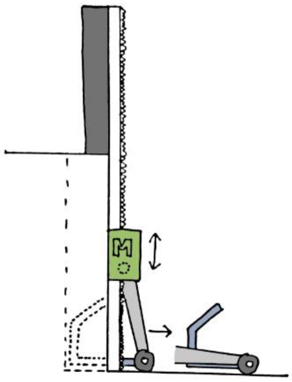
4.2.1. Selection based on discussion and intuition

The following concepts are discarded: *A. Ingenious, D. Embedded, F. Invisible, G. Submerged, L. Long*. The full arguments to discard the concepts are found in Table 27 in *Appendix C1: selection based on discussion and intuition.*

Opposed to the discarded concepts, concept *advanced* is continued with several alterations. The altered concept reduces the number of actuators, decreases water contact, removes the complex controls and is independent of the type of rolling gate used. Thus, the complexity is reduced while retaining the effective forward and sideways removal of siltation with a plough. The altered concept advanced is shown below:

H. Advanced (altered)

A hinging frame is connected to a motor which moves the system vertically along e.g. a linear gear or leadscrew. To remove siltation, the system moves downwards. At the bottom the wheels make contact with the lock bottom. Since the motor is continuing downwards, the wheels are forced in the direction of the lock chamber. Attached to the wheels is a frame with a plough, which pushes the siltation out of the recess. The linear gear of leadscrews are connected to the lock wall slightly outside the gate recess (both sides). Once the siltation removal is complete, the system moves upwards above shore. As a result, the gate is able to close. The system is switch based: down and up. Note: the plough is attached to the wheels with a frame, however the plough is open at the bottom. [1F, 2F, 3A, 4D+F, 5A, 6D].



4.2.2. Concept screening

The completed and filled in concept screening matrix is shown in Figure 19.

	Concepts						
Selection criteria	B. **Reference** Brute force	C. Quick	E. Simple	H. Advanced (altered)	I. Complete removal	J. Mobile	K. Exchangeable
- Non-interference of lock function	0	0	0	0	-	0	0
- Ease of use	0	+	+	+	-	0	+
- Maintainability	0	0	0	-	0	+	+
- Ability to remove siltation	0	+	-	0	+	-	+
- Ease of construction	0	0	+	-	0	+	+
- Mobility	0	0	0	-	-	0	0
- Reliability	0	0	+	0	0	+	+
- Costs	0	0	+	0	-	+	+
Sum +'s	0	2	4	1	1	4	6
Sum 0's	8	6	3	4	3	3	2
Sum -'s	0	0	1	3	4	1	0
Net Score	0	2	3	-2	-3	3	6
Rank	5	4	2	6	7	2	1
Continue?	Combine	Combine	Revise	NO	NO	Revise	Revise

Figure 19. Concept screening matrix.

The results of the concept screening per concept are:

- ***B. Brute force – C. Quick*: combined and continued.** The concepts are similar, with concept Quick scoring higher on two criteria. However, concept Quick requires the anchors from concept Brute force to remain fixated during siltation removal. As a result, the concepts are combined: the working principle of concept Quick and the anchors of concept Brute force.
- ***E. Simple* – revised and continued**: the concept could also be lowered by cranes on a small truck (in addition to "walking" over the edge).
- ***H. Advanced – I. Complete removal*: discarded.** The concepts have a significant number of features which result in [-] on the criteria. Furthermore, the features which result in [+] on the criteria could not be applied or combined with other concepts. Thus, the concepts are discarded.
- ***J. Mobile* – revised and continued:** the 0_2 jets are replaced by waterjets. Furthermore, wheels are added to the frame. As a result, the concept could "walk" over the edge to be lowered and raised by e.g. a winch.
- ***K. Exchangeable* – revised and continued:** the pump is placed on the frame, no further alterations.

The results from the concept screening are processed**,** leading to the remaining four concepts for concept scoring S1. The concepts are: *Concept 1 – Mobile, Concept 2 – Quick, Concept 3 – Simple, Concept 4 Exchangable*. The numbering (Concept 1 – 4) is random and has not further meaning. The concepts are shown in Figure 20 **-** Figure 23**,** with additional descriptions. The sketches and descriptions are sent to the experts for concept scoring S1.

Concept 1 – Mobile

All components of Concept 1 are integrated on a small truck, creating a mobile system. To remove siltation waterjets are used, which are powered by a pump. The jets and pumps are integrated in a rectangular frame. The frame is connected with cables to cranes on a small truck. First, the truck is positioned at the gate recess and subsequently the frame is lowered along the recess wall. Once the frame reaches the siltation, the pump is activated and the jets remove the siltation from the recess. Next, the frame is raised and placed on the truck, ready to transport to a new recess.

Due to the wheels on the frame, the system could be used when the truck could not reach the recess. The frame could be rolled to the recess and "walk" over the edge, Figure 20 (right). *Note:* the frame is empty to emphasize the working principle. To achieve controlled lowering, the frame is connected to a simple winch (e.g. located on the truck or on shore).

A short explanation of several components:

- **Suction hose of the pump:** the suction hose could be placed outside the recess to assure suction of (mainly) silt free water.
- **Wheels:** in addition to rolling to the recess and "walking" over the edge, the wheels provide vertical guidance during the lowering of the system.
- **Waterjets:** the jets are aimed in multiple directions to assure the frame remains "neutral" underwater, i.e. the frame will not swing.
- **Rectangular frame:** in addition to integration of the components, the frame fulfils another function: protection. The vulnerable components are within the borders (expect the top) of the frame, thus protected against collisions with e.g. the gate recess.

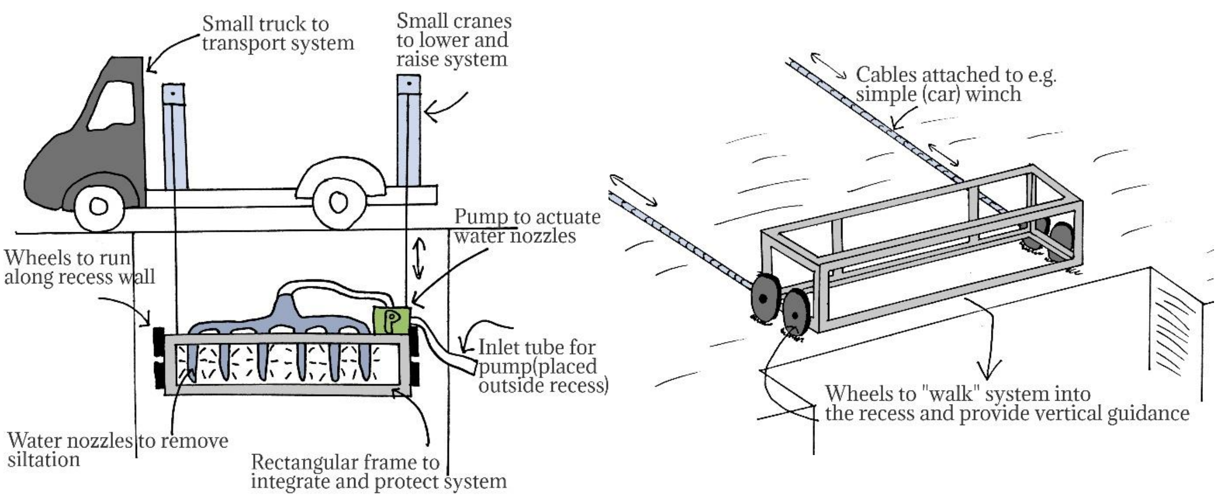


Figure 20. Concept 1 full (left), detail of the frame with wheels to "walk" the concept over the edge (right).

Concept 2 – Quick

A scoop is actuated by hydraulic cylinders to remove the siltation from the gate recess. The scoop and cylinders are integrated in a rectangular frame. The frame is connected with cables to cranes on a small truck (equal to Concept 1 – Mobile, thus the cranes are not illustrated in Figure 21). First, the truck is positioned at the gate recess and subsequently the frame is lowered and anchored at the bottom. Once in position, the cylinders are activated to rotate the scoop towards the recess wall. The wall functions as a stop block and forces the siltation into the scoop. Next, the scoop (with siltation) is raised and placed on the truck.

Subsequently, the siltation needs to be discarded. For instance, on a designated area on shore or back in the lock chamber. This could be achieved by repositioning the truck, positioning the frame with the cranes and reactivating the cylinders to unload the siltation. Once complete, the truck could reposition to a new recess.

A short explanation of several components:

- **Scoop:** a long scoop (length wise) is used to maximize siltation removal.
- **Rectangular frame:** equal to concept 1, the frame provides protection for the vulnerable components. However, to remove siltation the scoop protrudes underneath the frame during activation of the cylinders.
- **Anchor points:** anchor points are installed on the recess wall, to prevent the system from rotation during scooping. The anchor points could be installed on different heights to achieve siltation removal in several steps. Numerous options are available for anchor points, e.g. the use of a T-slot. A T-slot is realised in the frame, which slides over the anchor point. Illustrated in Figure 21 (right). Clearances within the T-slot and anchors points should simplify the placement on the anchor points.

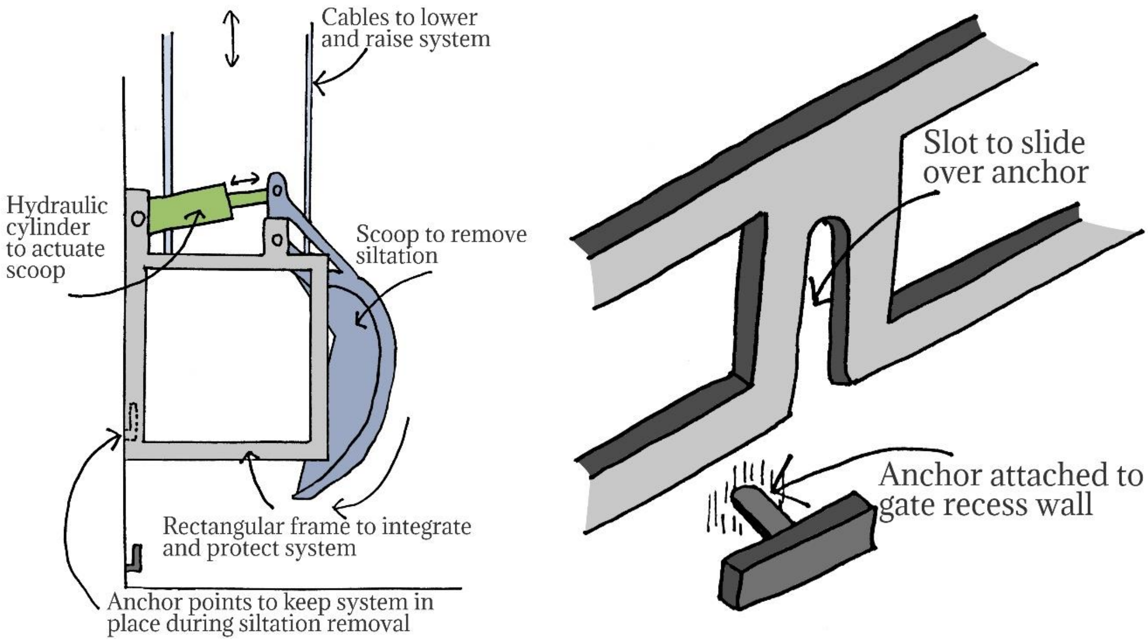


Figure 21. Concept 2 full (left), detail of anchor point (right).

Concept 3 – Simple.

A rectangular frame is equipped with a sweeper along the entire length. The sweeper is powered by an electric motor, to rotate the sweeper. The rotation, as illustrated in Figure 22 (left), is aimed outwards. As a result, the siltation is transported towards the lock chamber, away from the gate recess. The frame is connected via cables to cranes on a small truck (equal to Concept 1 – Mobile, thus the cranes are not illustrated in Figure 22). First, the truck is positioned at the gate recess and subsequently the frame is lowered along the recess wall. Once the frame reaches the siltation, the motor is activated and the sweeper removes the siltation from the recess. Next, the frame is raised and placed on the truck, ready to transport to a new recess.

Due to the wheels on the frame, the system could be used when the truck could not reach the recess. The frame could be rolled to the recess and "walk" over the edge, shown in Figure 22 (right). Note: the frame is empty to emphasize the working principle. To achieve controlled lowering, the frame is connected to a simple winch (e.g. located on the truck or on shore).

In addition, a short explanation of several components:

- **Wheels:** in addition to rolling to the recess and "walking" over the edge, the wheels provide vertical guidance during the lowering of the system.
- **Motor:** as illustrated in Figure 23 (left), the motor drives the sweeper with e.g. gears or belts. As a result, the motor is distanced from the sweeper and bottom, providing additional protection for the motor.

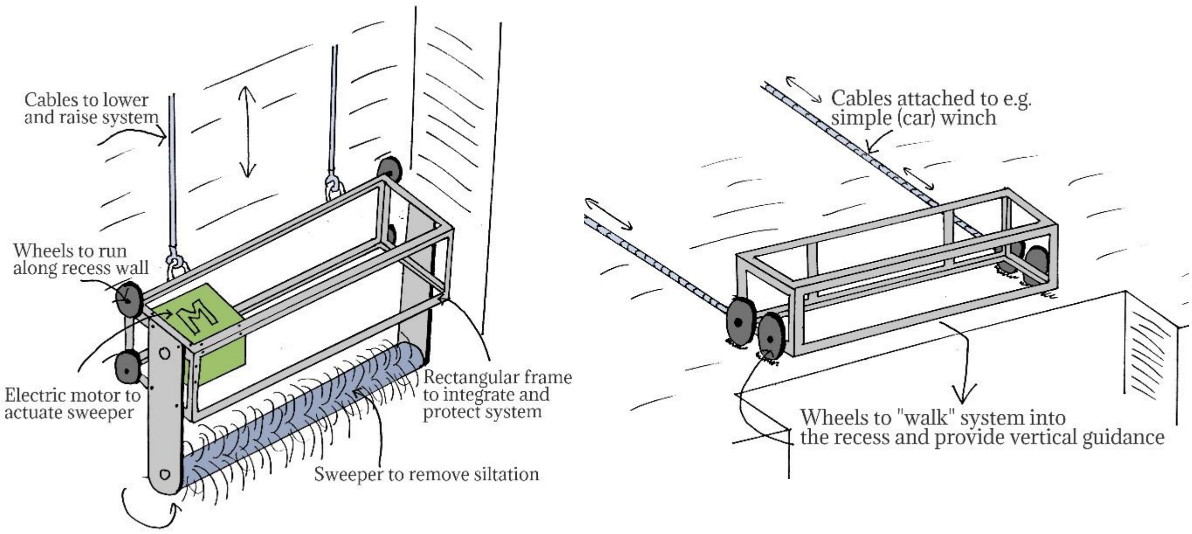


Figure 22. Concept 3 full (left), detail of the frame with wheels to "walk" the concept over the edge (right)

Concept 4 – Exchangeable

To remove the siltation, the concept utilizes waterjets powered by a pump. The waterjets and pump are integrated in a rectangular frame, which is connected via cables to a "window washing boom". The boom is located on rails, to move the system parallel to the gate recess. The rails are continued along the shore (approximately two times the length of the recess). To use the system, the first step is to roll the boom in front of the recess, while the frame is raised. Once in position, the frame is lowered until the siltation is reached. Subsequently, the pump is activated and the jets remove the siltation from the recess. Next, the frame is raised and the boom could be rolled away, to clear the space in front of the recess.

The frame could be decoupled from the "window washing boom" to be transported to another boom. However, the idea is to have a system present for the majority of the time, to achieve an easy to use system with no transport. If applicable (and desired), the rails could be continued along the entire lock chamber. As a result, one system could reach multiple gate recesses.

A short explanation of several components:

- **Suction hose of the pump:** the suction hose could be placed outside the recess to assure suction of (mainly) silt free water.
- **Waterjets:** the jets are aimed in multiple directions to assure the frame remains "neutral" underwater, i.e. the frame will not swing.
- **Rectangular frame:** in addition to integration of the components, the frame fulfils another function: protection. The vulnerable components are within the borders (expect the top) of the frame, thus protected against collisions with e.g. the gate recess.
- **Rails:** special rails, which are used for "window washing booms" on buildings, prevent the system from tilting due to the weight of the frame. Furthermore, certain rolling gates are used as a road in closed position. To prevent hinder from the rails, cable covers (e.g. for fire hoses) could be used to cover the rails.

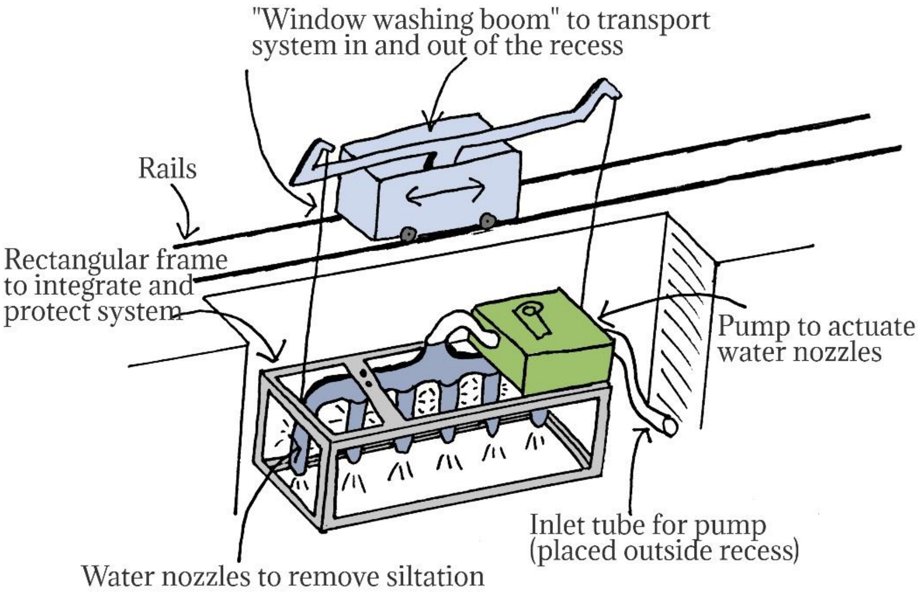


Figure 23. Concept 4 full.

4.2.3. Concept scoring stage 1

The scores regarding the weight factors of all experts are collected, resulting in the following weight factors: 1. non interference of lock – **21%**, 2. ease of use – **12%**, 3. maintainability – **14%**, 4. ability to remove siltation – **18%**, 5. ease of construction – **6%**, 6. mobility – **7%**, 7. reliability – **15%** and 8. costs – **6%**. The remainder of the pairwise comparison matrixes and the summarizing table are shown in *Appendix C3.1: weight factors.*

Subsequently, the concept scoring matrices from the experts are collected (shown in Figure 64 - Figure 68 in *Appendix C3.2: data concept scoring stage 1)* and analysed. The results are shown in Figure 24.

Concept scoring S1 results	**Concept 1: Mobile**	**Concept 2: Quick**	**Concept 3:Simple**	**Concept 4: Exchangable**	
Experts ↓	Score	Score	Score	Score	Ideal score
Expert 3	2.31	1.14	1.41	2.22	4
Expert 6	2.34	2.70	2.34	3.03	4
Expert 7	2.49	3.14	2.23	1.93	4
Expert 9	2.92	3.04	2.15	2.07	4
Expert 10	2.43	2.16	2.58	2.35	4
Average score	2.50	2.44	2.14	2.32	
Rank	1	2	4	3	
Standard deviation	0.25	0.82	0.44	0.43	
Percentage (average score/ideal score)	62	61	54	58	

Figure 24. Results concept scoring S1.

The first valuable information is the average score and accompanying ranking of the concepts: 1. Concept 1 – Mobile with an average score of **2.50**, 2. Concept 2 - Quick with an average score of **2.44**, 3. Concept 4 – Exchangable with an average score of **2.32** and 4. Concept 3 – Simple with an average score of **2.14.**

Ideally, the scoring shows large differences between the high and low scoring concepts, supporting the decision to continue with the high scoring concepts and discard the low scoring concepts. However, the percentages in Figure 24 show small differences between the average scores and additional arguments are required to select the winning concept(s). Visualization of data could be useful [12] and a column graph of the total scores per criterion per concept are shown in Figure 25 (no weight factors).

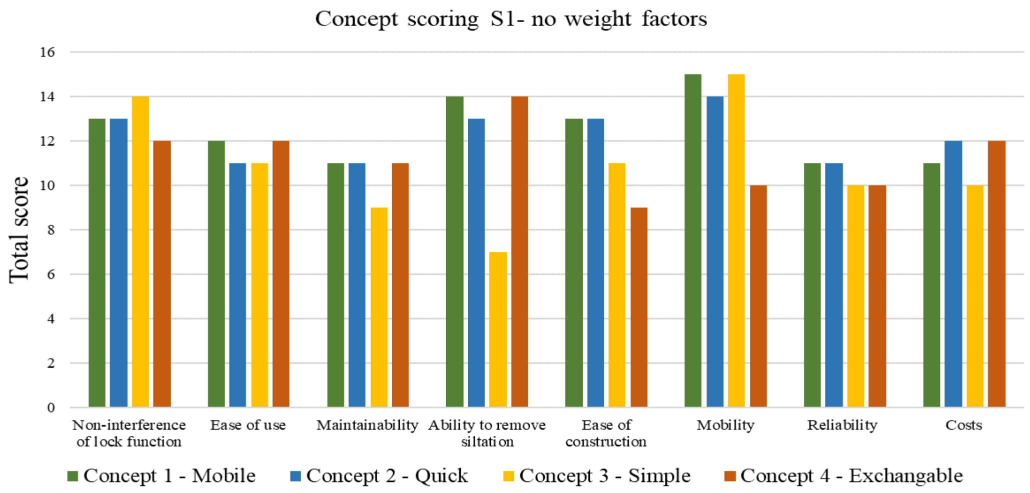


Figure 25. Column graph concept scoring S1

The graph immediately shows concept 3 (relative to the other concepts) scores considerably lower on the criterium *ability to remove siltation.* None of the experts are confident in the ability of concept 3 to remove the siltation, which is crucial. Concept 3 uses a sweeper to remove the siltation, which is the main distinction from concept 1. The additional aspects of concept 1 and 3 are similar. Thus, concept 3 has the lowest average score, scores considerably lower on a crucial criterion and has no additional unique features. Meaning *concept 3 is discarded*.

Concept 1 and 2 have the highest average scores. However, the difference with concept 4 is small. Noticeable are the similarities between concept 1 and 4: the main working principle is to transport the siltation with waterjets, powered by a pump attached to the frame. Concept 2 has a completely different working principle: scoop up the siltation with a scoop powered by hydraulic cylinders. Meaning, concept 2 is significantly different from concept 1 and 4. Since concept 2 has the second highest average score and is significantly different from concept 1 and 4, the decision is made to *continue concept 2*.

The final concepts to consider are concept 1 and concept 4. The average score of concept 1 (2.50) is higher than concept 4 (2.14), with a difference of 4%. Furthermore, the column graph (Figure 25) indicates no extremes in scoring of important criteria. Thus, to continue with concept 1, a method is required to prove concept 1 scores higher. The method used is a T-test.

T-test

The T-test is a statistical test to determine whether the mean difference between two sample groups is significant. The T-test uses the means and is commonly used in hypothesis testing, meaning a hypothesis is required. The purpose is to calculate whether concept 1 scores higher than concept 4. Leading to the following hypothesis:

- Ha: concept 1 scores higher than concept 4 $C1>C4$
- H0: concept 1 scores less than or equal to concept 4 $C1 \leq C4$

The T-test rejects or fails to reject H0. An one-tailed *paired two sample* T-test, with $\alpha = 0.05$ is used. The two sample sets are the unweighted scores for concept 1 and the unweighted scores for concept 4 (marked in blue in Figure 64-Figure 68 in *Appendix C3.2: data concept scoring stage 1*). The unweighted scores are used since the difference in scores is important (i.e. not the impact). Furthermore, a paired t-test is used since the scores are related to a person and a criterion, e.g. a score for ease of use could not be compared with a score for reliability. An one-tailed T-test is used to determine if there is a difference in a certain direction.

T-test results

The T-test failed to reject H0, implying that concept 1 ($M = 2.5$, $SD = 0.82$) might not score higher than concept 4 ($M = 2.25$, $SD = 0.93$), $t(39) = 1.57$, $p = .062$ (see Figure 69 in *Appendix C3.2: data concept scoring stage 1* for an overview of the T-test results). Since $p \nless \alpha$, H0 cannot be rejected. However, elaboration of the results is required.

A $p < \alpha$ results in a rejection of H0. The commonly used $\alpha = 0.05$, however the α could vary per case. In the completed T-test the p value is very close to the α, which could be argued to be a weak rejection of H0. Out of a 100 times, the H0 would be rejected 6 times while true.

In addition to the results of the T-test, a remark presented in the concept scoring is of great importance. As mentioned in section 4.1.3, the experts are asked for notes. *Expert 7* commented on concept 4 with regard to the rails. The main distinction between concept 1 and concept 4 is the use of a window washing boom for concept 4. The window washing boom moves along rails, which are located on shore, in front of the gate recess. According to *expert 7*, people walk along the shore of the lock chamber to e.g. help with mandatory mooring of the vessels. Meaning, rails are a NO GO due to obstruction.

The NO GO is not shared by other experts, however similar notes are not presented with regard to concept 1 by any of the experts. Thus, concept 4 is a NO GO for one expert and the T-Test provides a weak rejection of H0. The arguments combined provide sufficient confidence to select concept 1. Meaning, *concept 1 continues* to the final phase and *concept 4 is discarded*. To summarize, concept 1 and 2 are selected to continue to the final phase, while concept 3 and 4 are discarded. *For the final phase, the names of the concepts are removed and solely referred to as concept 1 and concept 2.*

Additional interesting notes by the experts on concept 1 and 2 are: 1. where will the siltation go with concept 1, 2. could the concepts be used for different sized recesses, 3. how does the anchoring work, 4. how long do the concepts take to clean, 5. will the jets cause the concept to move and 6. will the siltation fall out of the scoop if picked up. The notes are used as input for the prototyping.

5 Prototyping

As discussed in section 4.2.3, concept 1 and concept 2 remain and to reach a decision on the winning concept additional information is required. A crucial tool is the use of prototyping. Numerous studies show prototyping in the early phase of design is essential [34, 35] and according to Christie et al. [36] prototyping of concepts in parallel could aid in concept selection by providing essential feedback. The latter is confirmed by Camburn et al. [37], parallel prototyping of concepts is especially useful if the concept scores are close. Meaning, prototyping is ideal for the next step of the project.

However, prototyping for this research is challenging. The systems and environment are heavy duty, the budget is limited, facilities are limited and the COVID-19 pandemic further impedes prototyping. Which could be seen as a reflection of the civil industry, in which meaningful prototypes are difficult to realise and often not used due to aforementioned reasons (except COVID-19 in the normal situation). Thus, during the prototyping for this research one should keep in mind: 1. which tests provide valuable information and 2. could the tests be realised within the restrictions.

Subsequent to the prototyping, the experts will perform concept scoring S2. Meaning, the prototyping should provide objective information regarding the concepts, which could be used for the concept scoring. Thus, the information should link to e.g. the selection criteria, notes from the experts from concept scoring S1 and important features of the concepts. Tests are not directly focussed on criteria, e.g. there is not a specific test for ease of use, however a test of lowering and raising could provide information for ease of use, mobility and more. Meaning, tests could provide information for multiple aspects at once.

To realize prototyping several techniques are well known e.g. parallel prototyping, iterative prototyping, requirement relaxation prototyping and many more. A thorough overview is provided by Camburn et al. [37]. Furthermore, Camburn et al. [37] found the four most common objectives of prototyping: *refinement*, *communication*, *exploration* and *active learning*. In general, prototyping is performed ad hoc and largely depended on the experience of the engineer [38]. Thus, a structured approach is often missing even though options are available. Ulrich and Eppinger describe a four step approach [28] and recently methods for prototyping were proposed by Camburn et al. [38, 39] and Christie et al. [36]. The main goal of such methods is to improve the prototyping process and increase repeatability.

Several methods exist for a structured approach of prototyping. Nevertheless, the methods vary and are not a universal solution. Thus, such a method should not be applied at once, especially with the restrictions of this research. All projects involve tasks for which such a method is not efficient and an approach of simply "making it" yields more results. Such an approach is more common in Design Thinking, which could remove the limiting factors of a more structured approach. As a result, the used prototyping approach is a combination of several methods and consist of the following steps:

1. Determine the purpose and level of approximation [28] of a prototype, e.g. choose a frame geometry while ignoring connections to the wheels and scoop.
2. Asses the extent of the prototype (based on experience) and if **a)** a structured approach is necessary or if **b)** simply "making it" is more efficient. If option **a** is chosen continue to step 3. If option **b** is chosen, make the prototype.
3. Determine the general objective according to Camburn et al. [37]: refinement, communication, exploration or active learning.
4. Utilize the mapping from Camburn et al. [37] to link the objective to a suggested prototyping technique.

The described approach provides guidance during the prototyping process and allows for freedom if deemed necessary. However, as mentioned by Camburn et al. [37] methods and prototyping techniques do not dictate how to actually construct a prototype. The construction is largely dependent on the domain. However, two guidelines are dominant in this project: 1. do it yourself (DIY) and 2. minimization of the number of parts. DIY is ideal for repurposing of materials and reduction of costs [40]. Furthermore, DIY is extremely useful within the restrictions of this project. The reduction of number of parts is according to Yang [35], fewer parts often result in a more successful prototype.

The amount of information provided by the prototyping is extensive and heavily reliant on videos and pictures, *meaning not all tests and iterations could be shown*. Thus, the following sections discuss the most interesting results and lessons learned. Sections 5.1-5.4 could be seen as tests in advance to the final prototypes. Subsequently, the final prototypes are discussed in section 5.5 and are used for tests in a concrete scale model of a gate recess in sections 5.6 and 5.7. Finally, section 5.8 discusses how the information is presented to the experts in advance to concept scoring S2.

5.1. Waterjet configuration

The waterjets of concept 1 are the main working principle and should be able to remove the siltation, leading to the purpose of the test *to determine the optimal jet configuration to remove siltation from the gate recess*. The prototype is an easily adjustable set-up to test numerous iterations. The prototype (Figure 26 left) consist of a PVC elbow (yellow arrow) fixated to a wooden structure via a scrap piece of PVC. Glued onto the elbow is an adapter to a garden hose (green arrow). A piece of straight PVC is pushed into the elbow (red arrow) and closed off by an end cap and hose clamp (blue arrow). Holes are made in the straight piece of PVC to simulate the jets. The straight piece of PVC could quickly be swapped for a different jet configuration, e.g. change of angle, number of jets, diameter of jets and more.

The prototype is fixated to an aquarium via clamps (Figure 26 middle**)**. The fixation assures the position of the prototype is equal in all tests. Markings are drawn on the aquarium (Figure 26 right) to visualize the dimensions. Coarse sand (1-2 mm) and a small quantity of orange gravel is used instead of fine sand due to the increased visibility. The garden hose is connected to a butterfly valve to immediately activate and deactivate the jets.

The test method is: 1. prepare the prototype (connect the to be tested jet configuration) and fixate in position, 2. connect the garden hose to the butterfly valve and flush several seconds to remove air from the prototype, 3. add or remove water until the required level (equal in all tests), 4. use a flat board to push the sand to an even layer of 4 cm in height, 5. activate the jets for 10 seconds and 6. deactivate the jets and note the results.

Figure 26. Prototype concept 1 (left), test set-up jet configuration (middle), aquarium with grid markings (right).

During the tests different aspects are analysed: the clearance of the sand (measured from the corner) and visual inspection of slow motion videos and pictures. The clearance is not an ideal measurement, in certain situations the jets create “holes” or the sand is circulating and deposited at the starting location. Meaning, the clearance results are inadequate to reach a conclusion. As a result, visual inspection of the slow motion videos and pictures is required. For instance, a slow motion video could illustrate a circulating flow and how the jet configuration could be improved. Figure 27 illustrates from left to right: 1. a situation in which the clearance is obvious, 2. a situation in which a “hole” is created and 3. a screenshot from a slow motion video indicating a circulating flow.

The standard configuration is 5 jets (holes) of 2.5 mm, distanced every 1.5 cm. The angles used are -45°, 0° and +45°. The angles are indicated with the green, red and yellow arrows respectively in Figure 27 (middle). As mentioned, numerous tests are conducted. Table 5 summarizes the most interesting results and lessons learned.

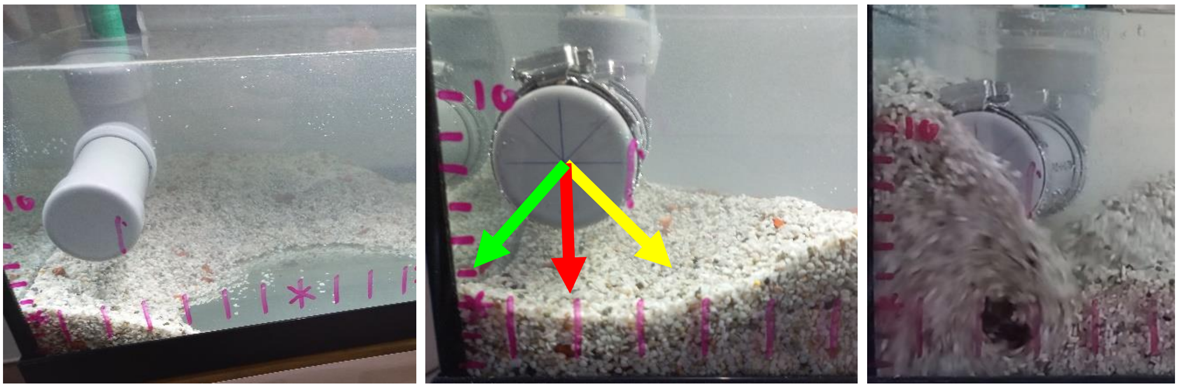


Figure 27. Obvious clearance (left), hole created by the jets + the angles (middle), circulating flow shown in video (right).

Table 5. Interesting test results optimal jet configuration.

Purpose: determine the optimal jet configuration to remove siltation from the gate recess						
#*	# of jets	Ø of jets [mm]	Jet configuration [°]	CV**	CH***	Notes
1	5	2.5	0	-	-	**1.** A hole is created, no real clearance.
2	5	2.5	-45	-	-	**2.** The jets create a swirl and “cuts” sand from the wall, however the sand is contained by the sand in front.
3	5	2.5	+45	-	from 6	**3.** successful in clearing the sand, however the jets do no reach the wall and sand remains at the wall.
6	10	2.5	-45 & +45	0.5	-	**6.** The +45° removes the sand in front and as a result the -45° can cut the sand from the wall. Thus, the wall is almost cleared. However, since the flow is divided over more jets, the power is insufficient to clear the sand properly.
Lessons learned: a combination of -45° and +45° is required to clear the sand in front and at the wall, however the power is insufficient to clear the siltation properly.						
8	5	4	0	-	-	**8.** Almost no penetration of the sand, weaker than jets of 2.5 mm.
10	5	1.5	0	-	-	**10.** Seems slightly weaker than the 2.5 mm jets.
12	5	1.5	+45	-	from 6	**12.** Same as test 10.
Lessons learned: larger jets have a strong negative effect and smaller jets seem slightly weaker than the standard 2.5 mm jets.						

21	10	2.5	- 45 & +45	0	all clear	**21. BIG PUMP.** A large pump is used instead of the faucet. Extremely successful, all sand is cleared.
22	10	2.5	-45 & 0	0	6	**22. BIG PUMP.** A big pump is no guarantee of siltation removal. The CH is only 6. Meaning the jet configuration is more important.
Lessons learned: the jet configuration is more important than raw power. A big pump will not automatically clear all siltation.						
24	7	1.5	-45 (2) & +45 (5)	0	from 8	**24.** two jets on -45° and 5 jets on +45. ° The configuration is extremely successful. The jets on + 45° remove the sand in front and the jets on -45° remove the sand from the corner. A major improvement on the standard -45° & + 45° configuration.
27	8	1.5	-45 (3) & +45 (5)	0	all clear	**25.** one more jet on -45 and works even better. All sand is cleared.

** The test number is the original test number, thus not all tests are shown.*
***CV means clearance vertical, the clearance at the wall. A CV of 0 means all is removed at the wall, a CV of 3 means 1 cm is removed. A dash (-) means there is no noticeable change in clearance.*
****CH means clearance horizontal. A CH of 5 means all is removed until 5 cm. A CH of "from 6 cm" means all is cleared from 6 cm. The maximum CH is 18 cm, farther is noted as all clear.*

Test 27 resulted in the most successful jet configuration. A combination of +45° and -45° is required. The jets on +45° remove the sand in front and the jets on -45° cut the sand from the wall and transport the sand into the flow of +45°. The +45° jets are crucial and require more flow, resulting in the combination of five jets on +45° and three jets on -45°. The five jets on +45° are distanced every 1.5 cm and the three jets on -45° every 2.25 cm (the centre jets on +45° and -45° are aligned). Furthermore, the jet diameter is essential. The configuration of test 27 is repeated with a jet diameter of 2.5 mm, which is significant less effective. Meaning the diameter of 1.5 mm is used.

Several additional tests are performed with the configuration of test 27, e.g. a thicker layer of sand, a test with the first prototype of a gate recess, extremely fine sand and aiming the jets to the right. All tests concluded that the configuration of test 27 will be used for the final prototype. The results of test 27 and a test with a gate recess of wood are shown in Figure 28, left and right respectively.

The jets clean a certain area and to increase the area the distance between the jets is increased. However, the effects are disadvantageous. The clearance is decreased significantly. Thus, for the final prototype the original configuration of test 27 will be used.

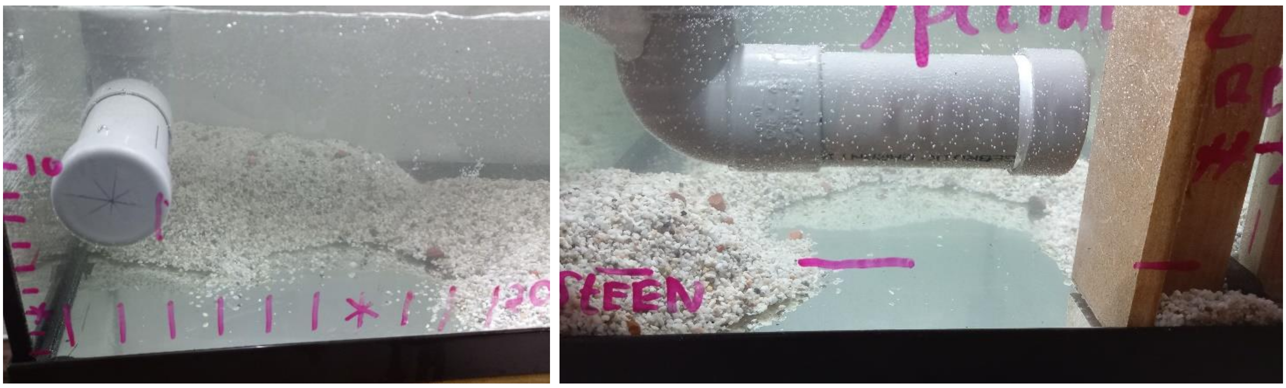


Figure 28. Results of test 27 (left), configuration of test 27 with a first prototype of the gate recess.

5.2. Scoop configuration

The main working principle of concept 2 is the scoop, which should be able to remove the siltation. Leading to the purpose of the tests *to determine the optimal scoop configuration to remove siltation from the gate recess*. A two dimensional approximation of the frame and scoop is realised. The connection point between the arm and frame, the rotation point (RP), of the scoop could quickly be adjusted: forward, backward, up and down. Furthermore, the scoop configuration could be adjusted. A grid is fixated behind the frame and the test method is (shown in Figure 29): 1. bring the scoop to the open position, 2. swing the scoop to the first contact with the ground and 3. continue the swing until contact with the wall is established. The contact points with the ground and wall are noted. In addition, the angle between the scoop and beam is noted. The angle between the scoop (yellow) and the arm (red) is determined by contact with the ground. At the point of contact the scoop should barely scrape over the bottom. The results are shown in Table 6.

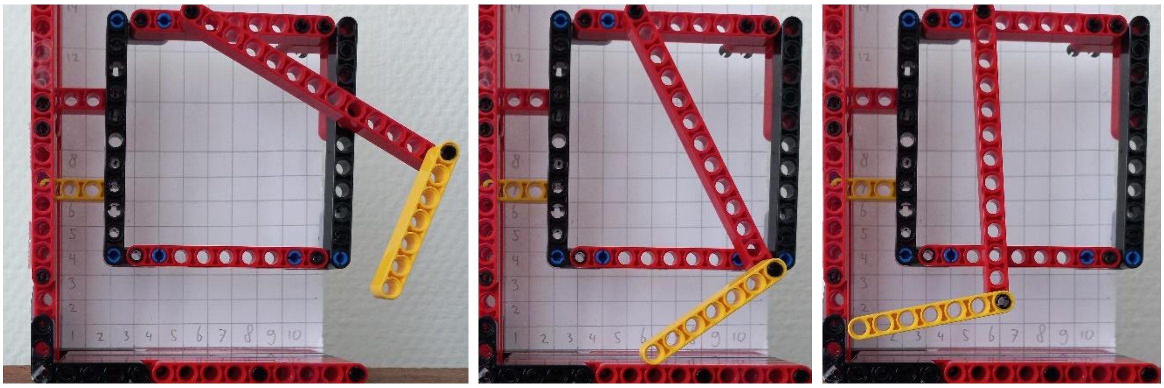


Figure 29. Rotation point 1: open position (left), first contact with the ground (middle) and first contact with the lock wall (right).

Table 6. Interesting test results scoop configuration two dimensional approximation.

Purpose: determine the optimal scoop configuration to remove siltation from the gate recess					
#*	RP**	Scoop	Angle scoop [°]***	Contact point bottom [cm]	Contact point wall [cm]
1	1	Straight edge	-11	5.8	0.75
2	1 - heightened	Straight edge	-30	5.8	0.75
3	1 – lowered	Straight edge	+3	5.8	1
4	1	Straight edge + curve	-11 (straight edge)	5.8	0.75
6	2	Straight edge	0	7.5	2
9	3	Straight edge	12	9.5	3.3
Lessons learned: moving the RP further from the wall increases the reach away from the wall (contact point with the bottom is increased). However, the reach into the corner is decreased (contact point with the wall is increased). Changing the height of the RP effects the angle of the scoop. A positive angle (lowering of the rotation point) is beneficial to retain siltation in the scoop, a negative angle could result in the siltation sliding out of the scoop. A curved scoop creates the effect of a positive angle for a section of the scoop, thus a curved scoop is better than a straight edge (for equal RP conditions).					

** The test number is the original test number, thus not all tests are shown.*

*** There are three RP’s: 1 closest to the wall, 2 in the middle and 3 farthest from the wall. Figure 29 illustrates RP 1.*

**** an angle of 0° is horizontal, a positive angle is pointed upwards and a negative angle downwards. Figure 29 (right) illustrates a negative angle.*

Rotation point 2 is chosen as the middle ground in terms of reach (away from the wall and into the corner). In addition, a curved scoop is used to maximize the positive angle to assure the siltation remains in the scoop. The set-up with RP 2 and the curved scoop is shown in Figure 30 **(**left**)**. The next step is transform the two dimensional prototype to a three dimensional prototype. Subsequently, the prototype is used for a test in which sand is scooped. The prototype is placed underwater against the wall of an aquarium and the scoop is activated by hand. The scooping and results are shown in Figure 30.

The main results from the 3D prototype are: 1. the frame obstructs the scoop in front and either the scoop should be lowered or the frame should be adjusted, 2. the scoop pushes the siltation towards the wall (as intended) and the wheels and anchor points should not obstruct the siltation (thus the anchor points and wheels should be placed higher or to the side), 3. a deeper scoop allows for more siltation to be removed and 4. side panels are essential to keep the siltation from flowing sidewards, however the side panels are obstructed by the frame as well.

The main lessons are used to create a model with CAD. Subsequently, the CAD model is 3D printed (SLA) for the final test prototype, discussed in section 5.5.

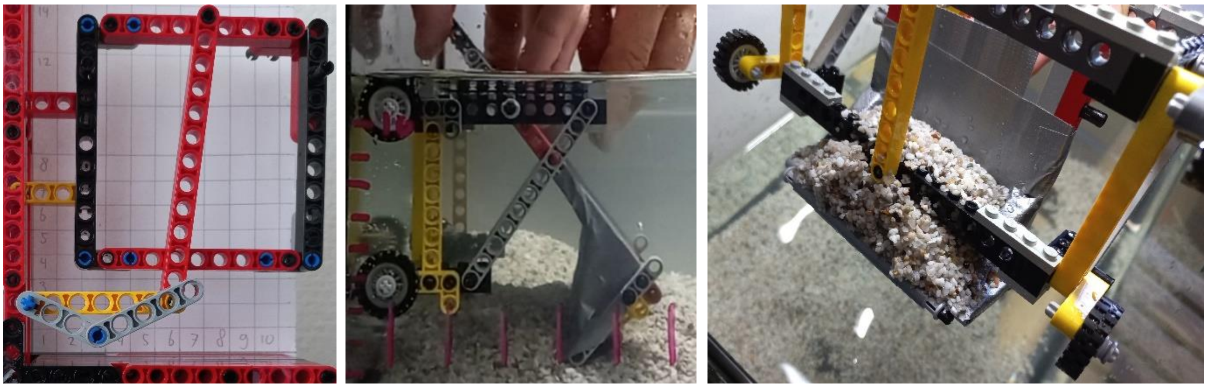


Figure 30. Chosen 2D set-up (left), 3D prototype scooping test (middle), results of the scooping test (right).

5.3. Anchor points

A 3D prototype of concept 2 is realised in section 5.2. A key element of concept 2 are the anchor points. Section 5.2 mentions the anchors should not obstruct the scoop and siltation, however no additional information is known. The purpose of the first tests is *to determine if the anchor points are necessary*. The 3D prototype is equipped with an air cylinder to activate the scoop and simulate the real life situation. The steps are: 1. suspend the prototype underwater (with cables) against the wall, 2. place the scoop in open position, 3. place sand in front of the scoop, 4. close the scoop. The test is repeated for a free hanging concept and for a concept which is fixated at the bottom against the wall (by a screwdriver) to simulate the anchor points.

The results are shown in Figure 31. The free hanging frame rotates around the top wheels once contact is made with the siltation and could not be used to scoop siltation. The frame fixated by the screwdriver (noted with the green arrow) remains in place. Thus, the anchor points are necessary. Subsequently, a prototype of the anchor points is realised. Vertical pins are installed in the wall and hooks (noted with the red arrow) are used on the frame as the anchor points. The prototype is shown in Figure 31.

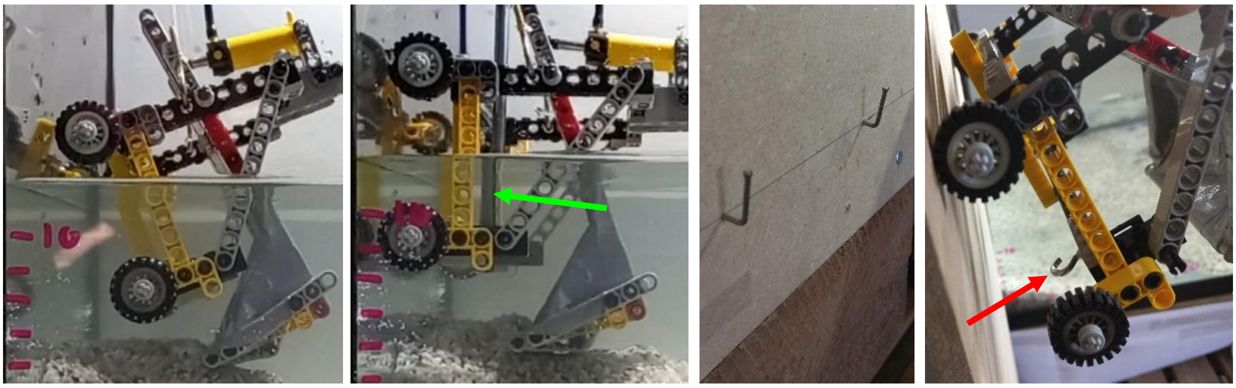


Figure 31. From left to right: free hanging frame, fixated frame by screwdriver, pins in the wall, hooks as anchor points.

The necessity of the anchor points is proven. However, notes from the experts question how the anchor points would work. Thus, the purpose of the second test is *to confirm if the anchor points work as intended*, i.e. is the prototype fixated during scooping and is the prototype able to lower onto and raised off the pins. The pins are placed underwater and the following steps are used: 1. align the prototype above the pins, 2. lower the prototype with cables towards the pins, 3. lower the prototype onto the pins with the anchor points, 4. activate the cylinder and scoop siltation and 5. raise the prototype from the pins.

The anchor points perform as intended. The prototype could be lowered onto the pins, is fixated during scooping and could be raised from the pins. The results are shown in Figure 32. However, during raising the concept is slanted. As a result, siltation could fall out of the scoop. The slanting is due to the change of the centre of gravity (COG). The COG of the system with an open empty scoop differs from the COG with a closed full scoop. Tests should be conducted to stabilize the concept in both situations.

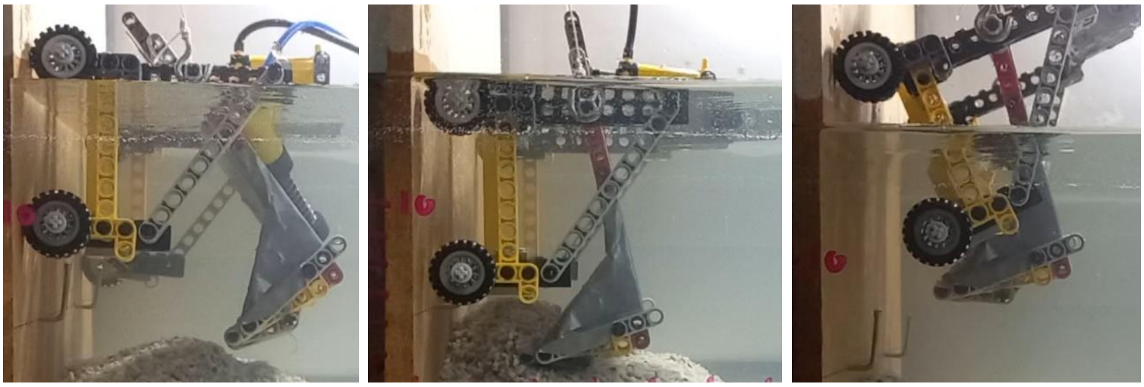


Figure 32. Lowering onto the pins (left), fixated during scooping (middle), slanted during raising (right)

5.4. Stability

As mentioned in section 5.3, stability is an issue with concept 2. Furthermore, one of the notes from the experts is with regard to the stability of concept 1. The concern is that the jets cause the system to move. Thus, the test purpose is *to determine how the concepts could be stabilized.* For concept 1 several adaptions are made to the set-up used for the jet configuration in section 5.1 .The adapted set-up is shown in Figure 33 (left).The prototype is free hanging (the hose runs through an oversized hole) to analyse movement and the sand is removed. The steps are: 1. prepare the prototype (connect the to be tested jet configuration), 2. connect the garden hose to the butterfly valve and flush several seconds to remove air from the prototype, 3. add or remove water to the required level (equal in all tests), 4. activate the jets in burst of several seconds (multiple times) and 5. deactivate the jets and note the results. Instead of altering the jet configuration, the prototype could be slanted to roughly simulate another angle. For instance, jets of 0° roughly simulate jets of +45°, an example is shown in Figure 33 (middle).

The main results are straight forward. Jets of 0° result in an upward motion of the prototype. Jets of -45° or +45° result in upwards and a sideways motion in the opposite direction. The effects are easily managed. Figure 33 (right) illustrates a jet configuration of 0° and jets in the opposite direction, pointed upwards. As a result, the upwards motion is cancelled. In a configuration which contains both -45° and +45° the sideways motion is cancelled, while the upwards motion remains. As mentioned, the upwards motion could be cancelled with jets pointed upwards. However, in case the concept has adequate weight, the upwards jets could be excessive.

The chosen configuration for the final prototype (section 5.5) is equipped with five jets on +45° and three on -45°. Thus, the sideways motion of the jets respectively is unequal and not cancelled. However, the resulting sideways motion is towards the wall and should not result in issues.

Figure 33. Stability set-up (left), slanted prototype (middle), upwards motion cancelled by upward jets (right).

For concept 2 the set-up is equal to the set-up used to confirm if the anchor points work as intended (Figure 32 in section 5.3). However, weight is added to the prototype to simulate more realistic conditions. The steps are: 1. attach cables to the to be tested cable holes, 2. lower and raise the prototype with an open scoop, 3. close and fill the scoop, 4. lower and raise the prototype with a closed and filled scoop, 5. note the differences. The cable holes are located in the top beams of the frame, illustrated with the green arrow in Figure 34. Two cables are attached in total, one to each top beam.

Figure 34 illustrates several interesting results. No cable hole configuration creates a stable prototype in both conditions due to the shifting centre of gravity. Either the prototype is slanted with the open scoop, or with the closed and filled scoop. Slanting could result in issues with e.g. lowering of the anchor points onto the pins or loss of siltation during raising. The notations written in red in Figure 34 (left and middle) are the used cable holes.

The decision is made to not further investigate options to stabilize the current prototype of concept 2. The final prototype will differ from the current version (e.g. materials, weight and dimensions). Thus, additional stability tests are performed for the final prototype in combination with the lowering and raising tests in section 5.6.1.

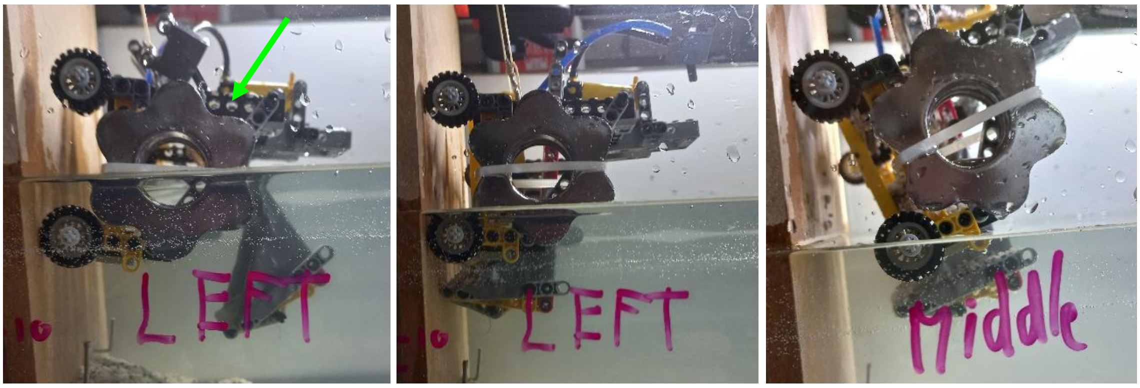


Figure 34. slanted with open scoop (left), stable with closed and filled scoop (middle), slanted with closed and filled scoop (right)

5.5. Final prototypes and scale model gate recess

For the remainder of the tests the final prototypes are required. To create the final prototypes, several practical matters are tested in advance, e.g. could syringes function as a hydraulic system, could a frame be realised with aluminium profiles and PMMA parts, how to connect PVC to PMMA and more. The results are combined with the prototyping result from the previous sections to realise the final prototypes.

CAD is mainly used for concept 2. The lessons learned from the scoop configuration (section 5.2) are implemented in a CAD model and further iterated. In addition, the frame and several fixtures (to fixate the syringes and parts of the frame) are modelled. Additional holes are implemented (e.g. for the wheels or syringe fixtures) in case adjustments are required once the prototypes are realised. Subsequently, the CAD files are used for laser cutting of the PMMA frame parts and 3D printing of the scoop (SLA) and the fixtures (FDM). For concept 1, solely the PMMA frame parts are modelled for laser cutting. For laser cutting and 3D printing the facilities at the University of Twente are used. However, all the remaining components and assembly are realised at home. The final prototypes are referred to as concept 1 and concept 2. The concepts with the essential features are shown in Figure 35. *Note: the wheels in Figure 35 of concept 1 are the wheels as a result of the tests in section 5.6.1 and are shown here to minimize the number of pictures.*

In addition to the concepts, a more realistic test environment is required. Thus, a concrete scale model of a gate recess and a water tank are realised. The scale model is placed in the water tank, which is equipped with a PMMA viewing window. The scale model and water tank are designed in CAD and subsequently realised at home (DIY). The scale model and water tank are shown in Figure 35 (bottom right).

The gate recess of the scale model is based on the gate recesses of Port of Antwerp, except for the length of the gate recess, which is extremely large relative to the height and width. The decision is made that a recess width of 80 mm in the scale model is sufficient and realistic with regard to the prototypes. The typical gate recess width in Port of Antwerp is 1300 mm, resulting in a scale of 1:16.25. However, a scale of 1:16.25 would mean the length of the recess in the scale model is approximately 646 mm. Such a length is not realistic due to several reasons, e.g. size of the water tank, weight of the concrete slab and more. The decision is made to choose a fictional length for the recess. The dimensions of the scale model are discussed in detail in section 5.7.

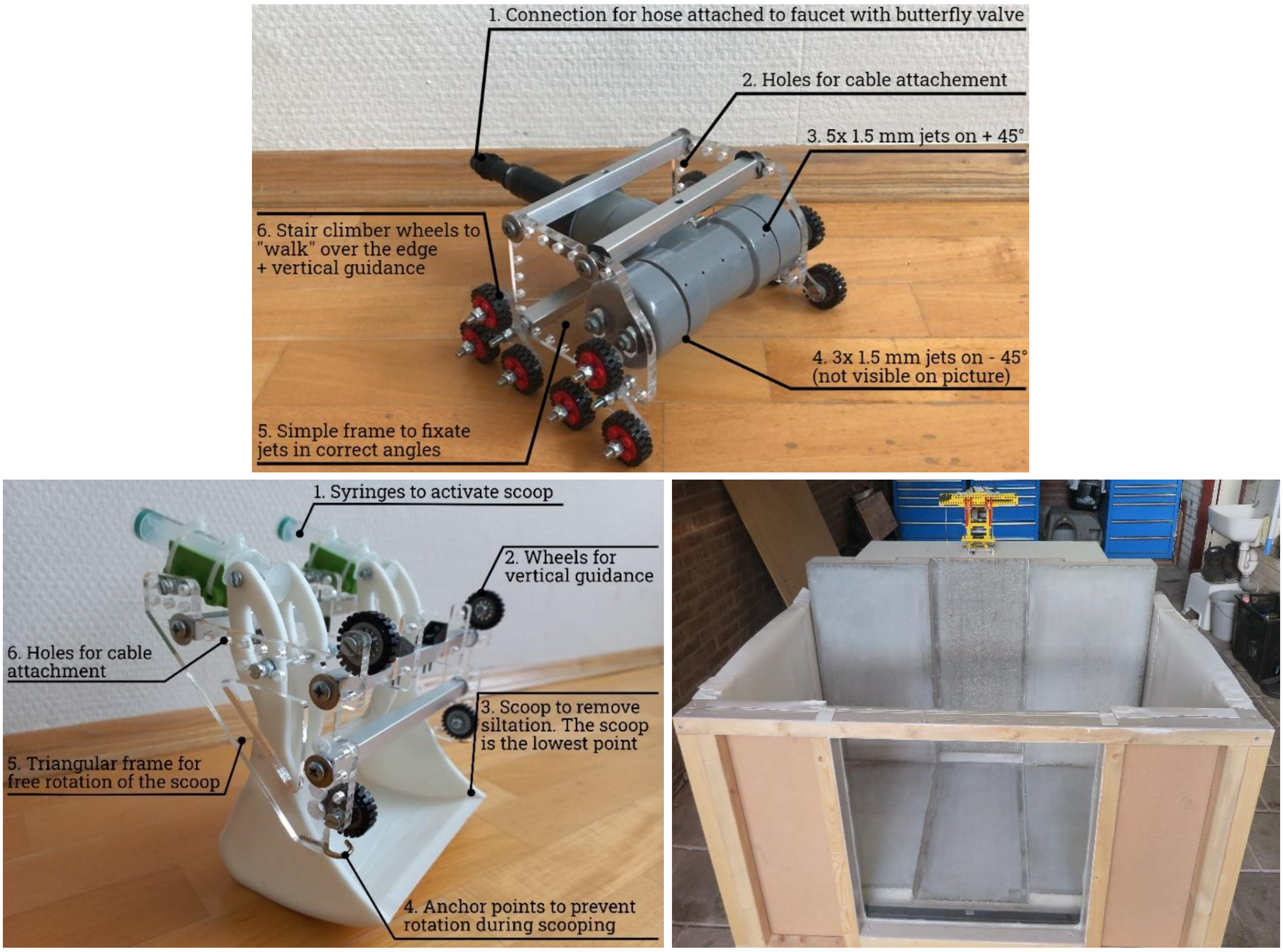


Figure 35. Concept 1 (top), Concept 2 (bottom left), concrete scale model of a gate recess within the water tank (bottom right).

5.6. Handling

A crucial aspect of the concepts is the handling. The handling is divided into lowering and raising (for both concepts) and discharging the siltation (solely for concept 2). All tests are performed on the scale model of the gate recess with a crane. To simulate the handling, a crane is build equipped with several options: 1. two cables attached to two (independent) motors, 2. two cables attached to one motor, 3. one motor with a V-split and 4. a cable attached to a winch. The crane is placed on shore and could be positioned according to the required configuration. For instance, to simulate a winch the crane is positioned such that the cable is close and horizontal to the ground. Furthermore, the crane is able to rotate 360°.

In Figure 36 several examples of the set-up are shown. During the tests concept 1 is not connected to the garden hose and concept 2 is not connected to syringe tubing. The stiffness of the hose and tubing is not realistic relative to the weight of the concepts and would interfere with the tests.

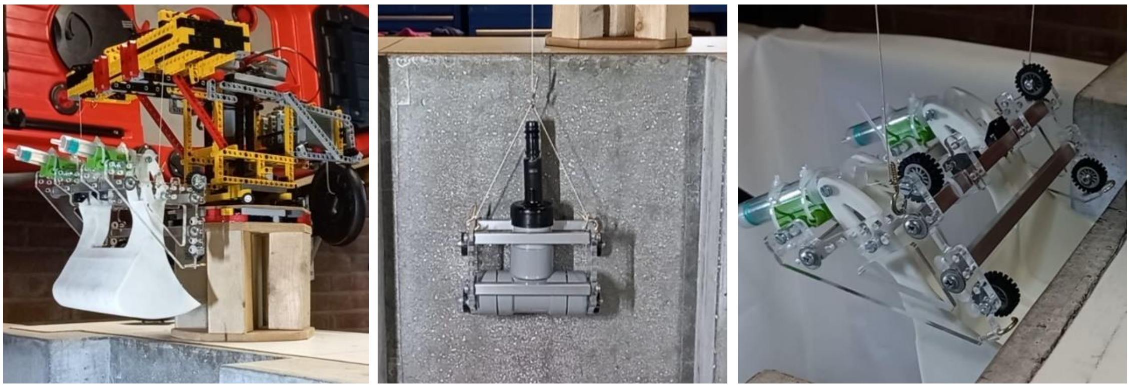


Figure 36. Crane set-up (left), lowering of concept 1 with a V-split (middle), lowering of concept 2 (right).

5.6.1. Lowering and raising

To reach the gate recess, the concepts need to be lowered and raised from shore. Leading to the test purpose *to determine a stable configuration to lower and raise the concepts*. The test method for both concepts is: 1. choose a configuration on the crane, 2. attached the cables to the to be tested cable holes, 3. lower the prototype along the recess wall, 4. raise the prototype along the recess wall. During the tests different aspects are analysed: contact between the wheels and wall, slanting of the concepts (meaning one the sides is lowered or raised more quickly) and difficulties with going over the edge.

For concept 1 the crane is positioned straight above the gate recess and the different options of the crane configuration are tested (Figure 36 middle illustrates one motor with a V-split). All configurations have similar results: proper contact between the wheels and wall and minimal slanting. Meaning, if the crane is positioned above the recess all options are viable and a V-split is the most realistic (easiest configuration). However, the interesting part of concept 1 is that the concept could "walk" over the edge. Which is simulated with the winch option: the concept is pushed to the edge and "walk" over the edge by gradually releasing the winch. The most interesting results are shown in Figure 37.

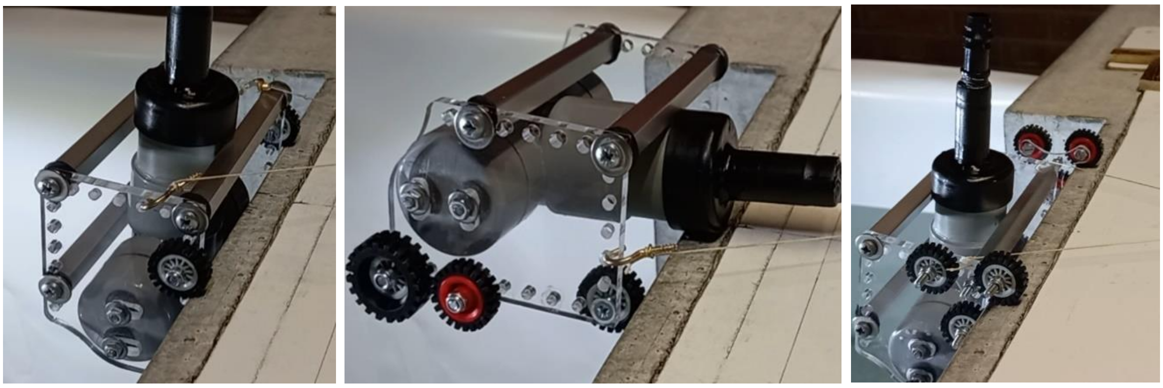


Figure 37. Large drop (left), issues being pulled back up (middle), smooth operation (right).

Figure 37 (left) illustrates the first issue. During lowering the back wheels are stuck behind the edge until the point of no return, which results in a sudden drop. Figure 37 (middle) illustrates the second issue. During raising the wheels cannot be pulled over the edge, causing the concept to rotate and crash against the edge. Numerous iterations are tested, e.g. additional wheels, larger wheels, smaller wheels, altering the location of the wheels and more. Eventually, the optimal configuration is the use of stair climber wheels, illustrated in Figure 37 (right). The wheels are connected in sets of three to an axle, allowing for a smooth operation (no drop or crash with the edge). In total four sets are used, illustrated in Figure 35 (top) in the previous section (section 5.5 regarding the final prototypes).

For concept 2 the crane is positioned straight above the gate recess as well and the different options of the crane configuration are tested. However, for concept 2 the winch is not an option and concept 2 is tested in two situations: 1. an open empty scoop and 2. a full closed scoop. As mentioned in section 5.4 (stability) the changing COG results in instability, thus the configuration should account for this. However, no configuration with two cables is able to balance the concept in both situations.

Figure 38 (left) shows an example with a closed and full scoop. The concept is stable and the wheels are in contact with the wall. However, Figure 38 (middle) **s**hows the same configuration with an open scoop. The concept is rotated such that the wheels could not make contact with the wall and the concept could not be used. Eventually, the optimal configuration is the use of two cable splits attached to two separate motors, shown in Figure 38 (right). One cable split is attached to the front (towards the lock chamber) and the other cable split to the middle or the back (towards the wall). As a result, the shifting COG is accounted for by lowering or raising one of the cable splits further than the other.

Figure 38. Balanced when closed and full (left), unbalanced with open scoop (middle), double V-split (right).

5.6.2. Discharging siltation

Concept 2 should be able to discharge the siltation from the scoop on shore, e.g. in a container. Thus, the purpose of the test is *to determine if the siltation could be discharged from the scoop.* The test method is: 1. raise concept 2 with a full scoop, 2. rotate the crane until concept 2 is above shore, 3. Open the scoop to discharge the siltation.

To activate the scoop, the syringes on concept 2 are connected to a large syringe filled with coloured water. The results are straight forward: the concept is stable during rotation of the crane and the siltation is discharged on shore (see Figure 39). The test is repeated with dry and wet sand and successful in both situations. However, wet sand sticks to the scoop and additional opening and closing is required to remove the majority of the sand.

Figure 39. Discharging of siltation.

5.7. Siltation removal

In sections 5.1 and 5.2 the optimal jet and scoop configuration are determined for siltation removal, however the data is not comparable. The following section discusses tests which provide comparable data regarding siltation removal of both concepts. All tests are performed in the concrete scale model of the gate recess. In advance to the siltation removal tests, the siltation removal time (referred to as cleaning time from this point forward) is determined.

A note from the experts is with regard to the cleaning time: how much time do the concepts require for cleaning. To create comparable data, the cleaning time of the concepts should be equal even though the concepts differ in working principle. Concept 1 could be lowered and activated, in theory, for an unlimited period. However, concept 2 has to be raised subsequent to the scooping of the siltation. Since concept 2 is the limiting factor, the cleaning time for concept 2 is determined and used for concept 1 (activating of the jets) as well. Leading to the test purpose *to determine the cleaning time of concept 2*. The test method is: 1. position concept 2 slightly above the pins, 2. start the timer, 3. lower the concept with the anchor points onto the pins, 4. activate the scoop against the wall, 5. release the scoop slightly, 6. raise the concept until the scoop is above the pins and stop the timer.

The main steps are shown in Figure 40. The test is repeated several times, however determining an exact cleaning time is difficult. The skill of the operator increases with each test, decreasing the cleaning time. In early tests the cleaning time is ~30 s and in later tests ~25 s. The decision is made a cleaning time of 25 s is realistic for the tests.

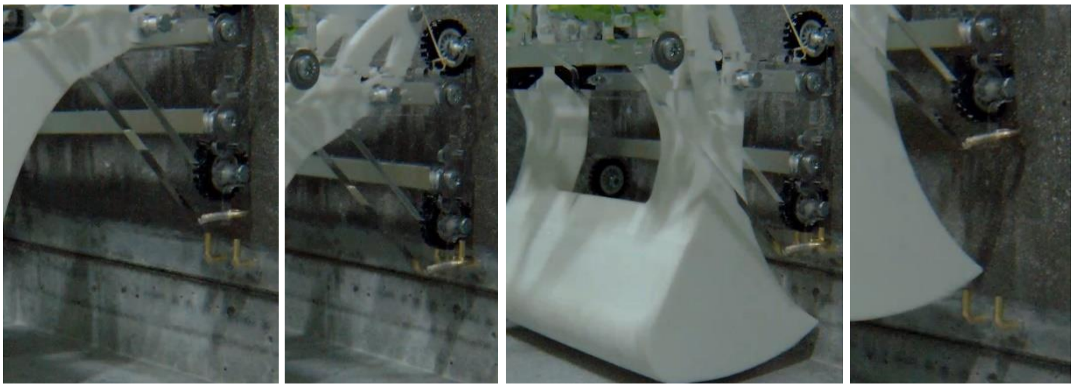


Figure 40. From left to right: slightly above pins, anchored onto pins, activated scoop, slightly released scoop raised above pins.

With the cleaning time determined, the siltation removal tests could be performed in the scale model. The relevant dimensions of the scale model are shown in Figure 41. The recess width (E) and height (F) are 80 and 43 mm respectively and scaled according to real dimensions from the Port of Antwerp (the scale of the model is 1:16.25). The recess length (C) is 338 mm and based on a fictional length due to restrictions (discussed in section 5.5). However, the recess length (C) is sufficiently large such that a concept could not clean the entire gate recess at once (which is realistic for the real life situation as well). Furthermore, dimensions A, B, D and H are maximised within the restrictions (e.g. weight) to simulate realistic conditions. The precise dimensions are shown in *Appendix E: dimensions scale model*.

For the tests a siltation reservoir is used, shown in Figure 41 (right). The siltation reservoir is realised from 2 mm PMMA sheeting and fits perfectly within the gate recess and sill. The reservoir is equipped with a barrier which could be placed in three different slots. The used slot determines the amount of siltation. Slot 1 (80 mm) means the entire recess is filled with siltation and slot 2 and 3 mean siltation is present up to 130 and 185 mm respectively.

Figure 41. Scale model recess (left and middle), siltation reservoir within the recess (right).

The purpose of the tests is *to determine the siltation removal capabilities of the concepts* and the test method is: 1. place the barrier in the required slot and fill (above water) with a predetermined weight of drained coarse sand (1-2mm), 2. assure the entire scale model is cleared from siltation from previous tests, 3. carefully place the siltation reservoir in the gate recess and remove the barrier, 4. position the required concept and remove the siltation (for concept 1 activating of the jets, for concept 2 activating the scoop, raising the concept and removing the siltation from the scoop), 5. carefully remove the reservoir with the remaining siltation and 6. drain and weigh the remaining siltation left behind in the reservoir. In addition, all tests are filmed underwater. The test set-up is shown in Figure 42 for concept 1 and concept 2.

The distance of slot 3 (G) in Figure 41 is based on a cleaning offer for Port of Antwerp. The offer required cleaning up until slot 3 (G). Since slot 3 (G) is at the edge of the siltation reservoir, *siltation outside of the edges of the siltation reservoir is seen as successfully removed*.

As mentioned in section 5.6 (handling), the stiffness of the hose is not realistic relative to the weight of concept 1. Thus, to assure the jet angles of +45° and -45° are achieved, concept 1 is fixated with a rod, shown in Figure 42 (left). In concept 2 the stiffness of the syringe tubing is less of an issue by straightening the tubing and the use of the anchor points.

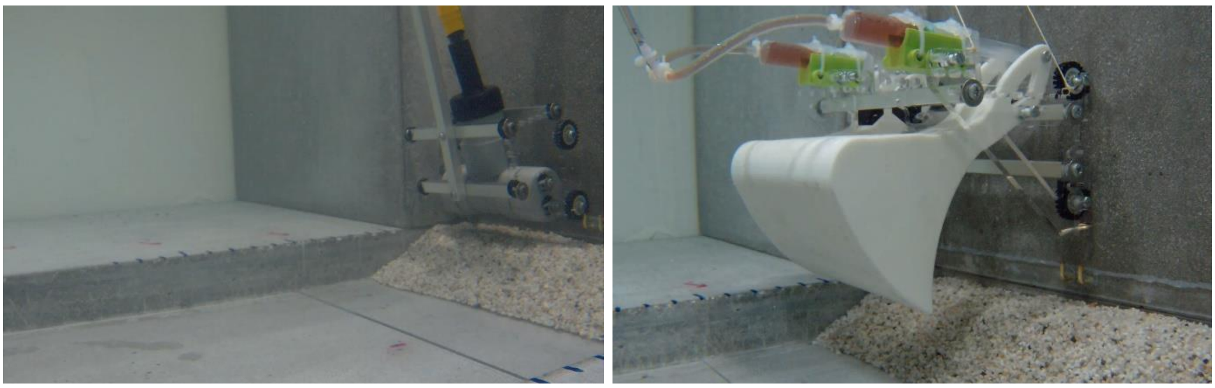


Figure 42. test set-up siltation removal concept 1 (left) and concept 2 (right).

Numerous tests are performed, e.g. solely cleaning of the left side, cleaning of the left and right side, several cleaning operations on one side (concept 2) and the use of different barrier slots. The most interesting and comparable results are shown in Table 7.

Table 7. Interesting test results siltation removal.

Purpose: to determine the siltation removal capabilities of the concepts				
	Barrier slot 1: solely cleaning left side		Barrier slot 1: cleaning left and right side*	
	Concept 1	Concept 2	Concept 1	Concept 2
Cleaning time [s]	25	25	50 (25 per side)	50 (25 per side)
Weight siltation before** [g]	1536	1536	1536	1536
Weight siltation after** [g]				
- Test 1	870	1214	174	829
- Test 2	759	1248	171	834
- Test 3	833	1233	138	812
- Average of tests 1-3	821	1232	161	825
Siltation removed on average [g]	715	304	1375	711
Siltation reduction [%]	46.6	19.8	89.5	46.3

**The concepts are repositioned after the cleaning of one side. Weighing is performed solely after both sides are cleaned.*

***Is the weight of siltation in the siltation reservoir before and after the cleaning operation*.

Based on the results in Table 7, the conclusion could be that concept 1 is much more effective in removing the siltation (46.6 and 89.5% siltation reduction) than concept 2 (19.8 and 46.3% siltation reduction). However, the results are an indication of how the concepts could perform since the concepts (and sand) are not perfect scale models and have completely different working principles. Analysing the pictures is equally important to understand the concepts. For instance, Figure 43 (left) perfectly answers a note from the experts: where will the siltation go with concept 1. The siltation is blown out of the recess and dispersed into the sill.

Figure 43. Results siltation removal concept 1 (left) and concept 2 (right).

Noticeable is that Table 7 solely shows tests with barrier slot 1. The reason is the difference in working principle of the concepts. Figure 43 shows the results of test 1 for solely the left side. Concept 2 could never remove siltation out of direct reach, while the jets of concept 1 are able to reach much further. Meaning, the results of concept 2 with barrier slot 2 and 3 are similar to slot 1.

Additional interesting results are shown in Figure 44. Figure 44 (left) shows the results of concept 1 with barrier slot 3 and cleaning of the left and right side. Noticeable is how the siltation reservoir is almost empty, while the piles of siltation outside the reservoir are quite substantial. Figure 44 (middle) shows the results of cleaning both sides three times with concept 2 (barrier slot 1). In several steps the concept is able to remove the majority of the siltation. The final picture, Figure 44 (right), is with regard to a note from the experts: will the silt fall out of the scoop if picked up. A fraction of siltation falls out (encircled in green) once the concept emerges from the water (water in the scoop flows out), however the amount is insignificant with the coarse sand.

Furthermore, this section has answered the following note from the experts: could the concepts be used for different sized recesses. If the concept fits within the recess, the concept could be used. For larger recesses the siltation removal could be performed in several steps (e.g. from left to right). For concept 2 this would mean additional anchors, while no alterations are required for concept 1.

Figure 44. Concept 1 barrier slot 3 (left), concept 2 subsequent to six cleaning operations (middle), siltation falling out of the scoop encircled in green (right).

5.8. Presentation to the experts

The next step is to present the results of the prototyping to the experts, which is difficult due to the amount of results. Creating a report would be ineffective due to several reasons. Even with the most interesting findings the report would be extensive, requiring significant time from the experts. Furthermore, videos are a crucial part of the prototyping, which could not be shown in a report.

Thus, the decision is made to realise a video for the presentation of the results. The video should be short, informative, interesting and contain the core information. In addition, the video should present comparable results in an objective manner and leave room for suggestions. Meaning, the video should not discuss advantages or disadvantages of the concepts. The final video is structured as follows:

1. General information (e.g. in short the objective of the concepts and an explanation of the prototyping process), 2. pictures of the concepts with the main features explained (Figure 35 top and bottom left are used) and a potential interpretation of the real life system, 3. explanation of the scale model and siltation removal test, 4. a full cycle of concept 1 ("walking" over the edge, lowering, cleaning, raising and "walking" up the edge), 5. a full cycle of concept 2 (rotating by crane, lowering, fixation with anchor points, cleaning, raising, rotating by crane and discharge of siltation) and 6. main comparable results of the siltation removal tests (Table 7 and corresponding pictures after siltation removal). For explanation, a voice over and text is added to certain parts of the video. The final video is ~ 6 minutes. Screenshots of the concept cycles from the video are shown in Figure 45 and Figure 46. *Note: text in the video is in Dutch for better communication with the Dutch speaking experts.*

Figure 45. From left to right (per row) the cycle of concept 1: "walking" over the edge, lowering into the recess, lowering into place at the bottom, removal of siltation with the waterjets, raising of the concept and finally “walking” back up the edge.

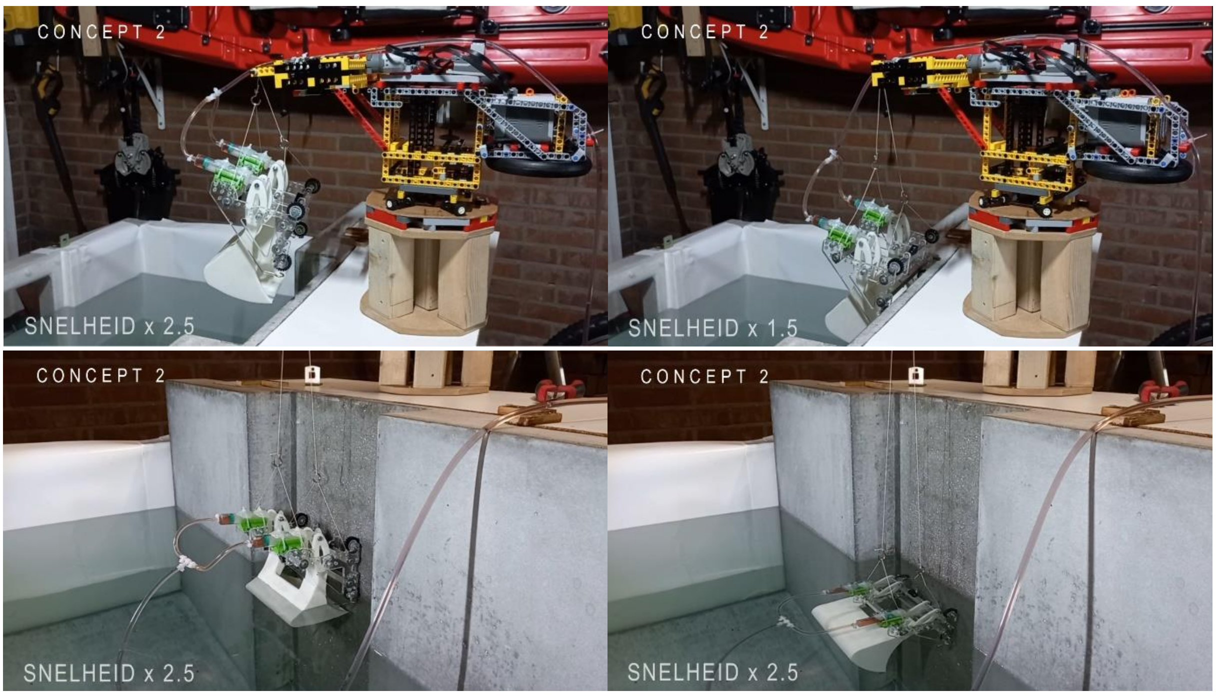


Figure 46. Note: the figure starts on the previous page. From left to right (per row) the cycle of concept 2: turning with the crane, lowering the concept over the edge, lowering into the recess (scoop closed), opening of the scoop before further lowering the concept, lowering onto the pins with the anchor points, removal of siltation with the scoop, raising the concept with a full scoop, raising the concept over the edge, turning with the crane and emptying of the scoop.

6 Concept scoring stage 2

The prototype testing is complete, resulting in extensive information regarding the two remaining concepts. Furthermore, section 5.8 discusses how the information is presented in a video, which is send to the experts. Subsequently, the experts are asked to perform the final round of concept scoring, concept scoring S2. The process for concept scoring S2 has been discussed in section 4.1.3 (concept scoring). One addition, in the Excel file used for S2 the pictures of the final concepts with the main features (fig Figure 35 top and bottom left in section 5.5) are shown next to the concept scoring matrix to prevent confusion during the scoring.. The concept scoring matrices from the experts are collected (*see Appendix F: concept scoring stage 2)* and the results are shown in Figure 47.

Concept scoring S2 results	**Concept 1:**	**Concept 2:**	
Experts ↓	Score	Score	Ideal score
Expert 3	3.18	2.38	4
Expert 6	2.59	2.44	4
Expert 7	3.39	2.51	4
Expert 9	2.86	2.58	4
Expert 10	2.74	2.11	4
Average score	2.95	2.40	
Rank	1	2	
Standard deviation	0.33	0.18	
Percentage (average score/ideal score)	74	60	

Figure 47. Results concept scoring S2.

Opposite to concept scoring S1 (see Figure 24 in section 4.2.3), the results of concept scoring S2 show a large difference between the average scores. Concept 1 with an average score of 2.95 and concept 2 with an average score of 2.40. Meaning, a difference of 14% (relative to the perfect score). To determine if the mean difference between the two sample groups is significant, a T-test is performed. The procedure for the T-test is equal to the T-test in concept scoring S1 (discussed in section 4.2.3), however concept 4 is replaced with concept 2. The data for the sample sets is marked in blue in *Appendix F: concept scoring stage 2*. The following hypothesis is tested:

- Ha: concept 1 scores higher than concept 2 $C1>C2$
- H0: concept 1 scores less than or equal to concept 2 $C1 \leq C2$

The T-test is performed and rejects H0, implying that concept 1 ($M = 3.08$, $SD = 0.86$) might score higher than concept 2 ($M = 2.28, SD = 0.75$), $t(39) = 4.28$, $p = 5.8E\text{-}05$ (see Figure 72 right in *Appendix F: concept scoring stage 2* for an overview of the T-test results*)*.

In addition, a column graph (Figure 48) immediately visualizes the large difference in scores. Concept 1 (dark green) scores higher than concept 2 (dark blue) on all criteria except the ability to remove siltation. The largest differences are in ease of use, ease of construction and mobility, which is reflected in the notes from the experts. Concept 1 is mainly described as quick, easy to use and mobile since the concept could be used without additional cranes. While concept 2 is mainly described as more complex due to the hydraulic cylinders and anchors points.

In addition, the column graph in Figure 48 visualizes the scores from concept scoring S1 as well in *light* green and blue. Interesting to see is how concept 1 and concept 2 are scored quite similar in S1 (the light coloured columns show no difference larger than 1 on a single criterion), opposite to large differences in S2 (differences up to 7 on a single criterion). Meaning, the prototyping certainly has an effect. For instance, the scores for ease of construction are equal for both concepts in S1. However, in S2 there is a large difference: concept 1 scores much higher than concept 2. The difference could presumably be explained by the use of sketches (for S1) versus prototyping (for S2). Sketches are useful, however a prototype provides more detailed information and a better "feeling" for the real life system. As a result, the experts are able to better differentiate between the concepts.

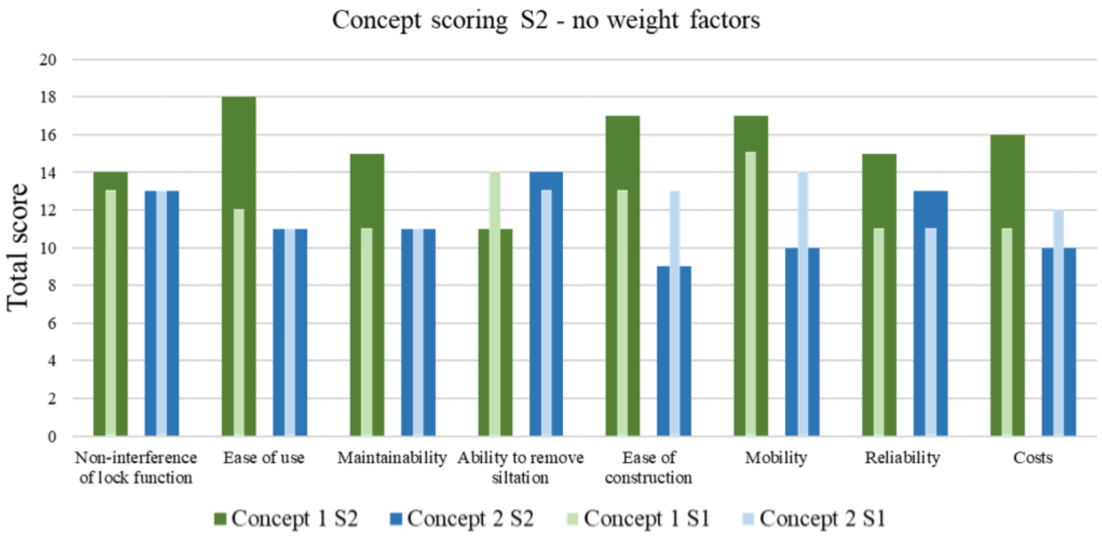


Figure 48. Column graph concept scoring S2.

Concept 1 seems the winning concept, however one concern remains: the lower score from concept 1 on *ability to remove siltation*. The lower score could be explained by the notes as well. Concept 1 removes the siltation by dispersing the siltation into the sill and the main concern is what happens to the siltation subsequent to removal: *will the closing gate push the siltation back into the gate recess*. However, due to several reasons the lower score is not significant problem.

Firstly, according to the interview regarding the Krammer locks [20] large vessels result in significant turbulence. Meaning, vessel movement could disperse the siltation out of the sill. Furthermore, during the closing motion the gate will probably not push the siltation perfectly back into the gate recess. Siltation could get underneath the gate, in the gate or go sideways as well. Suppose the process is repeated several times (cleaning, closing the gate, opening the gate, vessel movement), the siltation could be dispersed even further.

However, the main argument is with regard to the aiming of the jets. A note from the experts suggested aiming the jets sideways, to blow the siltation out of the sill. Such a test has been performed and is briefly mentioned in section 5.1 (waterjet configuration), however the results were not shown and are thus shown below in Figure 49. In both pictures (left and right) the same optimal waterjet configuration from section 5.1 is used. However, in Figure 49 (right) the jets are aimed to the right.

Clearly noticeable is how the siltation is blown to the right and stopped by the wall of the aquarium. As a result, a pile of siltation is formed which could not be cleared. However, if the wall is not present the siltation could presumably be blown sideways even further. Meaning, the siltation could be blown out of the sill, thus removing the main concern of a closing gate pushing the siltation back into the recess.

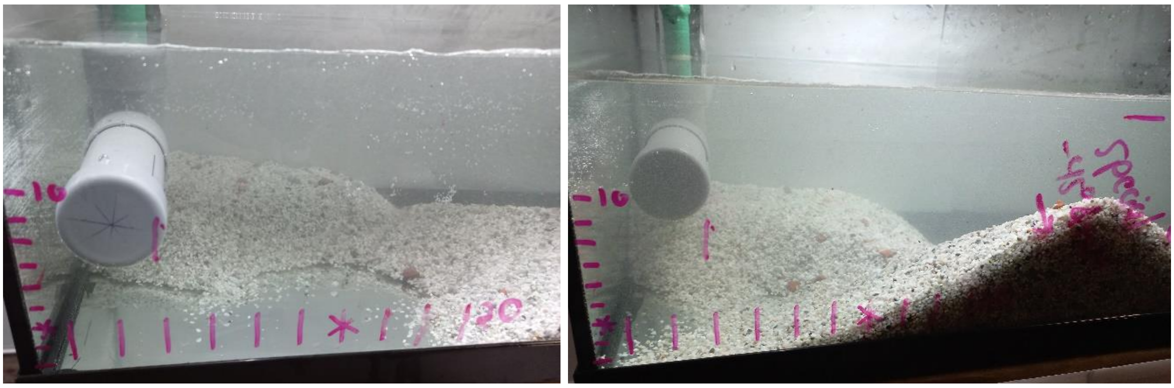


Figure 49. Optimal jet configuration normal (left), optimal jet configuration aimed to the right (right).

To conclude, based on the results (average scores, column graph, T-test and notes from the experts) and with the main concern for concept 1 addressed, there is sufficient confidence to select concept 1 as the winning and final concept.

Finally, additional interesting notes from the experts regarding concept 1 could be considered for future improvements: 1. what happens with compacted siltation, 2. waterjets which are separately controlled could be used for more precise cleaning (and could be a measure to see which jets are free of siltation), 3. the use of a guidance rail (fixated to or milled in the concrete) to prevent swaying and for improved guidance towards the bottom and 4. addition of a control to measure how clean the gate recess is subsequent to cleaning.

Discussion

The involvement of experts proved to be crucial from the start. Siltation of rolling gates is an extremely specific topic and the *literature is limited*. The limited literature which *is* available mostly mentions rolling gates are susceptible to siltation, however details regarding the siltation problem of rolling gates are not discussed. Thus, expert interviews are required to create a better understanding of the problem. Leading to the key findings regarding the locations of siltation, the effects and the current measures against siltation. The separation into the different locations (and the different effects) was crucial to realise a focus for the design. For instance, the context of the siltation problem for the gate recess is completely different from the siltation problem within the gates (e.g. different components, geometry and effects). In absence of such findings, the design presumably would have focussed on an overall and more generic solution, which would not have been effective. One of the main advantages of the use of experts is that a lot of the information is based on years of real life experience. As a result, there is proof for e.g. measures, problems or concerns (an example are the echo pictures from Port of Antwerp) which would otherwise be very difficult to acquire.
However, the assembly of experts in such a niche topic is a difficult, time consuming and meticulous process. For instance, finding experts required several databases, numerous e-mails, referrals and phone calls. Furthermore, certain experts were not willing to talk or could not talk due to confidentiality. Thus, the involvement of experts is essential, however the acquisition should not be overlooked.
Since the design within the context of the gate recess is successful, future research could include additional experts not related to rolling gates, e.g. siltation in general or dredging, to further improve the concept.

Concept scoring is a central part of the concept selection process in this research. Noticeable is the difference in scoring between concept scoring S1 and S2. In S1 the differences between the average scores of the concepts are small, e.g. 62% for concept 1 and 61% for concept 2 (relative to the perfect score). However, in S2 the differences between the average scores are large, 74% for concept 1 and 60% for concept 2. The large differences result in the ability to make better conclusions and are, as discussed, most likely due to the extensive information provided by the prototyping. *Meaning, for future improvement results of early prototypes could be sent to the experts before concept scoring S1 as well*. The prototypes do not have to be as extensive as for S2, the goal is create a better understanding of the concepts and are complimentary to the sketches and descriptions. Several criteria show large differences in scoring between S1 and S2, e.g. ease of use, ease of construction and mobility. *Advise is prioritize the early prototypes such that the prototypes provide information regarding multiple aspects*. For instance, the early prototype of concept 2 with a Lego frame and air cylinder would provide useful information for concept scoring S1 since the prototype could provide an impression regarding ease of use, ease of construction and costs as well. In addition, *future research could investigate if certain criteria benefit more from prototyping than others, to realise focused prototypes before concept scoring S1*.

In addition to the quantitative aspect, concept scoring emphasized the importance of qualitative data in this research as well. Concept scoring S1 showed small differences between the average scores of the concepts. In addition to a T-test, remarks from the experts were used to reach a decision between concept 1 and concept 4. A certain remark mentioned concept 4 would be a NO GO due to the use of rails. If the remarks were not gathered, such crucial input (which is not shown in the quantitative data) is overlooked, which could lead to wrong decisions.
The importance of qualitative data is furthermore shown in concept scoring S2. The experts are asked

for general remarks and a description of how the experts would use the system. Which leads to interesting remarks, questions and improvements for the future, mostly in line with the results of the prototyping. An important example is the aiming of the jets. During the prototyping in the aquarium a waterjet configuration is tested which aims the jets to the right to move the siltation sideways as well. The results seemed promising, however not suitable to present to the experts (not comparable to concept 2). Thus, the tests were not repeated in the scale model of the gate recess. Nevertheless, the results were kept in mind for future research. Subsequently concept scoring S2 is completed and notes from the experts mention the same idea: aiming the jets to the right (or left). Meaning, the suggested improvements of the author and the experts are equal, providing additional confidence (on top of the quantitative data) to select concept 1 as the winning concept. Opposite to improvements, notes from the experts mention concerns. The quantitative data shows concept 1 scores higher than concept 2 on all criteria *except* ability to remove siltation. However, the quantitative data is not able to explain the difference. The notes are required to understand the scoring, which mention the main concern: a closing gate could push the siltation back into the gate recess after use of concept 1. Such information is crucial to understand the scoring and think about solutions or if the concern is manageable. *Meaning, if solely quantitative data is analysed ideas, improvements, concerns and more are overlooked.*
Furthermore, a significant advantage of concept scoring with the experts is the presumably increased objectivity. The author would not have continued with concept 2 and would have continued with concept 4 until the end and expected the same from the experts. However, the experts continued concept 2 to the prototyping phase. The author was already fixated, which would have affected the concept selection if performed without objective experts. However, future research should investigate if the difference of opinion between the author and the experts is due to increased objectivity, or due to other factors (e.g. differences in knowledge, experience etc.).

For the concept scoring weight factors are used. As discussed, selecting weight factors could be achieved with numerous methods. Communication of the method is essential with the use of experts. A method which could be used with experts is the Analytic Hierarchy Process (AHP) from Saaty [13]. However, AHP is quite a complex method to explain, especially digitally (e-mail, phone calls and video calls). The method used in this research [12] is straight forward and clear. Nevertheless, mistakes did occur. To select the weight factors a pairwise comparison matrix was sent to the experts in an Excel file, accompanied by detailed explanations. Furthermore, solely the necessary cells could be selected and filled in with prescribed values. Even though all the described precautions were taken, a failed (half empty) file was returned. Which resulted in additional communication to correct the results, meaning additional time is required from the expert. *An improvement would be to show an example of the end result, in this case the filled in matrix, to prevent mistakes*. Nevertheless, mistakes could increase with increasingly complex methods. *Future research could investigate if the use of the different methods for selecting weight factors significantly affect the results of the weight factors, e.g. with a case study.*

Prototyping was an essential, however challenging process during this research. Several restrictions were in place: heavy duty systems and environment, budget, facilities and the COVID-19 pandemic to further impede the possibilities. As a result, all prototyping tests were performed in a garage. Nevertheless, the prototyping was essential and successful in validating the final concepts. Thus, providing objective information which could be used for concept scoring S2 (as discussed above). An approach was proposed to realise more structure in the prototyping. The approach is mainly based on methods by Camburn et al. [37], which provide guidance in connecting prototyping techniques to the general objectives of the prototype. The structured approach does provide certain guidance, however the prototyping process remains quite organic. Meaning, determining the purpose is essential, however level of approximation and the used techniques follow quite naturally. Nevertheless, the approach could be beneficial for designers with limited experience in prototyping, to create a starting point in the

prototyping process.
A guideline which was central in the prototyping, was the use of DIY. DIY is ideal for repurposing of materials and reduction of costs [40], both essential within the restrictions of this research. Numerous examples of DIY are found in the prototype process of this research and all increase the options of testing. The water tank and the scale model of the recess are completely DIY. The alternative would be an expensive custom made water tank or a significant reduction in scale, which would increase the difficulties of the tests. However, the skill of the designer should be kept in mind. The scale model of the recess (concrete) and the water tank are complex structures, which require a set of skills. *Meaning, with increasing skill more realistic tests could be realised*. Furthermore, the limitations should be kept in mind. The prototypes are not perfect scale models and the test equipment is not ideal as well. For instance, concept 1 uses waterjets connected to a faucet. The pressure of the faucet could be affected by e.g. equipment connected to the same network (washing machines etc.) or the water could even be disconnected, which was the case due to construction to the sewers. Meaning, tests are interrupted and delays could occur.

The final point of discussion is communication. Communication is crucial in a process which involves experts, especially in current times in which digital communication is excessively used. During the process questions arise as: how could this be communicated to the experts, would the explanation be clear or cause confusion, how much time is required from the experts (is this reasonable) and what kind of mistakes could occur. As a result, the decision is made to *not involve the experts in ideation* and the first steps of concept selection in this research. Involving the experts would certainly have advantages: different points of view, numerous ideas for solutions, important concerns regarding solutions and more. However, the main disadvantage would be an overflow of information with the risk of never converging and prolonging the design process. Furthermore, involving the experts in ideation and the early steps of concept selection would mean explaining the methods, informing the experts regarding large quantities of information and arranging group sessions with members from different organisations. Which would be difficult and require significant time from the experts. For instance, the concept selection based on discussion and intuition was performed with solely the design team, which are informed at all times, and the session already took two hours.
Communication is considered during the presentation of the prototyping results as well, resulting in a video. The video should be enjoyable to watch, informative and relatively short. However, the main disadvantage is that not all results could be shown in the video. *For future research, the process of prototyping and informing the experts should be more parallel*. Instead of one video at the end (which could not include all the results), already send several short videos during the prototyping process and ask for remarks. Since the videos are short and the experts are solely asked for remarks, the required time is minimal. *As a result, concerns, ideas or questions could arise during the prototyping, which could then be addressed before concept scoring S2*

Conclusion

This research has successfully designed a siltation removal system to effectively remove siltation from the gate recesses of rolling gates. The final concept utilizes waterjets to remove the siltation from the gate recess and blow the siltation towards the lock chamber. Prototype tests confirmed a jet configuration of +45° and - 45°, with more flow to the jets of +45°, is the optimal configuration of the numerous tested configurations. The jets on +45° remove the majority of the siltation in front, clearing space for the jets on -45° to remove the siltation near the wall. In addition, the system is easy to use and has a high mobility: the system utilizes stair climber wheels and could "walk" over the edge. As a result, the concept could be lowered into the gate recess with a simple winch located on shore. In the current set-up the siltation is successfully removed out of the gate recess and dispersed into the sill. *Future research should investigate the effect of a closing gate on the dispersed siltation in the sill. In addition, tests should be conducted by aiming the jets sideways, left or right, to investigate if the jets could blow the siltation out of the sill. Lastly, tests with different types of siltation should be performed, e.g. fine or compacted siltation.*

Additionally, the research provides an extensive and detailed overview of the siltation problem of rolling gates with the use of expert interviews. The acquired information is valuable since literature on such a specific topic is limited. The work presents how the siltation problem of rolling gates is mainly divided into four different areas: 1. the gate recess, 2. the gate chamber, 3. the rails/sill and 4. within the gate on top of the buoyancy tanks. Furthermore, the work presents how the context of the siltation problem differs per location, meaning an universal siltation removal system is difficult to achieve. As a result, the design should focus on one location. Siltation in the gate recess and gate chamber remained the significant issues, leading to the decision to focus on the gate recess. The main reason is the presence of additional features in the gate chamber (e.g. rails), while the gate recess could be described as a "blank canvas".

Finally, in this research an effort has been made to include experts in the design process from start to finish. The experts provide extensive information, knowledge and experience which proved to be crucial in this research. Firstly, the experts were required to create a better understanding of the siltation problem of rolling gates. Which could not be achieved without the experts due to the extremely limited literature and the difficulty of the subject. Subsequently, the acquired information is used to realise a focus and foundation for the design. Furthermore, the experts are involved in an extensive concept selection and prototyping process. Concept scoring with the experts, in combination with prototyping, provided both quantitative and qualitative data for concept selection. The qualitative data proved to be especially useful, resulting in crucial input regarding concerns, ideas and future improvements. Furthermore, involving the experts resulted in a presumable increased objectivity in the concept selection. The author was fixated on a certain concept and could not remain objective. Meaning, without the use of experts the concept selection would have been affected.

In conclusion, the proposed method resulted in the successful design of a siltation removal system and could be used for similar projects. Communication proved to be a crucial aspect which influences choices, leading to the decision to not include experts in ideation. Future research should focus on improving the method by involving the experts in the ideation (to benefit from the input of the experts) without diverging and prolonging the design process. *Furthermore, to better understand the effect of the experts on the design process a comparative study should be performed between the proposed method and a method without experts in similar conditions, e.g. on a case study.*

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Appendix A: additional information rolling gates

Structure

The gate is exposed to multiple loads, e.g. wind loads and horizontal water loads (dominant). To create a stable and well functioning gate the structure is divided into several components: 1. skin plates, 2. the frame and 3. buoyancy tanks. The components are illustrated in Figure 50.

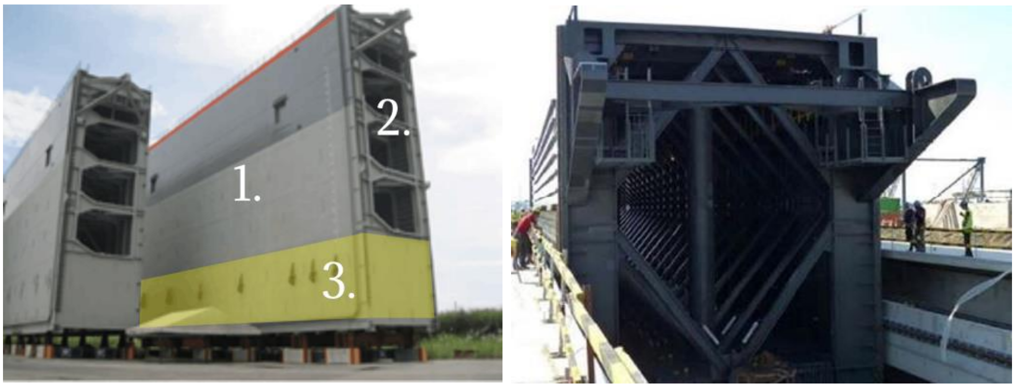


Figure 50. Rolling gates of the new Panama Canal showing side panels (Left) [6], rolling gate of the new Kieldrecht lock showing the framing system (right) [6].

The main function of the frame is to provide stability and receive the loads transferred by the skin plates. As illustrated in Figure 50, different types of frames are used with advantages and disadvantages. The choice is project specific. Noticeable is the open contour along the longitudinal axis to allow water flow through the gate. Connected to the frame are the skin plates, which retain the water pressure and thus fulfil the retention function of the gate.

Since rolling gates are commonly used for large locks, the weight of the gate is significant. For instance the weight of the Kieldrecht lock gate (currently the largest sea lock in the world) is 2000 tonnes [6]. A high weight could increase e.g. operating loads and wear on components. To reduce the weight, the inside of the gate is relative hollow due to the use of a frame. In addition, buoyancy tanks are incorporated. Air inside the buoyancy tanks create lift while the gate is underwater, reducing the operating weight. Buoyancy tanks are required with large locks, however could be removed from the design of smaller gates. Furthermore trim and ballast tanks are present. The combination of all tanks is used to submerse and balance the gate. As a result of the buoyancy tanks, the gate is self supporting and is able to be transported with a tugboat to the correct position. However, if no buoyancy tanks are used placement is realised with a crane by land.

Gate chamber and gate recess

As discussed, the gate chamber is the area in which the gate is able to recess to open the gate. In general the gate chamber should have sufficient space to fully retract the gate and perform maintenance. To perform maintenance the gate chamber is sealed off in front with the use of external panels and the water is removed. The gate recess is used to receive the gate in closed position and the loads are transferred from the gate to the civil structure.

An important aspect of the gate chamber and recess is top guidance. Due to the large height of the gate and e.g. wind loads or waves the gate could start to tilt and top guidance is required to allow safe entry conditions. For top guidance wheels are used at the entry of the gate chamber and recess. The wheels could be adjusted with the use of cylinders to assure the gate are centred. Examples are illustrated in Figure 51.

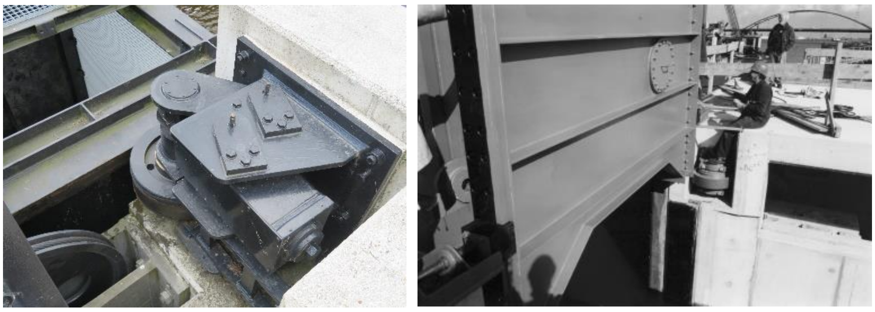


Figure 51. Top guidance Meppelerdiep lock (left) [22], horizontal guidance wheel from rolling gate Nieuwe Oranje lock in Amsterdam (right) [3].

Sill

The sill is comparable to a train track. In general the sill is a u-shaped foundation realised from concrete or arduin (type of stone). The sill of the Meppelerdiep lock [41] is illustrated in Figure 52. Additionally the sill of Kieldrecht lock is illustrated in Figure 55.

The rails are located on the bottom of the sill. Commonly the top of the sill is positioned level with the bottom of the lock chamber. As a result the rails are recessed into the bottom to reduce the possibly of damage by vessels to the rails. The sill is a high precision and high cost component. The sill in Meppelerdiep is a prefab component, however with increasing gate size a prefab sill is not feasible and the sill is realised on location. Tolerances for the rails are extremely high since deviations result in instability and uneven load distribution.

In addition, the sill is required to realise a seal at the bottom, which is explained in the following section.

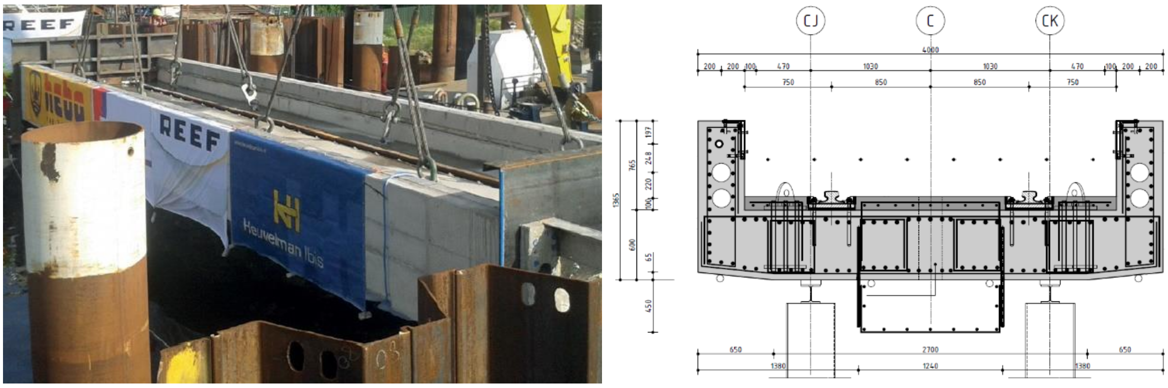


Figure 52. Sill Meppelerdiep lock [41].

Sealing

To fulfil the water retention function and thus create a watertight lock chamber, sealing is required at several locations: at the bottom of the gate (horizontal), at the entry of the gate recess and at the entry of the gate chamber. The different locations are noted in Figure 4 (left) in section 2.2. *Note*: the sealing is noted consecutively on one side, however the sealing is present at the opposing sides as well.

Generally the difference in water pressure is required to create a seal. Suppose a vessel has entered the lock chamber from the low water side, both gates are closed and water levelling is engaged (see Figure 3 in section 2.1 for a visual representation). The water level in the lock chamber rises and a differential head is created between the lock chamber and the low water side. Due to the difference in water pressure, the gate is pushed against the sill, the gate recess and the gate chamber. A similar situation is realised at the high water side since a differential head is present between the high water side and the rising water level in the lock chamber.

To allow small displacements for sealing, features are incorporated in the undercarriage (see section *undercarriage*). In addition, a spring plate is a commonly used method for sealing at the bottom. A spring plate deflects due to water pressure and is forced against plastic strips in the sill, see Figure 53 (left).

The vertical sealing is established between the entry of the gate chamber and gate recess in combination with the gate. Traditionally a combination of hardwood and stone is used, however recently combinations of Polyethylene and stainless steel are used. An example is the Meppelerdiep lock: steel plating on the gate chamber and recess and Polyethylene strips on the gate [22].

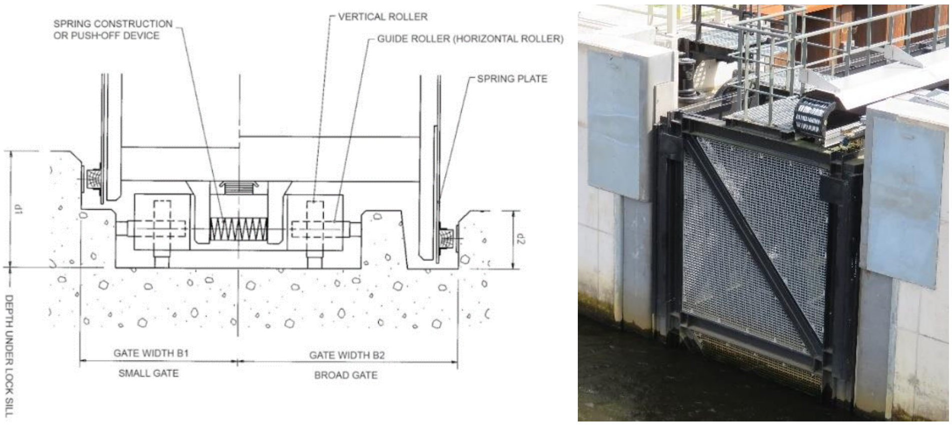


Figure 53. Undercarriage with spring plate for horizontal sealing (left) [3], vertical sealing Meppelerdiep lock (right) [22].

If the differential head is not significant, issues could arise with sealing. To assure the required seal, a push off device could be used in the undercarriage to force the gate against the sill, gate chamber and gate recess. The push off device is discussed in the following section.

Undercarriage

A crucial component is the undercarriage. The undercarriage is required to support the weight of the gate. The loads from the gate are transferred by the undercarriage to the rails. In addition, the undercarriage should be able to transfer horizontal loads, if necessary. As a result, different configurations of undercarriages are used. First the basic principles are discussed and subsequently different configurations are shown.

During installation of a rolling gate the procedure is to first position the undercarriage on the rails and then place the gate (structure) on top of the undercarriage. The connection between the undercarriage and the gate is realised by the weight of the gate and geometry: commonly a recess in the gate is positioned on a dowel incorporated in the undercarriage [6]. A simple configuration (A) is shown in Figure 54 (left). An elastomeric bearing (or block) is located between the undercarriage and the gate, as a result small displacements are allowed for sealing. The dominant loads on the undercarriage are vertical and load transfer and guidance along the rails is provided by vertical wheels, resulting in the rolling motion. However, horizontal loads could occur and should be accounted for. In configuration *A* the horizontal loads are negligible and horizontal wheels are not required. However, flanges are added to the vertical wheels. Two configurations are illustrated in Figure 54.

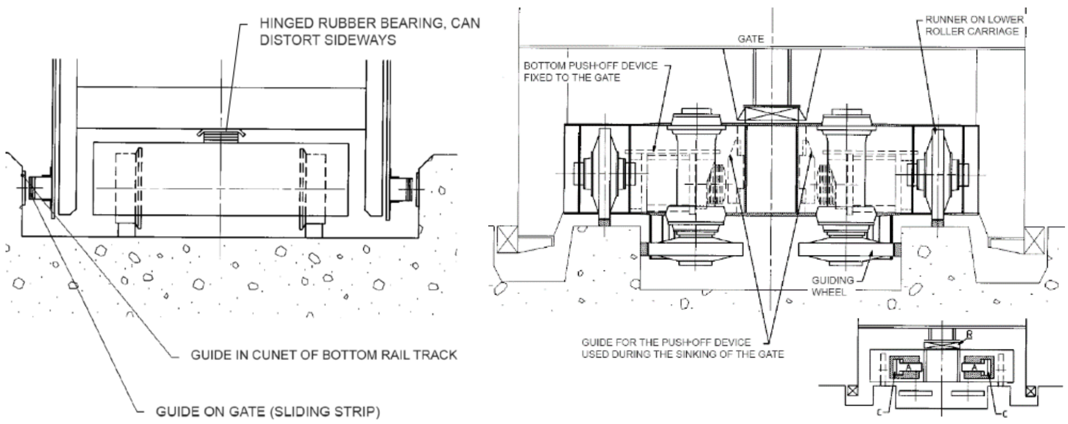


Figure 54. Different types of undercarriages [3]: configuration A (left), and configuration B (right).

Several differences are noticeable between the two configurations. Even though the horizontal loads in configuration A are negligible, all gates require horizontal guidance. Configuration A makes use of sliding strips in combination with pads on the plating. Configuration B uses the horizontal wheels for guidance. The bottom guidance is combined with the top guidance. As mentioned, an elastomeric bearing could be used to allow for small displacements. The displacement is a combination of lateral movement and tilting as a result of the difference in water pressure. As described in section *undercarriage*, additional devices are used in specific situations to force the displacement. Configuration B uses push off devices, which could force the gate to the left or right.

A real life undercarriage of the Kieldrecht lock is illustrated in Figure 55. Noticeable are the flanges on the wheels. Furthermore, the undercarriage is equipped with lateral rollers (noted with the arrow) instead of the elastomeric bearing.

Figure 55. Undercarriage Kieldrecht lock [not to be copied without permission of Port of Antwerp].

Driving mechanism

To realise the rolling motion of the gate, a driving mechanism is required. Typically the driving mechanism consist of cable drums, a motor, a brake, a drive shaft and a network of cables. Variations are available in e.g. the amount of motors or cable drums used. The wheelbarrow support system is the preferred system for large locks [6], illustrated in Figure 56.

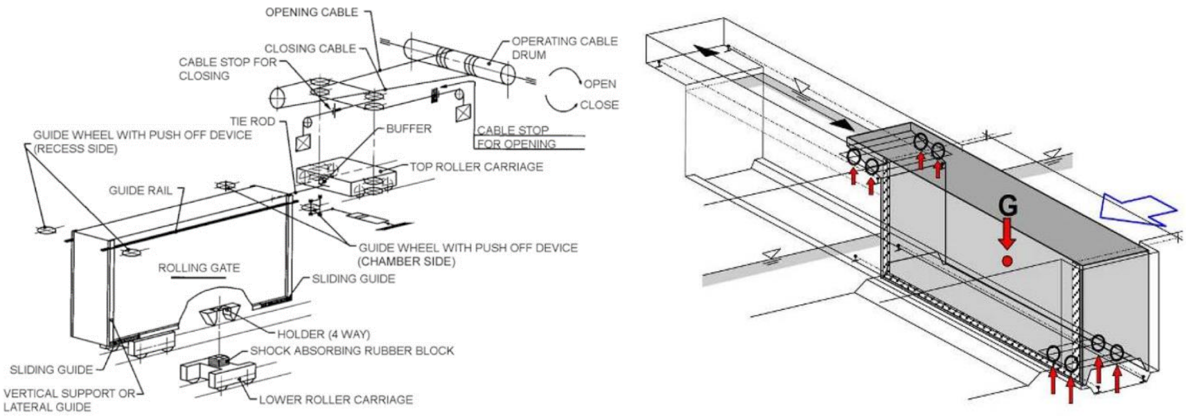


Figure 56. Working principle of an operating mechanism of a rolling gate (left) [3], wheelbarrow design support system (right) [6].

Since the cables are connected to the top carriage (which is connected directly to the gate) and anchor points in the lock chamber, the door is opened and closed by rotation of the motor. In general, a rolling gate is supported by two undercarriages, however the wheelbarrow design utilizes one undercarriage and a top carriage. The main advantages are [6]:

1. Increased stability: the centre of gravity is near the diagonal of the top and undercarriage.
2. Improved maintenance: less components are submerged, meaning increased accessibility and reduced corrosion.

Nevertheless, the wheelbarrow design increase the complexity of the gate chamber significantly. The top carriage require a rail inside the gate chamber and the gate chamber is elongated since the top carriage is positioned behind the gate.

Appendix B: interviews

Appendix B1: interview expert 1

Contents	First interview with *expert 1* (Table 8), civil adviser, regarding siltation in de Terneuzen lock. Furthermore, relevant information from e-mails (Table 9) and follow-up questions (Table 10)
Attendees	K. Koets – interviewer (KK) | Expert 1 – interviewee (EX1)
Date	First interview: 16-07-2020 | 15:00-16:00 | Mobile phone call
Remarks	Both interviews were mobile phone calls. As a result, the interviews were not recorded. The answers were written down during the interviews. The interviews were performed in Dutch. Subsequently, the interviews were translated. Relevant information has been taken from the e-mails and translated.

Table 8. First interview expert 1.

KK	Could you tell me about the siltation problem in the Terneuzen lock?
EX7	The Terneuzen lock consists of several lock chambers: middle lock, East lock and West lock. In addition, they are also working on a new project, the new lock Terneuzen. In 1968 they build 3 gate recesses and 2 door docks. The door docks had in increased width compared to the gate recess. They planned to use the door docks as dry docks, however currently these are not used. If a dry dock is needed, this can be realised in the gate recesses. The Terneuzen lock is located in the Western Scheldt, which has a lot of sediment and silt. The water will enter the lock chamber and as the gates are moving for operation of the lock, water will enter and leave the gate chamber. As a result, the sediment will settle/accumulate in the gate chamber and rails. The exact composition of the sediment is dependent on a lot of factors like the weather and the season. It is difficult to say what kind of material it is, it is a mixture of sediment. However, if you reach the bottom you will see there is a lot of sand which will become rock solid and needs to be chopped off.
KK	How is the silt removed from the gate recess?
EX1	Normally there is maintenance every 8-9 years in which the gate recess is pumped dry, but this is not often enough. So, for now every half year the locks are dredged. However, this is not based on data, this is completely random. Between 1968 and 2018 dredging 2 times per year was sufficient, however now we see with some doors that this interval needs to be increased.
KK	How is it completely random?
EX1	I suggested we would base it in data. We know how much force we need to open and close the door. Siltation increases the used force, we can measure this and set up a minimum and maximum. If the force exceeds the limits we know we have to undertake a cleaning operation.
KK	Do you have any data of the dredging?
EX1	Only recently we have started to record how much we dredge. I can provide the information from last April (2020). I recall it once was 3000 m^3 for both locks (East and West lock).
KK	Could you also describe if there is a difference in where the silt is accumulated?
EX1	More siltation is found in the West Lock, when compared to the East lock. Furthermore, you see that there is more siltation on the seaside than on the canal side.
KK	And could you also describe specific areas regarding the rolling gate itself?
EX1	Most silt accumulation is at the end of the gate recess. This could reach up to 3-4 meters and decrease to around 1 meter at the lock chamber. There will also accumulate silt in the gate itself.
KK	In what way did you consider siltation during the design process?
EX1	Siltation was thought of during the design process in different ways. At the end of the gate recess a big pump was placed, which was connected to the sewer, to suck away the silt. However, this is not allowed in the current day and age. The pump was placed a long time ago. Furthermore, the effect of the system was limited. Also, in the door dock they placed a pipe which was supposed to blow the silt back into the lock chamber by the use of waterpower. This was done in the 80's. However, again the effect was limited and the operating costs were very high due to the required power.
KK	Do you have any idea's on how to remove the silt?
EX1	I think innovative nozzles (which are currently used for sewer cleansing) could be used, but these also use a lot of power meaning high costs.

Table 9. Additional data regarding removed silt in West lock Terneuzen.

Gate	Amount of silt (mixed with water) [m^3]
West lock gate A	312
West lock gate B	200
West lock gate C	176
West lock gate D	128
West lock gate E	128

Total	944
Total silt without water (estimated)	750

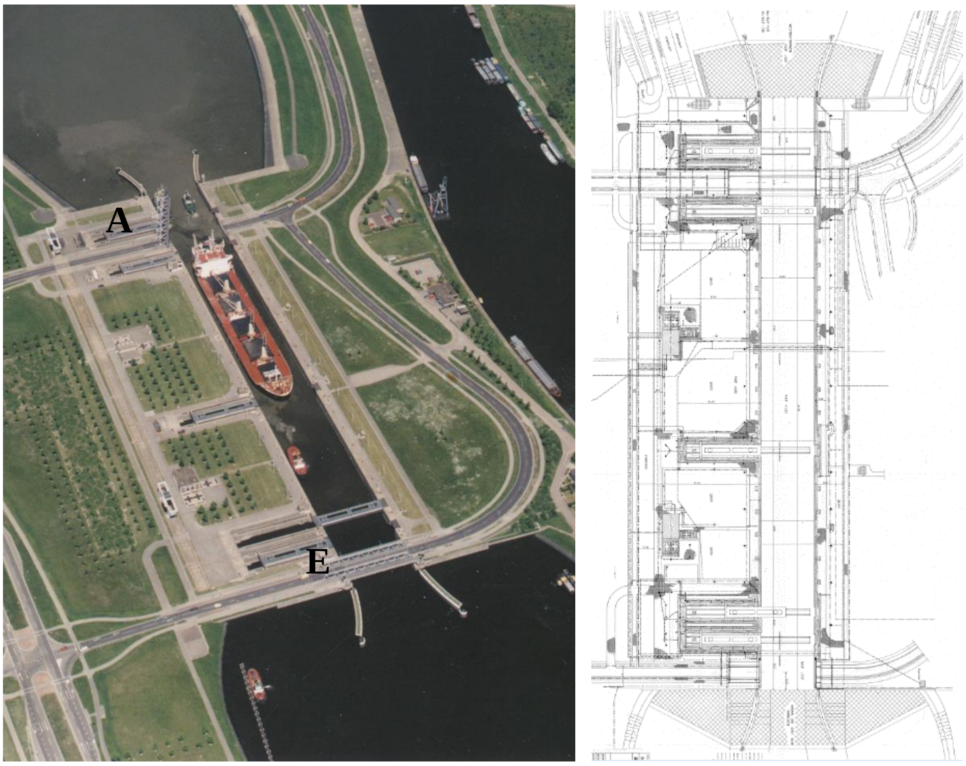


Figure 57. Layout of the west lock Terneuzen (left), official dimensional drawing of the west lock as provided by expert 1 (right)

Gate A is located at the top of both pictures in Figure 57 and gate E at the bottom. Gate A is connected to the Western Scheldt and Gate E to the canal to Ghent. Meaning, the most silt is accumulated (according to Table 9) at the side of the Western Scheldt and will decrease toward the canal to Ghent.

Table 10. Follow-up questions 19-08-2020.

KK	We talked about the siltation in the gate recess/chamber. I want to make sure this is the large recess? The one where the door moves into when opening the gate and lock?
EX1	Yes, in the large gate chamber. We actually have no problems in the small gate recess. Sometimes something gets stuck, for instance car tires. Then we need to send a diver. We have a big tidal difference. Sometimes 4.5-5 meters of difference. If you then open and close you have a lot of water flow and most will be washed away. There is a lot of swirl.
KK	Do you also make use of air chambers inside the gate and thus have siltation on top of the air chambers or in the gate itself?
EX1	We do have air chambers. In some of the gates we placed a kind of Styrofoam inside of the chambers to assure we will not loose buoyance when we have a leak in the air chambers. If we didn’t have the Styrofoam and an air chamber would leak, if would add a lot of weight and thus reduce the buoyancy.
KK	Where are the air chambers located?
EX1	I believe at the bottom of the gate. I think we have 16 in total which are spread along the gate. Last time we had the gate above water there was some silt on top of the air chambers, a couple of centimetres, but no real issue
KK	At other locks they use some kind of reservoir to collect silt, so when the door closes they push it into the reservoir. Do you have such a system? Do you also use ploughs or waterjets on the undercarriage?
EX1	No, we do not have jets or a plough and also no reservoir. There is only the general “slibvang”. The “slibvang” is not present at the West Lock since we have culverts, so it will be flushed away automatically. We do have extra space at the end of the gate chamber (when the door is open and thus recessed in the gate chamber). This is where the silt will accumulate. It will be pushed into the gate chamber. This could reach 4/5 meter of silt.
KK	Is your gate open at the front?
EX1	It is closed on the seaside. We have no issues in the gate itself, just in the gate chamber and the accumulation there is quick. If the gate hasn’t been moved for a couple of times we already have issues. We have a protocol to open and close the middle gate (which is not normally used in the locking process) once every 12 hours. The main reason is to clean the rails.
KK	You also mentioned that for the cleaning process you make use of dredging, do you also use divers?

EX1	No, we use a dragline crane. It drops a large scoop and scoops out the silt. At the seaside we have a couple of meters of silt. There could be some variation per gate. One time the middle door was out of order for a couple of months due to maintenance. When we wanted to move it after all that time it wouldn't move at all. So that time we had to send people (divers) in the water with jets and pumps. Normally we don't.
KK	Can you even use the dragline when the silt is hardened?
EX1	Well, it happens each half year so then it doesn't really harden and we are able to use the scoop. But if you let it harden then you need the divers. We also do large (dry maintenance) in periods and then we have a big clean up where we sent bobcats in the chamber and completely clean everything.
KK	What depth can the dragline crane reach? I am asking for the Kieldrecht Lock.
EX1	I believe up to 40 meters or something. It depends on where it can be positioned. If it is close to the edge you can reach deeper. But the Kieldrecht lock used a different approach, right? They have only one undercarriage?
KK	I am not entirely sure if they have 1 or 2 undercarriages. But they have at least 1 top carriage and they use the wheelbarrow concept. With 60% weight on the undercarriage and 40% on the top.
EX1	A right, yeah we have around 95% on the undercarriages and we have 2 undercarriages. We have some kind of top carriage, but it is more for positioning, not for load support. The top rails aren't even rolled.
KK	Okay, that were al my questions. Thanks!
EX1	Thank you, bye!

Appendix B2: interview expert 2

Content	Interview with *expert 2* (Table 11), Maintenance Manager, regarding siltation in the New Lock IJmuiden. Furthermore, relevant information from e-mails (Table 12).
Attendees	K. Koets – interviewer (KK) | Expert 2 – interviewee (EX2)
Date	Interview: 20-07-2020 | 16:00-16:45 | Microsoft Teams
Remarks	Permission to record the interview has been asked and given. The interview was performed in Dutch. First the interview was transcribed and subsequently translated. Relevant information has been taken from the e-mails and translated.

Table 11. Interview expert 2.

KK	Could you tell me more about the siltation problem?
EX2	The short and honest answer is no because the lock is not yet complete.
KK	However, I suppose you have run into issues during the design. Though, I don't know in which stage of the design you are.
EX2	The design is almost complete. I have been involved since the tender period, about 5 years ago. The design of the largest sea lock worldwide is a project with numerous issues, which require solutions. The siltation problem was not a priority, not a lot of attention was given to this during the tender period. I remember we talked to dredgers van Oord and Boskalis. The canal to the lock is deeper than the surrounding area. In the area multiple locks are located next to each other: the Northern Lock, the Southern Lock and the Middle Lock. In between, the New Lock is being build with a sill depth of -18 meters. Which is 4 meters deeper than the Northern Lock, I think. As a result, all of the surrounding area had to be deepened. That's why we had a discussion with the dredgers. However, we didn't outsource a hydrodynamic study regarding the possible siltation of the canals. Two/three years after the start, the Belgian equivalent of the RWS gave us a visit. They made fun of us for not having done such a study. They thought this was high risk: committing to the construction of the lock and 26 years of maintenance without a study regarding sedimentation. The studies we did perform were focussed on loads on the gates, levelling, speed of levelling and the resulting loads of levelling. So, the current situation: construction will take another year and dredging of the canals is outsourced to van Oord and Boskalis for a fixed budget. Thus, no risk for us. And now you ask about sedimentation of the rolling gates. Several factors are in play. Sedimentation will occur, this is a fact. During the tender period we were in contact with the Kaiserschleuse in Germany. They had problems with damaged rails due to siltation since the undercarriage would constantly roll across the rails. At least, this is what we understood. This was one of the reasons why we choose an undercarriage with a lot of wheels, to limit the point load.
KK	How many wheels?
EX2	8.
KK	How many undercarriages in total?
EX2	One undercarriage per gate, two in total. The weight of the gate in use is around 100 tonnes divided by 8 wheels. Why are you interested in this?

KK	I'm also trying to further specify the siltation problem at rolling gates, maybe some types are more prone to siltation than others. For example, is the problem depended on the location of the gate, or also the type of undercarriage or number of wheels. That's why I'm interested in this.
EX2	In addition, we have a system to clean the rails during every closing motion with a blower/waterjet. The systems spray in front of the wheels. During opening of the gate, the gate will enter the lock chamber, the system is not used. Even though, siltation could also occur during the opening motion. Furthermore, we have a "silt reservoir" in which silt from the rails could be pushed. The reservoir is around 1.5-2 meters deeper than the rails. We know sedimentation will occur; from the Northern Lock we know this will be a problem in the back of the gate chambers. This needs to be removed. In our maintenance regime we planned cleaning of 1-2x per year of the gate chambers. The frequency is lower in the Northern Lock, resulting in more compact silt. As a result, the silt is more difficult to remove. We hope to be able to blow away the silt, or suck up to silt, as long as we clean regularly. We think it's cheaper overall to clean more often than to neglect the problem. In addition, we clean the entire bottom of the lock chamber. I believe 2x per year. It's a concrete floor, which they clear with waterjets and a dredging vessel. They force the silt over the sill into the cannels, where it's removed by large dredging vessels. This is the complete story.
KK	The siltation removal pump you mentioned, is this installed on the gates or an external device of the dredging company?
EX2	The pump to spray in front of the rails was integrated in the design and will retrieve power from the gate. Nozzles are located just in front of the wheels.
KK	So, the nozzle can spray in both directions (front and back) and you hope by spraying backwards to clean the gate chamber?
EX2	No, the nozzle is solely for the rails and only sprays during closing of the gate. To clean the gate chamber, an external dredging pump is used.
KK	This is done periodically, but not a part of the design?
EX2	Correct. We did consider "smart" systems to press the silt out of the gate chamber during each motion of the gate. However, we decided not to do this. Thus, 2x per year a crane will arrive on top of the gate, or next to the gate chamber, with a silt pump. This is done with the gate in closed position, meaning the gate chamber if empty. The pump will be moved back and forward, sucking up water with sand. With this method, the siltation problem in the gate chamber will be kept under control.
KK	Does the "silt reservoir" have any special features?
EX2	No, just a deepened reservoir.
KK	Not an attached drain or pipe?
EX2	No, in Belgium they do have an ingenious draining/suction system (like a venturi). However, this did not work in the end. I saw this during the construction of the silt reservoir. They mentioned that according to their hydrodynamic study, silt could be transported back to the Western Scheldt. However, it did not work. Anyway, we just have a simple reservoir.
KK	Could you tell me a bit more regarding the water retention function of the IJmuiden Locks? It's a lock complex between the sea and a canal. Do you permanently block the sea water, or do you also let sea water through to the canal?
EX2	Both cases. The canal is at -0.4 NAP and the sea varies between +2 NAP maximum and -1/-1.5 NAP minimum. During high tide sea water will enter the canal and during low tide the canal will lose water.
KK	Do you also need to keep the North Sea canal at a certain depth, is this a factor?
EX2	No.
KK	Clear, this was a separate question from the siltation problem. Earlier you mentioned siltation in the gate chamber of the Northern Lock, which I have heard before. You also mentioned a "smart" system to remove the silt, why did you discard this idea?
EX2	It often comes down to lack in knowledge of how such a lock works. Furthermore, there was to little information. As a result, you have to fix a lot of problems with a team in a certain period. Meaning, you make decisions on what to focus on and what not. With regard to the sedimentation, we did not know a lot about this. We spoke with people from the Northern Lock and divers of RWS and an external party. Which lead to the conclusion that the gate chambers were cleaned 1x per 2/3 years. However, experts said this should be done more frequently because delayed cleaning will harden the silt and result in long cleaning operations. That's why we thought of the "smart" system with bulkheads at the bottom of the gate, to agitate the silt with each motion. Subsequently, the silt is transported out of the gate chamber. We discarded this idea because we have an extremely high required availability of the gates. Every hour the gate is out of order, we have to pay 160000 euro. Additional parts to such a gate are components which could break off, which would reduce the availability. That's why we were cautious with the addition of nonessential parts. Our risk analysis (time after time) concluded the addition of such components would not increase the availability. The fine I mentioned is of such an order, that an additional dredging operation is relatively cheap. Thus, no "smart" systems.
KK	Clear. Could it be that after 2 years of operation you notice you should have taken the siltation problem more serious in the design? Meaning, the problem is bigger than anticipated in the tender period.
EX2	That's an option. It could be better than expected, or worse than expected.
KK	Did you also work together with the Northern Lock since they both have rolling gates?
EX2	No.
KK	Those projects were separated?
EX2	Completely.
KK	I expected more connections between the two, also more influence of the Northern Lock on design choices. Then I have a couple of practical questions. How is the sealing realised, with the use of cylinders or difference in water level?

EX2	Difference in water level.
KK	Could you explain to me the working principle of the undercarriage? I believe the gate is 75 meters in length, how does it not tip over with 1 undercarriage? How is it balanced?
EX2	Due to the wheelbarrow principle. Suppose the gate is in closed position. At the top of the gate, you have a top carriage on rails, 5 meters above water. The top carriage has a towbar, on which the gate will hang. On the other end of the gate, you have an undercarriage, at -18 meter. As a result, the gate is balanced.
KK	I did read about the working principle of a top carriage, but I thought this was in combination with 2 undercarriages. I guess this is not required?
EX2	No.
KK	Interesting, I will take a second look. You would have fewer submerged components, which is an advantage.
EX2	For sure. The availability was a real struggle. We are allowed 18 hours of downtime per year. This translates to the reliability of the Space shuttle, which is very difficult.
KK	What's the increase in size, when compared to the Northern Lock?
EX2	The Northern lock is 50 meters.
KK	That's a big difference, it would mean that the largest vessels could only pass through the New Lock.
EX2	No, the large vessels could also pass through the Northern Lock, there are practically no vessels with a width more than 50 meters. The Northern Lock is suitable for vessels with a length up to 300-400 meters, actually there are no longer vessels. The most massive vessels, oil and ore tankers, won't go trough the lock. They have mooring facilities in the outer port. They are situated next to Tatasteel or near the Europoort, even before the Maeslantkering in harbours with low- and high tide. Vessels smaller than these tankers can all pass through the Northern Lock. The main reason to build the New Lock, is because currently they are dependent of the tides with a sill depth of -14 meters. Which is, in combination with low tide, not enough for large vessels and Amsterdam wants to be independent of the tides. The New Lock has a sill depth of -18 meters, meaning large vessels can enter at all times. The reason for the enormous width is unknown to me.
KK	Could it be to increase the capacity? More vessels could fit inside the lock.
EX2	Search on the internet for the Pieterheijn (or something like that), the ship they use to lift entire oil platforms. Even that ship does not have a width of more than 70 meters.
KK	I believe the Lock in Kiel or Antwerp is currently the largest sea lock worldwide.
EX2	Indeed, Antwerp with a width of 65-67 meters. That's the one with the drain/suction system that does not work.
KK	I believe there is just a small difference in depth, -17.8 in Antwerp and -18 for the New Lock. I got the feeling it became a competition: we need to exceed those dimensions.
EX2	Yes, we had the same impression.
KK	Well, you succeeded.
EX2	The assignment was a width of 65 meters. RWS requested a lock of 65 meters, but you could gain extra points during the tender if you could increase the width to 70+ meters. It wasn't a requirement, but a method to win the tender.
KK	I wanted to ask if you have documentation regarding siltation, but that wasn't executed.
EX2	No, we have no practical experience.
KK	I'm hoping to speak to someone from the Northern Lock in the coming period, I will ask about problem in the gate chambers.
EX2	Do you already know who you will speak with?
KK	[redacted] told me to speak to [redacted].
EX2	I would do the same. He is direct and tells you his opinion with a strong attitude of "contractors are unreliable and losers". He is a good guy; I spoke with him regarding the sedimentation problem in the Northern Lock. He was one of the people who said silt will become hard like limestone if left alone. As a result, it would be difficult to remove. Thus, the solution seems simple.
KK	So, [redacted] is a valuable contact.
EX2	You could also talk to [redacted], but [redacted] has more practical information.
KK	Do you have more contacts regarding locks with rolling gates? I'm trying to reach these people via via.
EX2	No, to be honest I do not have these contacts.
KK	I will have to try with RWS.
EX2	Yes, I think so.
KK	Alright, that's all for now.
EX2	How will you use this information?
KK	Well, for my graduation project I'm working on the siltation problem of rolling gates. Ideally, I will design a system to remove the silt. One of the main questions is, is the problem bigger in the gate chambers or on the rails. At first W+B thought on the rails, but I hear from several people the gate chambers are a bigger issue. I will also look at existing solutions and if there are successful. The system in Belgium could be interesting. It's designed against siltation but doesn't work. Do you perhaps have a contact of the lock in Antwerp?
EX2	Dear friend, you're asking somebody with my age to use his memory. Let me take a look. Yes, he's called [redacted]. His e-mail is [redacted] and he is the maintenance specialist over there. He is my only contact at Antwerp. He is responsible for the Stieltjes Lock, but I call it the "deurgang dok" since it's the lock leading to the Deurganckdok. He knows everything there is to know about that lock.
KK	Okay, I will send him an e-mail and hopefully he is open to a phone call.
EX2	Yes, it's certainly interesting because they did perform hydrodynamic studies. During the construction phase they were very pleased, since they would never have to dredge with this method. So, they were disappointed when it did not work.
KK	I can imagine, with the money and effort invested.

EX2	It was fascinating to see the size and complexity. It is a different lock though; we level through the gates and they use the walls. That's an essential difference. I have no idea if this effects the sedimentation.
KK	I do not know exactly how they level, but suppose they only drain the water on top I can imagine this will result in more sedimentation, since you have less circulation.
EX2	Well, the culverts are on the same level as the lock bottom. They level on a low level. Also, it's a better system since culverts only have 1 hatch and 1 backup hatch. We already have 16 hatches per gate and 16 movement mechanisms, which could all fail. It's a shame we have to use these.
KK	What's the reason for this?
EX2	Construction is within 5 meters of the foundation of the Northern Lock, we simply had no space, and the Northern Lock could not be demolished. They could build in an open space, with slopes going as far as 60 meters. Enough space to construct culverts. We would have much much rather used culverts. Much cheaper in design and maintenance, but we were at -22 meters and within 5 meters of the Northern Lock. You try and stop the Northern Lock. That was the problem.
KK	Clear. When is the construction finished?
EX2	The current (formal) end date is the 22nd of January 2022. Or December 2021.
KK	Okay, that's all I wanted to ask.
EX2	You're welcome.
KK	Yes, thank you! It was very helpful. I you want I can transcribe the interview and send it to you. You could sign it and then I could use it.
EX2	That's okay, but I would like to see a copy of your final report.
KK	That can be arranged, I hope to be ready in March.
EX2	Yes, if you have more questions let me know!
KK	Will do, thanks and enjoy your evening!
EX2	You're welcome. Thank you as well. Bye!

Table 12. E-mail correspondence 24-7-2020.

KK	Regarding the "silt reservoir", in which silt is pushed during closing of the gate, what's the location of the reservoir. Would it be at location 1 (green) or location 2 (red)? I used the Northern Lock for illustration. I think it's location 1 (this way it's collinear with the rails), but I'm not sure since it could be that the rails need to go across the reservoir. 
EX2	We have 2 reservoirs, one at location 1 at the "closing point" of the gate. This one will catch things pushed forwards by the gate. Another one on location 2, along the complete length of the gate. This one is to catch silt for the entire lock chamber.

Appendix B3: interview expert 3

Content	Interview with *expert 3* (Table 13), Technical Adviser, regarding siltation in de Krammer Locks. Furthermore, follow-up questions (Table 14).
Attendees	K. Koets – interviewer (KK) | Expert 3 – interviewee (EX3)
Date	First interview: 23-07-2020 | 10:00-11:00 | Microsoft Teams
Remarks	Permission to record the first interview has been asked and given. The follow-up interview was a mobile phone call and not recorded, the answers were written down during the interview. The interviews were performed in Dutch. The first interview was transcribed and subsequently translated. The follow-up interview was translated.

Table 13. First interview expert 3.

KK	I will first introduce myself and the project. I'm a student Mechanical Engineering doing my graduation project at Witteveen+Bos. At Witteveen+Bos they had several projects with rolling gates, and they noticed siltation is a problem. However, they did not know a lot about siltation. That's why I got the assignment to further investigate siltation at rolling gates. Eventually I have to design a system to remove siltation from rolling gates. Currently, since it is a very open

	assignment, I'm looking at where siltation commonly is a problem. If it is even a problem and what I should keep in mind when I continue to solve the problem. That's how I started to focus on existing locks with rolling gates, to investigate if siltation problems are known. Which led me to you. My first question is: could you describe the siltation problem at Krammer Locks in your own words?
EX3	Before I start, do you know about the Terneuzen Locks? These also have rolling gates and recurring problems. They regularly have silt. I can give you a contact person.
KK	Who is your contact person?
EX3	[redacted]
KK	I actually have spoken to him.
EX3	You have? Well then, I don't have to tell you about the Terneuzen Locks anymore.
KK	Additional information is always welcome.
EX3	No Expert 1 knows way more about the situation over there. So, the Krammer Locks have rolling gates and issues with silt. However, we have regular measures against the siltation. We clean 1x per year everything surrounding the rails and the sill (since the rolling gates move in a sill). In the past they made a beam in front of the gate which would push everything on the rail's forwards. The beam was around 2-3 cm above the rails. Somewhere in the sill there is a deepened hole (kind of like a reservoir) in which the silt is pushed. The silt is basically buffered into the reservoir. Somehow we also have rocks in the lock, which end up in the reservoir. The beam also pushes the rocks forward. The sill (including the reservoir) is cleaned completely. They suck up the silt with divers. They use pumps to clean everything. They have several methods. Often a barge is used, they blow silt onto the barge. The silt is stored on the barge and clean water runs back into the lock.
KK	Sorry I did not understand completely, the blow silt onto the reservoir?
EX3	No, they clean the reservoir. The pump sucks up the silt, mud and shells onto the barge. It enters the barge on one end and leaves on the other side. The barge kind of acts as a buffer in which the silt, mud and shells stay behind.
KK	Alright and they transport it away.
EX3	Right. Another way is to first take samples to see if there is contamination. Then sometimes they suck it up and dump it right outside of the lock head back into the water. However, this is not allowed anymore. They used to do this back in the day.
KK	Okay and how often is this required?
EX3	1x per year, usually in week 40-50.
KK	Okay, so that is a set period?
EX3	Yes
KK	Is that also related to siltation? Is siltation a bigger problem in that period? Or is it just a random period?
EX3	No, it is related to the siltation. If we extend the cleaning operation, we have more problems and if we clean more often it has no use. So 1x per year is the maximum we can extend it to. You can not wait longer than a year, then we get problems. Siltation at the Krammer Locks is relatively low. We have a lot of big vessels which agitate the water when they pass through the locks. When they accelerate they agitate the water and once they are past the last gate they accelerate even more.
KK	Alright, so big vessels improve removal of siltation/sedimentation?
EX3	Yes, the sedimentation will agitate and spread. The Krammer Locks also have perforated floors, which are used during levelling. We don't know how much siltation there is underneath the floors. We never look there. We know there is silt, for sure, but not how much. They once cleaned there in the 80's, before I worked here. Since I worked here (the last 25 years), we have not cleaned underneath the floor.
KK	Is this a concrete floor with numerous nozzles?
EX3	No, you have concrete floor with another level beneath. This is a hollow space through which the water is brought in and released. The silt will accumulate on the perforated floor and sink into the hollow space. We have no idea what it looks like down there.
KK	But this has never cased any issues?
EX3	No. In the culverts we also have silt and shells. However, the water speed will reach a level at which noting will accumulate. You get a venturi effect, which will further increase the water speed. This will take away the silt.
K	Okay so those are culverts. Do they go to a stilling chamber, or just the perforated floor with the culvert?
EX3	Correct, just those two. In the past we would sometimes drain the culverts and clean them, but not anymore. The culverts have the diameter of a truck, so very big., so very big. If you want, I can look up a drawing of the culverts.
KK	Yes please!
EX3	I will make a note. I will also add some drawings of the perforated floor and the rolling gate with the beam. The beam is just simple U or H beam in front.
KK	What is the height of the rails, you mentioned 2-3 cm?
EX3	No, the rails are much higher. At least the size of train rails.
KK	Will the beam pass straight over the rails, or is the beam shaped to the rails?
EX3	Correct, straight over the rails.
KK	So, there could remain siltation between the rails. You cannot reach this?
EX3	Correct, you can not reach this.
KK	Alright. I'm curious, are there locations near the gate where siltation is a bigger problem than at other locations?

EX3	At the back of the gate chamber, where the gate is stored when the lock is open, is in general more silt. It is pushed to the back of the chamber and remains there. You do have some blind spots where the silt will settle.
KK	Okay. This what I also gather from the other interviews, that siltation at the back of the gate chamber is a big problem. Do you also have issues with the rails? Are there components which have e.g. increase wear of failure as a result of the silt?
EX3	No, the components are able to withstand the conditions. In the design the right materials were chosen. For example, the material for the wheels is heavy cast iron. Furthermore, the rails are made of really though steel.
KK	But if the components are able to withstand the conditions, what is purpose of the beam?
EX3	To prevent accumulation of e.g. shells or other heavy debris like rocks which could lead to problems.
KK	So, the beam is meant for the heavy debris, not the silt?
EX3	Correct, but silt is also removed by the beam. Don't forget that the gates open and close around 200x per day, they continue to move.
KK	Do you also have information regarding the design process?
EX3	Yes, but I think your question is if took measures against siltation during the design?
KK	Exactly.
EX3	I do have the design document somewhere; would you like to see this? Is this interesting for you?
KK	Yes, I'm curious to see if it was a foreseen problem. To see if they looked at different options to remove siltation: do we need to design something special or is dredging enough.
EX3	They did make the reservoir (hole in the sill), but I don't think that was a calculated decision.
KK	The reservoir is just a simple hole of a certain depth?
EX3	Yes, I believe of around 0.5 m, to be sure I have to look at the drawings.
KK	Won't it overflow very quickly?
EX3	No due to the continues movement of the gates and vessels the silt is agitated. Also keep in mind that we are primarily exposed to sand. We are in the Eastern Scheldt. There is some mud, but primarily sand.
KK	Eventually my report will be in English in which they call it siltation and in Dutch slib. What is your definition of slib, or what is the definition of slib for the Krammer Locks?
EX3	Yes, I do know the definition. You can divide it into several categories. Real silt is really light and can be agitated by vessels. Another fraction is sand, which will enter the reservoir. Mostly it is a combination of sand and the "light material". Furthermore, we also have growth of shells, which sometimes is an even bigger problem than silt. The shells are heavier and sink.
KK	Do the shells grow in the Krammer Locks?
EX3	Yes, the shells grow everywhere in the Eastern Scheldt. Due to currents, they release and flow to the Krammer Locks. You have a constant change of tides.
KK	Okay and the Eastern Scheldt is brackish water if I'm correct?
EX3	Nope, all salt. The Krammer Locks is an interesting lock which is surrounded by fresh water (the Volkerak Zoomlake is completely fresh water), which exchanges with the salt water. So, the locks have several buffer basins. At low tide water is taken from the high buffer and a high tide, water is transported to the low buffer. During normal tide they have a direct opening to the Eastern Scheldt, so they level back to the Eastern Scheldt. This is an old system, but it still functions well. They know the incoming water flow and where the salt/sweet edge is located, since fresh floats on top of salt. In the lock walls we have vents which open and salt water is brought in through the perforated floor, which will push the fresh water on top back into the Volkerak lake.
KK	Alright. A colleague of mine also worked at the Krammer Locks. I believe you have a smart system to separate the fresh a salt water? With a bubble screen?
EX3	No right now we still use the vents and perforated floor, but this will change in the coming years. Currently they are working on the new system to replace the vents in the walls. The vents are high in maintenance and thus expensive, several millions each year. You will always be between fresh and salt water, resulting in oxidation leading to rust. Furthermore, the two different types of water will result in electrolyse.
KK	What is the working principle of the new system?
EX3	Not clear right now, still in development. It will be something with a bubble screen. However, a lot of captains are not happy with this decision. It will make your vessel instable if you pass the screen. This is not that big of an issue for large vessels, but for smaller vessels like a sailboat this is relevant. You will get pushed aside.
KK	Exactly. How deep is the lock chamber?
EX3	I believe the sill is around -7 to 8 meters.
KK	Okay. Regarding the dredging, they clean several locks and at the Krammer Locks do they also clean the entire lock chamber?
EX3	No just the gate chamber and the sills and reservoir. So basically, the areas around the rolling gates.
KK	So, the lock chamber itself is not a problem?
EX3	No, they do send divers down for large debris like anchors and ropes. However, not for silt. There are no issues in the chamber itself.
KK	Do they also use divers for the gate chamber
EX3	Yes, this is always done with divers.
KK	Expert 1 said they clean at Terneuzen 1x per half year. He said this was based on nothing. It should be done more frequently. If they wait to long, the sand layer will harden and won't be able to be removed with suction. They need to hammer the sand loose. Do you also have this problem, hardening of the silt?
EX3	With us it remains an emulsion (soft). I think mainly because we are at the end of the Eastern Scheldt. Expert 1 is in front of the Western Scheldt, where there is way more current. A higher current means more sand can be transported. We are at the end with less current and thus you have a different kind of silt. Normally it will not harden with use. The frequency of 1x per year is enough. A diver will go down and suck away the silt like a vacuum cleaner.

KK	I would also like to speak to the divers and dredgers. Because I have no idea what the costs of such an operation are. Could you give me an indication? Suppose I will eventually design a system, then the costs will be a big argument: will it be cheaper than to clean once a year with divers?
EX3	They take around 1.5-2 days per lock head. They use a barge, a diving team of 3 and a telescopic crane to take the divers in and out of the water as well to switch pumps. That is the main material plus 2 pumps and some reserve materials. A barge is around 700-1000 euro per day. Divers around 250 euro per hour and a telescopic crane around the same price. Then some additional material and you arrive at the total costs.
KK	Alright I will check this. Do you have a fixed company which performs the cleaning operation?
EX3	Yes, we have a prestation contract, which says they have to clean it 1x per year. We use VolkerRail infra. They clean and have a fixed diving team. We (RWS) do not contribute, we only have a controlling function. Once it is cleaned, we get video's and that's it. You can call the guy from [redacted]. His name is [redacted].
KK	Do you have an email or phone number
EX3	Yes, his mail is [redacted]
KK	Okay, I will contact him
EX3	So, they currently do the cleaning.
KK	Yes, such information is always interesting.
EX3	They can probably tell you how much silt it is and what they do with it.
KK	You said RWS just has a controlling function. Do you also look at what they remove?
EX3	You mean the removed material?
KK	Yes e.g. the percentage of shells or silt?
EX3	Nee, once it is removed it is gone. We don't take sample or look at the material. At least not RWS. Maybe VolkerRail has to pay to dump the material so they separate the materials, but I'm not sure.
KK	I will probably design something which I have to test, and they want me to compare it to something. Meaning I am in search of e.g. a classification of clean. Do you have such a classification? How do you know if it is clean?
EX3	It is similar to vacuum cleaning. If half is not cleaned, you have to go again. There is not really a classification. There will always remain some silt, we do not look down there to see if there is 1 or 2 grams of silt.
KK	Clear. I thought maybe they look at the amount of silt per m^2.
EX3	Could be, be we don't. Suppose the reservoirs are empty, then we are lucky. However, due to a bad year we could have a totally different situation. It varies.
KK	But you never had to dredge 2x per year? 1x per year is always enough?
EX3	Yes, 1x per year is enough.
KK	I already have a lot of information and having these conversations is more useful than research on the internet. You know about the situation. On Monday I had a conversation with somebody of the New Lock IJmuiden. They also had the reservoirs. Are your reservoirs collinear with the rails (in between) or more to the side?
EX3	Yes, like a tunnel. I will look up the drawings, but it is in between the rails.
KK	What is the width of the rails? The gate has a massive width, and the rails are in the middle?
EX3	Yes, they are in the middle.
KK	And what is the width of the rails?
EX3	I believe around 4 meters, but I have to review the drawings.
KK	Then a practical question: do you use cylinders to seal to gate, or water pressure?
EX3	No, we use cylinders and this will also remain in the new situation.
KK	What is the reason for this?
EX3	Due to the tides. The gate has a weight of 400 tones, meaning you need 400 tonnes of water pressure to create a seal. With a small height difference between the lake and the Eastern Scheldt this is difficult to reach, so that's why we chose the cylinders. Furthermore, you are dealing with the separation of salt and fresh water. You want a watertight seal between the two, which can be realised with the cylinders. Otherwise, you would have major leakage of salt water before the required water pressure is eventually reached. The disadvantage is that salt water will settle underneath fresh water. There are already spots in the Zoom lake (in deeper spots) contaminated with salt water. These are basically saltwater bubbles in which nothing will grow. You want to prevent this.
KK	If I'm correct, the water level in the gate chamber will follow the water level in the lock chamber? At least, if the gates are closed. This was difficult to understand at first. You have a low water side and a high-water side. Suppose you arrive from the low water side and the gate at the high-water side is closed. Once you are in the lock and the gate at the low water side is closed as well, water will flow in. The gate will seal against the low water side and the gate chamber will simultaneously with the lock chamber. Is this correct?
EX3	Let me think. I believe both gates seal in the direction of the lock chamber, but this is shown on the drawings.
KK	I will have a look. Suppose you seal against the lock chamber and increase the water level, then you always have to seal against the water pressure created by the lock chamber.
EX3	Yes correct. One of the cylinders is leaking and will be replaced in week 41-42. To do so a part of the gate chamber needs to be drained and then the cylinder will be removed. But indeed, the cylinders press against the water pressure. They are enormous and there is a total of 4 on a gate.
KK	Could the gate still function if 1 cylinder is defect?
EX3	The cylinder itself still functions. To prevent salt water from reaching the seals in the cylinder a kind of pressure chamber is present. It's a kind of a hydraulic overpressure which protects the seals. If there is some small damage it will be discovered by the first low pressure chamber, since oil will leak and you know there is a problem. So now the first chamber is broken and does not function anymore for a while, so the cylinder needs to be replaced.
KK	I have 2 more questions. I noticed there is also a recreational lock with mitre gates?
EX3	Rotating gates.

KK	Is siltation a bigger problem at rolling gates when compared to the rotating gates, or about the same?
EX3	About the same, it does not differ. We also clean it in the same period, then we also clean the rotating gates. However, this isn't always the case. We also have the Zandkreek Locks. If we don't clean in time, they will push the silt against the sill and eventually they won't close anymore. Over there you need to clean additionally.
KK	Last question. I spoke to the guy of the New Lock (IJmuiden) and they concluded that the siltation issue wasn't the biggest problem in the design process. Thus, they didn't pay a lot of attention to this. Speaking from your experience with the development of a new lock, do you think you should keep this in mind? Or is it a relatively small problem if you look at all aspects of the design?
EX3	If you look at all aspects, it doesn't really matter. It is solved with cleaning 1x per year (with us). I can imagine it is different for other locks. With us the costs of development and installation are too high to be profitable, I think. However, perhaps it costs around 10000 for a day of cleaning and this for 50 years. Then it could be interesting. You could do a lot with air or nozzles. You will agitate a lot of silt and maybe you only have to clean every 2,3,4 years. This could be profitable.
KK	I have most of the information. I have the name of a maintenance party which I will ask some questions. By the way, I made a list of all locks with rolling gates managed by RWS and I'm trying to reach these. Do you have some contacts at certain locks? Let me get the list. I mainly found the Roompot Lock in Zealand. Do you know somebody over there?
EX3	Let me think who is in management. You could contact [redacted]. I don't know if he is responsible for large maintenance, but he works over there and otherwise he could redirect you to somebody else.
KK	What is his email?
EX3	That's [redacted].
KK	Okay so he works at the Roompot Lock. I also found a lock in Weurt?
EX3	No, I wouldn't know. That one isn't located in Zealand I believe.
KK	No, that one is fresh water. I will look up the location, I believe in the middle of The Netherlands. No sorry, in the Maas-Waal canal. The remainder of the locks in not located in Zealand. Oh no the Lock Hansweert is. Do you know somebody over there?
EX3	You are right, that one belongs to us and has rolling gates. However, that one is cleaned in the same period as the Krammer. So basically, they clean several locks in a row.
KK	No special measures, or does it have the beam in front?
EX3	No, it is the same concept. However, it does have "rinketschuiven", which is another method for water levelling. Both sides of the lock are salt water, so no ingenious system. Just a gate with hatches.
KK	I found another lock in Groningen, the Dorkwerder Lock.
EX3	No, I can not help you with that one.
KK	Well, I at least have the contact details of somebody at the Roompot Lock.
EX3	Baby steps.
KK	Yeah, I started with nothing.
EX3	Haha indeed. What is the status of your project? Are you at the start?
KK	Yes, the beginning. It should take around 9 months. I started in May, but that's not official. I didn't even have a supervisor from the University, I had no idea of what to do. So right now, I started around 1.5-2 months ago. Slowly I'm getting the picture of what to do.
EX3	Great, I'm curious. If you find something interesting let me know. You can always contact me if you want to have a discussion.
KK	Is it also possible for me to visit the Krammer Locks?
EX3	That's difficult right now. We would have to pick a date at which I'm present as well. If I'm there I could give a tour, but this is not routine. You used to be able to go to an information centre, but this was discontinued because RWS is not an educational or touristic institution. I still think we have an obligation towards education and people like you to provide information and ideas. More people think this, we also have a lot of interns. The cleaning operation would be the most interesting for you to see. I do have some pictures.
KK	Yes great.
EX3	I made a note, but I won't be able to work for you all afternoon. I will look up when it's planned and let you know. I just received an e-mail about this. Let me check (EX3 looks into his emails). Ready while you wait! I see they planned quite some time. They will start on 26-10 and it will take around a week.
KK	Wow a week!
EX3	Yes, and on 2-11 they will continue in the Duwvaart Lock. So, you could visit between 26-10 (Friday) and 6-11 (Friday).
KK	Okay so between October 26th and November 6th. You have two lock chambers correct? Does this result in any issues? Since you have a week of cleaning per lock chamber?
EX3	Well, the first one is not really an issue. The other one is use for high vessels. You also have a bridge. So, if the second one is out of order you block the high vessels. This will result in more issues.
KK	That's something to consider, you will block vessels.
EX3	Yes indeed, you block the high vessels. Small vessels are still able to go through the other lock, but the large vessels are blocked for 5 days. That's also one of the reasons we clean in this period, there are fewer vessels.

KK	Yes, fewer recreational vessels.
EX3	I'll let you take the initiative. If you want to take a look in the cleaning period, make sure you arrive in the beginning of the week. Sometimes they progress quickly and are finished by Thursday.
KK	Alright, that's a deal.
EX3	I prefer you let me know early, so I will be able to plan the visit.
KK	Alright.
EX3	I will take a look at the drawings and pictures of the cleaning operation. If you need more, let me know in an e-mail.
KK	Okay, thanks!
EX3	Good luck. Will you go on holiday?
KK	No, I will just continue till it's finished.
EX3	Yeah yeah, that's the attitude of a potential RWS employee. Enjoy your weekend!
KK	You too, bye!

Table 14. Follow-up questions (03-08-2020) – Mobile phone call.

KK	I have a few follow-up questions regarding our last conversation. I spoke to someone from the Port of Antwerp and as a result I want to a few things with you. The first check is regarding siltation in the gate chamber, as we discussed. With the gate chamber you mean the large space in which the gate will "slide" to open the lock?
EX3	Yes, the gate chamber is the large space in which the gate will "slide" to open the lock.
KK	Alright clear. The second question is regarding siltation in the gate itself. In Antwerp they have buoyancy tanks inside the gates to make them lighter. Furthermore, the gates are open at the front and back. As a result, a lot of silt will accumulate in the gate itself. Which is one of the biggest problems in Antwerp. How is this compared to Krammer Locks?
EX3	At the Krammer Locks the gates are open on the front and back side, but we have no issues with silt in the gates itself. If the gates are cleaned, we remove maybe 500-600 kg of debris like silt, oysters and mussels. However, no real issues.
KK	Alright. We also talked about the location of the "silt reservoir". Do you already know where this is located?
EX3	No, I couldn't find this, but I suppose near the gate recess. So, during the closing motion of the gate, you push the silt towards the reservoir.

Appendix B4: interview expert 4

Content	Interview with *expert 4* (Table 15), Asset Manager, regarding siltation in de Northern lock IJmuiden. Furthermore, follow-up questions (Table 16).
Attendees	K. Koets – interviewer (KK) | Expert 4– interviewee (EX4)
Date	First interview: 28-07-2020 | 11:00-12:30 | Skype
Remarks	Permission to record the first interview has been asked and given. The planned Microsoft teams meeting was not possible due to technical difficulties. As a result, the interview was moved to Skype. The Skype interview was recorded, however during playback the recording appeared empty. Thus, the interviewer wrote down the main points from the first interview and checked these with the interviewee. In addition, some clarification was asked regarding certain points. The follow-up interview was a mobile phone call and not recorded. The answers were written down during the interview. The interviews were performed in Dutch. Subsequently, the interviews were translated.

Table 15. First interview expert 4.

KK	Could you describe in your own words the siltation problem of the Northern Lock in IJmuiden?
EX4	Siltation is mainly accumulated at the end of the gate chamber. During operation more and more silt will enter the gate chamber until a certain level where it will cause a failure. There are sensors present on the door and when to much silt has accumulated the gate can not properly open anymore.
KK	What does this mean exactly? Is the door in this situation still halfway in the lock chamber, meaning ships cannot pas?
EX4	No, the door is still able to fully retreat into the gate chamber. There is enough space, however the end sensors are a tool to tell the system the door is properly opened and for instance ships can enter or leave the lock chamber. If the sensor fails due to accumulated silt this needs to be resolved.
KK	How would you solve this issue? Do you need to get a dredging team on the spot?
EX4	No, we can move the end sensor a small distance (around 50 cm) in which case the failure is temporarily fixed. However, it does mean the gate chamber needs to be cleaned on short notice since there is to much silt accumulated.
KK	What are the methods used to remove the silt when this situation occurs?
EX4	Several methods are used. We used to have a pump which we could drop into the gate chamber with a crane. The pump would be moved across the bottom and clean silt. If for instance the door is closed during levelling for big ships, the pump could clean for quite a while. When the door would open (and move into the gate chamber) the pump could be stored at the end of

	the gate chamber. When the door is placed in the end position (meaning the lock is open and the door is completely inside the gate chamber) there is still 6 meters between the door and the end of the gate chamber. However, the problem with this pump was that it would get clogged. Meaning the pump would need to be removed from the water with the crane, be cleaned etc. This would cost a lot of time and money and so this method was not profitable. So now it is cleaned by a diving team which will go down there.
KK	How often is the gate chamber cleaned?
EX4	Well, there are some problems with this. The maintenance regime is not done properly. Meaning there is no determined interval in which is cleaned.
KK	What would be the definition of siltation at the Northern lock?
EX4	We are close to sea. So, we have salt water from the North sea and the North Sea Canal is brackish water. Meaning there is a lot of sediment in the water. Normally the silt is a combination of sand and grit. Furthermore, oysters and mussels are present.
KK	I also spoke to expert 3 regarding the Krammer locks, they also have mostly sand but normally the silt remains relative fluid and they can remove it with a pump. But I also heard from other interviews the silt could become solid?
EX4	Yes, if the silt will not be cleaned regularly if will become solid and be difficult to removed. As I said the maintenance regime is not done properly, so this certainly happens at the Northern Lock.
KK	If the silt is solid, how is it removed?
EX4	The divers have to remove it with high pressure washers and then suck it up.
KK	Could you give me an estimation of a cleaning operation by the cleaning team?
EX4	Probably around 60000 per door.
KK	These are methods to remove the silt with "external" systems. Do you also have systems which have been added to the design?
EX4	We have reservoirs to catch the silt. You can look at it like this: the rails itself is placed on a mound (it lays above the bottom of the lock). In front of the gate we have placed a solid beam which removes the silt in front of the wheels and moves it to the reservoirs, which lay around 50 cm below the tracks. These reservoirs are located all along the tracks, on both sides. Meaning also in the gate chamber. Furthermore, we have placed waterjets on the door. This was not done in the original design; this was an addition later on. The water jets prevent silt from setting on the rails and blow the silt into to gate chamber. Meaning eventually the gate chamber will be full as we discussed earlier.
KK	Is the siltation also in problem in other area's, for instance on the tracks?
EX4	No not really. The main issue is within the gate chamber. In de small gate recess (deurnis) we only have problems with large and "hard" debris like stone and beams (wood)
KK	What could be the result of the siltation? In terms of failure
EX4	For instance, the loads on the driving mechanism will be increased. This could lead to increased wear of the gear's drums and pinions. Which could lead to metal particles in e.g. the grease, more wear and eventually failure and even a motor revision. Siltation plays a large part in these problems and it is difficult to say whose fault it is. Because the contractor could say: we cannot see how much silt there is down there. Also, what if the silt suddenly accumulated?
KK	Okay. I also have some practical questions. How many undercarriages does the door have? And how do you achieve sealing if the complete rails are placed on a mound?
EX4	Each door has 2 undercarriages. For the sealing you should look at it like a train station. So, the rails are placed higher than the bottom of the lock chamber, but the rails are placed in a sill. This is similar to a platform at a train station. When the train arrives this could be seen as the door. The train moves along the tracks and when the train arrives at the platform there is a small gap between the train and the platform. This is the gap between the door and the sill. The due to a difference in water height, the door will be pushed against the sill to create a sealing.
KK	Okay, what kind of materials are used for the sealing? Is this wood?
EX4	No hakorit or UHMWPE, this is a plastic.
KK	Is the bottom of the lock chamber made from concrete?
EX4	No, the bottom is realised out of stones.
KK	For the levelling, do use vents in the door or do you use culverts?
EX4	We use culverts.
KK	Do you also have siltation in the culverts?
EX4	No, the speed of the water is way to high in the culverts for siltation.
KK	And siltation on the bottom of the lock chamber?
EX4	This is not really an issue and this can also be move around, it does not need to be removed completely in the lock chamber.

Table 16. Follow-up questions 20-08-2020 – Mobile phone call.

KK	We talked about the siltation in the gate recess/chamber. I want to make sure this is the large recess? The one where the door moves into when opening the gate and lock?
EX4	Yes, our siltation problem is in the big gate chamber. In the small recess the only problem are big obstacles like tires etc.
KK	Do you also make use of air chambers inside the gate and thus have siltation on top of the air chambers or in the gate itself?
EX4	We do have air chambers. They are around the bottom/middle of the gate, but we have no problems with silt on top of the air chamber. At least not when compared to the silt in the gate chamber. A bigger problem there is the growth of marine life (like clamps etc). This makes the door heavier.
KK	Is your gate open at the front?
EX4	Yes, it is.

KK	But there a still no siltation problems in the gate itself?
EX4	No. We have enough water flow from opening and closing of the door to wash this away. You also have the suction when opening the gate in the gate chamber.
KK	Okay great. Last question what is your official function? So I can write it down for my report.
EX4	Asset manager/Asset specialist. Both are fine.
KK	Great, thanks!
EX4	Alright bye.

Appendix B5: interview expert 5 and 6

Content	First interview with *expert 5* and *expert 6* (Table 17), Advisor water management and object expert respectively, regarding siltation at the Meppelerdiep Lock. The interview was performed during a visit to the Meppelerdiep Lock. Furthermore, follow-up questions (Table 18) and relevant information from e-mails (Table 19 and Table 20).
Attendees	First interview: K. Koets – interviewer (KK) | Expert 5– interviewee (EX5) | Expert 6 – interviewee (EX6)
Date	First interview: 29-07-2020 | 13:00-15:00 | Physical visit and interview
Remarks	The first interview was during a visit to the Meppelerdiep Lock, during which all colleagues were free to ask questions. The interviewer would ask questions with focus on the siltation problem and solutions. Since the visit was outside no answers could be recorded. The main points of the answers were written down. The questions in Table 17 are not in the exact order of the visit. The following day (30-07-2020) an additional mobile phone call with expert 6 was performed to check the information and ask several follow up questions. The interviews were performed in Dutch. Subsequently, the interviews were translated. Regarding the e-mails, relevant information has been taken from the e-mails and translated. The e-mails were solely exchanged with expert 6

Table 17. First interview expert 5 and expert 6..

KK	Why was the decision made to transform the lock from a flood lock to a navigation lock?
EX5 EX6	The flood lock was built a long time ago and the function was to stop high water. The lock could be seen as a divider between the Lake IJsel and the water surrounding Meppel. Normally the water level in the Lake IJsel is around -0.40 m NAP, meaning water that rains down around Meppel will flow into the Lake IJsel. However, with specific conditions, e.g. a North Eastern wind, the water level of the Lake IJsel will rise and the area around Meppel will be in danger. That is why the flood lock was build. There is another lock in the village called the “grote kolk”. If the flood lock was closed, ships could pass through this lock. However, as time went on ships got bigger and the “grote kolk” was not sufficient anymore. As a result, the flood lock was transformed into a navigation lock. When the water level is steady (no difference) the lock is open. Normally the lock only needs to close 26 days of the year, but if it closes ships still have to possibility to navigate through the lock instead of waiting until it could be opened again when the water level would equalize.
KK	Could you describe the siltation situation at the Meppelerdiep Lock?
EX5 EX6	Normally the current is from Meppel to the Lake IJsel. The soil around Meppel is rich in peat, small chunks of wood and mud as well. This all together creates silt. For siltation we have measures installed. We have a waterjet system. We have two undercarriages and each undercarriage has 4 nozzles. 2 in front of the wheels and 2 in back of the wheels. What we do is blow water during opening and closing of the gates. The rails are installed on a sill which has sides against which the gates are sealed. As a result, you have a u shape in which silt will accumulate. During closing of the gate, the waterjets will blast the silt forwards. At the end of the track, in the small gate recess, we have created a reservoir in which the silt is collected.
KK	I have spoken to people about other locks and the silt could also get rock solid, do you have that issue as well?
EX5 EX6	No with us it is always kind of fluid, we do not need to cut it away. But we also sometimes find the weirdest things like car tires or large driftwood and other garbage in the reservoir.
KK	In what way did you consider siltation in the design of the navigation lock?
EX5 EX6	Well, we knew there was siltation in the water so that’s why we considered the siltation problem from the beginning and how we came up with this system.
KK	Are there certain areas within the lock where siltation is a bigger issue and what are the causes?
EX5 EX6	The system works quite well and the silt is collected in the reservoir. We have no issues in the large gate chamber. However, the reservoir fills up way quicker than we anticipated. We thought we had to clean maybe once per year, but we have to dredge 4 times each year. One of the reasons for this is that is seems that a flow develops around the small recess which also transports more silt into the reservoir, not just the silt blasted of the tracks.

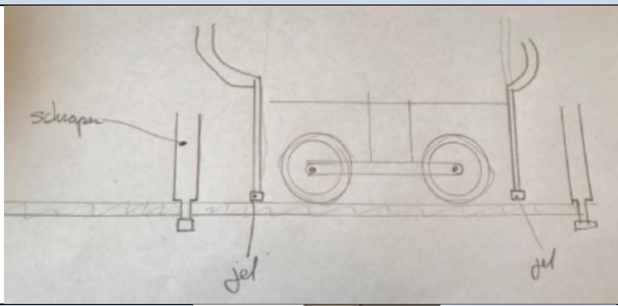
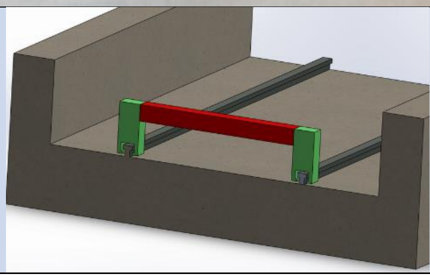
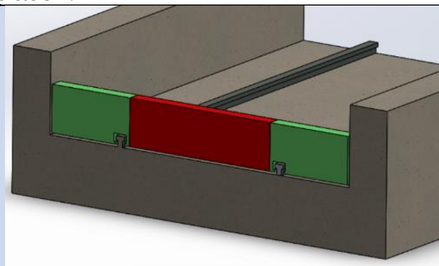
KK	Could you tell me about the construction of the rolling gate? Especially about the rails, under carriage and rails? e.g.: - Are the rails located in a slot or are due to protrude above the bottom of the lock? - How many undercarriages? How many wheels?
EX5 EX6	As discussed, the rails are realised on a sill. We have 2 gates, a small one and a big one. For the small gate a prefab was created at once and placed onto the bottom. This was not feasible for the big one, so this was casted in two sections (dry). So, the rails are located in this sill and thus in a slot and do not protrude above the bottom of the lock. The sides of the sill do protrude of the bottom of the lock. The rails lie about 50 cm deeper than the top of the sill. In total we have 2 undercarriages. Sealing is realised by plastic and steel. So, the gate is from steel and plastic strips are present on the sides of the sill. Due to the water difference the gate is pressed against 1 side to create the sealing. This sealing is also present at the beginning of both gate recesses. However, since the water level difference is sometime not that high this does not always work perfectly.
KK	How would the diving team clean the reservoir?
EX6	They would need a barge and an excavator on top which will remove the silt. You would also need a diving team for the eventual inspection. For the cleaning process they will keep digging until the driver of the excavator will notice less and less will come up. Then the divers will go down there and check, but this is sometimes difficult to see due to muddy water and silt that is brought in suspension. As a result, sometimes not all the silt is removed. In total the costs are around 100000 euro's each year, meaning those are the costs for 4 times of dredging for both gates.
KK	In your opinion, how should siltation be considered when designing a new lock with rolling gates?
EX5 EX6	It will always be a problem so you should think of some kind of system to reduce the siltation maybe with culvert or something if possible to flush out the reservoir.
KK	How would you know there is to much silt and it needs to be cleaned?
EX6	We time the opening of the gate. If we know it will normally take around 40 seconds to open the small gate and this will increase then we know we have silt accumulation.
KK	Could you describe to me the working principle of the waterjet system?
EX6	It is a waterjet system; we do not know exactly how it works. We have electricity on the gate, so we assume there is some kind of pump present in the gate. I will check if I can find some photo's and if I am allowed to share them. If not, I will make a sketch for you.
KK	How is the levelling of the lock realised?
EX5 EX6	We use vents inside the gate. In total we have 6 vents for the large gate which can be opened by cylinders. The gate is "hollow" in the middle, but the vents could be seen as tunnels through the gate.
KK	With regard to siltation, how is the failure of components a factor? (e.g. are particular components more prone than others, how do they fail, what are the costs)
EX6	We cannot tell this right now; it is a new lock, it has only been in use for 2 years. So, this is something that we have to monitor. It could certainly be that for instance in 10 years we say we should also have built a reservoir for the big gate chamber. For now, greasing of the cables (driving mechanism) is the biggest maintenance task. Advise would be to always design with maintenance in mind.
KK	When you consider the overall design of a rolling gate, how would you estimate the importance of the siltation problem?
EX6	The rails will always lay within some kind of sill, so you need something to keep away the silt. Otherwise you would need to design a completely new sill and then you go to different types of gates. So, you will always need some kind of system.
KK	So, the system right now works but ideally you would also need something to flush out the reservoir? Like with culverts or something?
EX6	Yes, that would be ideal, but is also difficult since there is normally not water level difference and the current is also weak. Normally 0.5m/s and in extreme cases 1.5 m/s. With a canal you could create something with vents.
KK	When cleaning, is there a way to classify "cleanliness"? How is the cleaning process monitored and checked?
EX6	As discussed before the operator of the excavator will say when he feels that he is removing less and less material and then the diving team will check. But this is difficult to suspended silt and muddy water. So, there is no real way to classify cleanliness.
KK	How would you describe the siltation problem with rolling gates compared to other gates, e.g. mitre gates?
EX6	Mitre gates require no cleaning in my opinion, this will flush out naturally. But it is difficult to compare to the Meppelerdiep Lock since mitre gates often are operated a lot of times each day and the Meppelerdiep Lock only active 26 days each year. We also have lifting gates on the Twente canal and over there we have no siltation problem, but this could also be because a canal and a river are different kind of waters. So hard to make conclusions.
KK	What kind of material is used for the bottom?
EX6	I know for sure it is not concrete and the lock approach is some kind of natural stone with geotextile underneath. I assume the lock chamber is the same and for the sills of course concrete is used.

Table 18. follow-up questions 03-08-2020.

KK	Do you also make use of air chamber inside of the gate?
EX6	No, we do not use those.

KK	Okay. We talked about silt in the small gate recess, but do you also have siltation problems in the gate itself?
EX6	Currently we have no problems with silt in the gate itself. We do have some sand in the gate openings (for the levelling) but that is minimal.
KK	Is your gate open at the front?
EX6	Yes, it is.
KK	Do you know why?
EX6	Not exactly but I think it is to reduce the energy during opening and closing of the gate.
KK	Okay great that's all, thanks!
EX6	No problem, bye!

Table 19. E-mail correspondence 30-07-2020 | 04-08-2020.

KK	What does the waterjet system look like?
EX6	(See the figure in this cell) In front and behind the wheels there is some kind of scraper. The function of the scraper is to push the big debris to the reservoir. In front and behind each wheelset there is a waterjet 
KK	Would the scrapers look like the attached picture (see the figure in this cell)? 
EX6	The red part is up to the bottom and it is wider: it will scrape out the complete sill.
KK	So, you mean more like in the attached picture (see the figure in this cell)? So, the debris/silt is first scraped away and then what is left is blown away by the jets (since they are behind the scraper)? 
MJ	Correct.
KK	What are the dimensions of the silt reservoir?
EX6	Around 5x5x5 meter.
KK	You mentioned you sometimes get a silt analysis from the dredgers. Could you share this with me?
EX6	We haven't received it our self, but from what I have seen it is mainly sand, organic material of different dimensions (from 10cm to several millimetres) and debris left behind by people: e.g. cans and rope.
KK	How many wheels do you have per under carriage?
EX6	4 wheels per undercarriage, 8 in total (2 undercarriages)
KK	To confirm, the costs of cleaning the gate recess each year is 100000 euro's each year for both gates?
EX6	That is correct
KK	Do you have additional reservoirs besides the one in the small gate recess?
EX6	No, just that one.

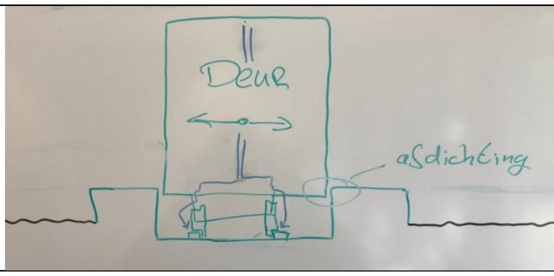
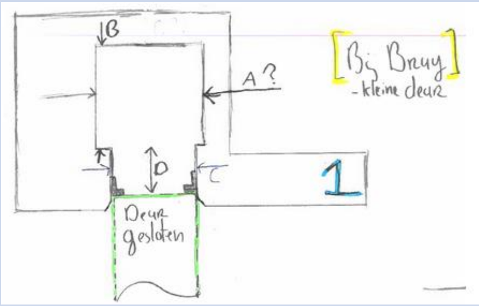
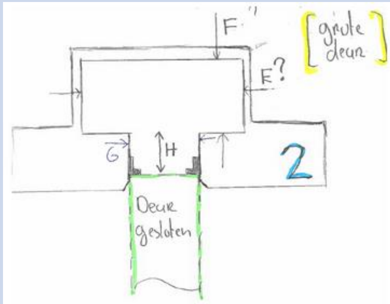
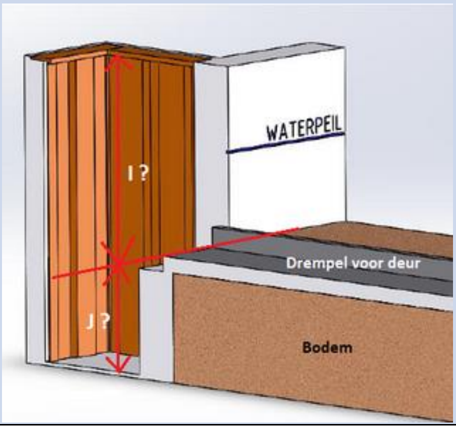
EX6	I also attached a sketch of how the sealing is realised (see the picture in this cell)	

Table 20. E-mail correspondence 29-09-2020.

KK	There is a difference in shape between the gate recesses. Is there a reason for this and does it influence the amount of silt in the gate recesses?
EX6	Well one gate recess is larger, thus more silt could accumulate eventually. Right now, we see no differences, but the lock is still new. The reason for the difference in shape is because there is less space available near the bridge, so the gate recess near the bridge is smaller. There is also a foundation for a house nearby, which might have influenced the shape.
KK	Could you give me the dimensions of A, B, C, D, E and F in the pictures below? So basically, the main dimensions of the gate recesses. 
EX6	I was not able to find exact dimensions, but for the upper head approximately 4x3.35 m (A, B). For the lower head approximately 6X2.70 m (E, F)
KK	Am I correct that the water depth is -3.35m?
EX6	Distance to the sill is 5.15 NAP
KK	What are the dimensions of I and J in the picture below? **Especially J** is important, since this is what I call the depth of the silt reservoir. Suppose the dimensions of 5x5x5 meter are correct, then it is important to know from where this is measured. There is a big difference between measuring from for example the water level or the bottom. 
EX6	I cannot find exact dimensions, but from what I can find J seems to be around 1 meter.
KK	In our earlier conversations you mentioned that sometimes you find debris while cleaning out the silt reservoirs, like cans or rope. Is there ever large debris in the reservoirs like tree trunks, beams or bikes? Or just the small debris?
EX6	The debris is always around the size of a fist, sometimes a bit large sometimes a bit smaller. But never “large”.

Appendix B6: interviews expert 7

Contents	First interview with expert 7 (Table 21), Maintenance Specialist, regarding siltation in the Port of Antwerp where in total 24 rolling gates are present. Furthermore, relevant information from e-mails (Table 22 and Table 23), follow-up questions (Table 24) and an interview regarding requirements (Table 25).
Attendees	K. Koets – interviewer (KK) | Expert 7 – interviewee (EX7)
Date	First interview: 31-07-2020 | 14:30-16:15 | Microsoft Teams
Remarks	Permission to record the interviews has been asked and given. The interviews were performed in Dutch. First the interviews were transcribed and subsequently translated. Relevant information has been taken from the e-mails and translated.

Table 21. First interview expert 7.

EX7	Port of Antwerp is a harbour area with around 1500 employees. We get income from ships that enter the harbour and funds from the government. So, we are a semiprivate and semi government organisation. In total we have 24 rolling gates in our harbour. We solely accept industrial vessels; recreational vessels are not allowed.
	Start of recording, Expert 7 shares his screen.
EX7	We have 2 locks per dock and a total of 6 locks with an equal layout. Let me zoom in on the Kieldrecht Lock. You have the dock side and Scheldt side. This is currently the largest lock worldwide, but IJmuiden will beat us. Are they operational yet?
KK	No, I believe another 1.5 years until there are finished.
EX7	Alright, so currently it's the biggest lock, built in 2016. On the Scheldt side we have 2 gates, no middle gate (we find this ridiculous) and 2 gates on the dock side. Furthermore, you have 2 bridges on both sides. We start counting from the Scheldt side towards the dock side, with 1-2-3-4. We speak of a gate chamber and gate recess. Each lock has additional free space at the back. Meaning, in open position there is a couple of meters between the back of the gate and the gate chamber. We have 2 undercarriages per gate. If we need space to pick up the undercarriage at the front, we move the gate into the free space at the back. Next, we need to drain that space to remove the siltation. Currently we do not remove siltation manually (Expert 7 points to the additional space at the back of the gate chamber). We have no real problems, keep this in mind, but we do have a system to control the siltation. We don't remove siltation, we control it. We know that if we drain it, we need about 2 weeks with divers to remove the siltation, but this is once per 10-15 years. This is not our concern, that's basically it for this side. The other side, the gate recess, is more critical and is supported by data I have often presented. We have vessels which accelerate rapidly towards the upper side. Here there is a well, or deepened hole (Expert 7 points underneath the gate, where the sill is located), where mud and debris will accumulate at the gate which is barely used. You'll understand this gate is barely used (it's a backup gate). So, we have accumulation, and we know we have an accumulation of debris and silt (Expert 7 points towards the gate recess). So, we clean periodically with divers and pressure washers to remove the debris. We have multiple images of the accumulation of debris, telling us it's required to clean periodically. How does it accumulate? The gate moves and I see it as a snowplough. We do not have a waterjet system, we removed this 30 years ago on other locks. The system is way to critical with motors and underwater components, which would more often than not fail. So, you should see it as a snowplough effect resulting in accumulation at the gate recess. That's a brief summary of the situation of the rolling gates.
KK	Okay, and the space at the end of the gate chamber, this is extra? You normally don't use this unless you want to move the gate further backwards to reach the undercarriage at the front?
EX7	Yes, correct.
KK	Is this used for maintenance?
EX7	Yes, I think so. Also, we bring it back for something else, but I cannot remember what right know. I will get back to this. Even for me, siltation remains a difficult and hard to understand phenomena. It's a great subject, but with no real truth. It's not easy, but from my position (as maintenance engineer) I have to look at certain maintenance tasks to determine the added value. If we have regular malfunction in the gate recess, we have to fix this. On the opposite side, if we have methods we think are useful, I want to analyse these to determine if they are worth the invested time. Do we want to use divers? Do we want to use airlifts (Let me just name drop this), which are labour intensive? The question remains, what's the effect. So, I'm really interested in siltation since 75% is submerged and we cannot see this. I cannot say: Eureka this is the truth. The knowledge is far from complete. Let me go back to what we have done in the past, the so-called hyper system we use in Port of Antwerp. I have and 3D image, but first let me show a drawing.
KK	Before we continue, can I ask one thing? You have the Scheldt, which runs through the Port of Antwerp. Is the function of the gates to keep a constant water level in the docks?
EX7	Yes. The principle of a lock is to compensate for the difference in water level, 6 meters at Port of Antwerp, to allow vessels through the lock.
KK	Yes, exactly. Are there certain periods during which the vessels cannot enter?

EX7	No, not really. Except vessels with a large depth, they cannot be accepted during low tide. However, these are enormous vessels. The largest is 360-370 meters. The are specifically planned to arrive during high tide, they have absolute priority. Otherwise, they might get stuck in the Scheldt. To confirm, for me the principle of a lock is assure passage for vessels at all times. Let me show you a typical cross section of our rolling gates (Expert 7 shows a 3D model of a rolling gate). You can see the contours. The gate is 55 meters in length. Here you see the top carriage, which moves along rails, and the undercarriage. The undercarriage also moves along rails, on the bottom with all of the siltation. The structure of the gates is entirely made out of steel, roughly 1500 tonnes (when above water). It's filled with air, reducing the weight with Archimedes' principle. So, the air chambers need to be submerged at all time. This leads to the siltation issues. If to much silt will accumulate on the air chambers, the weight and thus resistance will increase. As a result, the gates are more difficult to move (longitudinal direction).
KK	So, we're talking about siltation within the gates?
EX7	Correct. This is an exposed section in the drawing, showing the air chamber. The air chamber is absolutely required, otherwise the gate weighs to much. The chamber is filled with air (which is typical), resulting in an upwards force and reducing the weight on the top carriage, since the gate is supported by the top carriage (hanging). Meaning, siltation on the air chamber is the biggest parameter. If it's to high, the weight will increase, increasing the resistance and thus increasing the required power to a critical level. The driving system is a cable drum with cables. If it's to high, it could be the gates do not close or open. Another issue is the accumulation of growth of shells etc. Recently in Zeebrugge a gate was surfaced with a weight of 2200 tonnes, which should have been 1700 tonnes. That's a big increase in weight, especially on the seaside. We only have this issue (in small doses) with one lock, but this is not a real concern. Also, you shouldn't focus on this. This is not the scope of your project. Remember the following. The bottom is located at -20 meters. The gate is very thin, around 9 meters. Here you see the top of the air chamber. It's an important drawing. This (Expert 7 shows a new drawing) is the top part. The air chamber is made entirely out of steel. It's has a unique shape for an improved flow (from the 70's), as long as it moves in longitudinal direction. Here you see the plating, but we will remove it for now. A couple of years ago (early 90's) we installed agitation mixers on the gates. These 4 mixers (Expert 7 shows the location of the mixers).
	Expert 7 get's a phone call and the meeting is paused. Expert 7 is back and once again shares his screen.
EX7	Here you see the water level will reach up to the green mark. For example, this is during low tide and you see a lot of siltation. If you compare this to the drawing from earlier, we look at the air chamber from above. Normally we shouldn't be seeing this, it should be deep enough, thus this was during an extreme low water level. You see a lot of siltation, which is bad news. The siltation is not allowed. This is an image of another gate with slanted members and reinforcement screens, you can see this is a typical place for siltation. You can also see zinc anodes, to prevent rust. This is a typical image of siltation during low tide, you can see the -0.1m mark. Which is quite deep. I'm presenting this information to show we are aware of the problem and that we should do something about this.
KK	Okay, so you installed the mixers?
EX7	Well, we are installing the mixers systematically. This has been completed on all gates, except 3. An installation of 2 mixers costs around 250.000 euro, which is significant. Here you can see (Expert 7 shows a drawing of the upper frame) the edges on the air chamber, and this is the top part. You need to weld a lid and a frame needs to be attached with a base plate. This is the mixer (or agitation screw) from "Schillen", I will send you the information. This is 1 mixer which, by rotating, will force a water flow along the top of the air chamber to slowly remove the siltation. Basically, you will keep the water moving. That's the principle, but for this we need a power supply and a frame going upwards. We need to inspect this at least 1x annually. Debris can get stuck, blocking the mixers. Per gate we have, ideally, 4 mixers.
KK	Alright, 2 in the middle and 2 in the back I suppose.
EX7	Yes, in the back (at the side of the gate chamber). We also hope to remove siltation from here (Expert 7 points towards the end of the gate chamber) and blow it forwards. We would prefer the siltation in the lock chamber, here we have vessels to remove the siltation. The same installation is installed in the middle.
KK	Okay. So, it will accumulate on top of the air chambers. Siltation could also occur at the bottom, is this not an issue since it could not settle onto something? Would it settle on the rails or undercarriage? Does this not result in issues?
EX7	If you have insufficient movement it will result in issues. That works both ways. The intensity of siltation is 1: how much is present in the water. With brackish and silt rich water you will (of course) have more issues. Plus, if you don't move with the gates it could settle. So, we have taken the following measures: gates which do not move enough (Expert 7 points to the inner gates, 2-3, but especially gate 3) should be moved frequently. No discussion. If you do this, it's similar to snow. If you frequently pass with a snowplough, the road is clear and you have no issues. If you wait to long to move, you will have issues.
KK	What's frequently?
EX7	We gave the instruction to move the inner gate 1x per 12 hours. We have locks with a mean of 6,7,8,9 gate movements per 12 hours. No, even more. Maybe 8 à 15. People of the "bras" prefer we optimize the space within the lock when a vessel enters. A couple of meters is no issue, but with limited space the puzzle will increase in complexity. So, they prefer to use the outer gates. However, we gave the instruction to use the inner gates. In combination with the mixers, to prevent siltation on the air chambers, this results in enough freedom of movement. Or that we remove enough siltation. So, these are our operational measures. This needs to be done. If we do, we actually have no real issues. However, what we have to do is clean the gate recess periodically with divers, at least 4x annually. We used to do this with a crane, but now we

	use divers. We would like to go back to using the crane. With divers it's dangerous, e.g. due to the currents. That's why I asked about the crane in Meppelerdiep. I would like to have that information. Another measure we use, are airlifts. This is a second measure to control the siltation.
KK	So, you clean the gate recess 4x annually. Otherwise, the gate would not close? Or because it would cost to much power to close the gate?
EX7	Yes, it would cost to much power and eventually a maximum is reached at which the system says: I quit. So, the gate is not closed sufficiently, and sealing cannot be achieved. This will result in warning signals (alarms). Sometimes we are able to close the gate by going backwards and then trying again. However, this functions kind of like a press: you are compressing the debris.
KK	I think you have 2 gates per lock head, so the second gate is a backup gate?
EX7	Yes, correct. The second gate is actually not required, but we have it in case we need it.
KK	The pictures you showed me with the siltation on top of the air chamber, is this the situation before the mixers were installed?
EX7	What do you mean?
KK	We saw a lot of siltation on top of the air chamber, were those pictures taken before the installation of the mixers?
EX7	No, the pictures we just saw were also of gates with none or just 2 mixers in total. We said 2 mixers on thinner gates would be sufficient, but we noticed 4 is more effective. What's also important, is that the mixers require electricity. That's why we first investigated if they are necessary. We notice the mixers are certainly required on the side of the Scheldt, but not on the gate at the dock side due to the less silt rich water. So, we gave instructions to not use the mixers on the dock side, as an energy reduction. This is what I mean with analysing if measures are really necessary. We also started a campaign to measure the weight of the gates. If we turn off the mixers, we would suspect this will result in siltation. However, this is not the case at the dock side. So, we can conclude we don't need the mixers at the dock side. However, we have to be cautious. We cannot look down there. We can only confirm the previous conclusion if we put the gates in a dry dock. I'm dependent on the weight of the gate. This is how we measure the weight (a very important parameter): between the top carriage and the gate you have a connection beam. You could see this as a shoulder joint, which keeps the gate upright. In the shoulder joints on both sides, you have a load cell. The load cells work according to a Wheatstone bridge to measure the weight of the gate. The weight is a parameter for the amount of siltation on the gate.
KK	However, once you have installed the 4 mixers on The Scheldt side, the problem isn't fixed completely?
EX7	Well, with the combination of the mixers and frequent movement, we control the siltation on the air chambers. Those two measures are important. Let me show you something else. This is also important for me. Look at this (Expert 7 shows a picture of the profile of the lock bottom) and translate it to this picture (Expert 7 shows a google maps picture of the Kieldrecht Lock). You can see two lock chambers on both sides. What we do, is measure the siltation. You can see 4 lock chambers. A deeper blue colour means an increased depth. These are the sills of gates 1 and 2. Here you can see siltation. This is insufficient to do a proper analysis regarding the amount of siltation. What I want to show with these pictures, is that in each gate chamber a sill is present. The gate moves within this sill, which will also act like a "reservoir". However, by moving frequently the amount of siltation remains at a low level. The undercarriage has a small clearance, meaning with frequent movement you will push away the silt. The siltation underneath will remain, yes, but this is something you have to live with. It sticks to the rails, but this isn't a problem. Expect when you have to disassemble the rails, but this only has to be done once every 20-30 years. I'm fine with siltation sticking to the rail because the other option is to blow away all the siltation. Which would mean you will make the rails more fragile with attachments, taking away the protection. My opinion is: don't remove the siltation, just make sure you have enough movement. Thus, the siltation is basically pushed away. At the front of the undercarriage, in front the wheels, small ploughs are used to push away the silt. So, this is part of my main theme: enough movement to control the silt. What I actually wanted to show you is the use of air bubbles to agitate silt on the bottom and suck it up. If the siltation hardens, this will not work. If the siltation is still in suspension, we can remove it. Do you know the term airlift?
KK	No.
EX7	You should write it down.
KK	I know they use an air bubble screen to separate salt and fresh water at the Krammer Locks, is this the same concept?
EX7	No, absolutely not. I'll show the principle of an airlift. We use compressed air to suck up siltation along the trajectory of the gate. We create a suction effect at the bottom to prevent the silt from compressing. Here you see the same top part as earlier (Expert 7 shows a picture of the top of the air chamber), but you don't see the mixers. Here you have the bottom of the gate. You can see an empty gate chamber. Here you see 4 tubes. The tubes run entirely to the bottom. With compressed air at the top, we will suck up the siltation. Here you have a schematic drawing.
KK	The tubes run vertically?
EX7	Yes, and the outlets are situated just below the air chamber. Underneath the air chamber, you have tubes with the goal of dispersing silt rich water, to create a kind of "mist". These are the 4 tubes on 1 side, so 8 tubes on each side of the gate. So, on the front and back side we have 8 tubes (16 in total). The principle is the following: compressed air is blown into the tubes, creating an acceleration with the Venturi effect. It creates an underpressure, which will suck up the siltation from the bottom. So, silt rich water is transported upwards. It's combined with the air and dispersed at the top. We equipped all gates with this system. Currently, we use this to remove siltation from the bottom (if it has not hardened). This is labour intensive and costly. We have to be present with a compressor and connect this to the gate. Furthermore, we have to reduce the gate movement speed and we cannot see the effects.
KK	So, this is not a permanent system? You have to go down there with a compressor?
EX7	No, it's not permanent, but we don't have to go down there. We can connect the compressor at the top to a tube, which will go down. We have to connect it separately per tube, 1 by 1, in total 16x. However, we do it in sets of 4 (so 4 tubes at once). This is labour intensive. I've always wondered what's the point of this. We still have discussions if we should continue or not.

	With regard to siltation issues, we do use the compressor and it seems it has some effect. We cannot deny this, but we have played around a lot with the frequency of use.
KK	So, there is no fixed frequency?
EX7	There is in theory, but this is not feasible. Logistically is a difficult operation. You need a mobile compressor on a truck, which you need to park on the gate. As a result, you need to reduce the movement speed of the gate. I seriously wonder, what's the point. My theme remains: achieve frequent movement, then you have no problems. The problem at the gate recess will remain. You will get siltation, for which we require divers. Furthermore, you will get siltation at the back of the gate chamber. Currently we do the following: go backwards with the gate (with the mobile compressor attached) to remove the silt at the back of the gate. With the airlifts at the back, we take the silt from the bottom and blow it upwards. Subsequently, the mixers blow away the silt, so it settles in front of the gate. This is the backside. The next step is to try to go back a bit more and more. We want to remove the siltation at the back, and we use the mixers for this. Next, we have to bring the gate forwards, to agitate the siltation in front of the gate, so the vessels can further disperse the siltation. I prefer the siltation in front of the gate instead of at the back. That's the theory. In practice, this is difficult to confirm.
KK	So, the airlift is only situated at the back?
EX7	No, also in front. It's a double feature, both in the back and front. 8 tubes in front and 8 tubes in the back, 16 in total. The mixer is poorly drawn in this picture, it should be more in the middle. To confirm this method, we used a little boat to see if the volume of siltation at the back was decreased. However, I cannot give a confirmation. In the past, we used the gate with compressor to go forwards and backwards and we also used the airlift to clean siltation out of the gate recess. We have a lot of stories about the debatable effectiveness. I remain sceptical and it's limited to the method I just described. Meanwhile, we reinstated the old method, but this only shows we do not fully control the process and we do not know the optimal method. We have several tools (the mixers and airlifts) which create opportunities. Another example. We have one gate of which I showed the pictures. Those pictures show the amount of siltation is alarming. If you know the gates at times reach this level, -0.06 meters, you know it results in an enormous increase of weight. Dried siltation is roughly 2-3 times as heavy as wet siltation. When we confirmed the pictures, we started increasing the movement frequency. Way more frequently. Instead of 1x per 12 hours, move at all times.
KK	Always?
EX7	Yes, so instead of 1x per 12 hours, 8-9x per 12 hours. We noticed the driving power is reduced systematically. So, it seems to be successful, at least I think so. Compare it to a river creating a canyon over millions of years, it's kind of the same principle. If you keep moving the gate, no matter the slow speed of the water. At least, do you know the movement speed of the gate?
KK	Well, it's probably different with such a large gate. It will probably move even slower, but I have an idea of the movement speed.
EX7	Exactly, it not very fast, but still enough to decrease the siltation. So, that's certainly a plus.
KK	Is it okay I'm saving my questions till your about done?
EX7	Yes, I want to show you something else. Look at gate 3, the gate from the pictures with the serious siltation, starting from 2020-01.
KK	Gate 3? Gate 1 is at the Scheldt side?
EX7	Yes, this the gate which is moved the least. It's an inner gate with almost no movement. Plus, it has no mixers. What we see is (Expert 7 shows a power graph): each dot is 1 movement and the average power value, relative to the other gates. So, the green dots are gate 3 and it used to be 160 Ampère, which is very high, and 100 Ampère for the other gates. We started using the gate more intensively in January, leading to a decrease to 120 Ampère. For me, this is a cautious confirmation of reduced siltation on the air chambers. That's my theory, but I cannot prove this yet. We would need to take a look. That's my complete story. Here another picture of the mixers and a picture of an old gate without mixers. You can see how problematic it is. I think that's all.
KK	Well, that's a lot of useful information. Let me take a look at my questions. Until now, nobody mentioned a siltation problem within the gates. The gates in Meppelerdiep are relatively small and do not have an air chamber. Furthermore, it's freshwater and the gate is not used frequently. That's why they have no issues within the gate chamber and the gate itself. They only have a grill on the front side against large debris. I suppose you do to?
EX7	I would not know what for? It's on the front side?
KK	Yes, on the front side, like a grate. Do you have such a grill?
EX7	No, we wanted to optimize the water flow. A grill would increase the resistance. I cannot think of advantages of such a grill. Maybe to stop rope and other debris, but it would get stuck. Which would increase the resistance and we would need divers to remove it. So, I prefer a free flow through the gate. Actually, we use the mixers to accelerate and force the water flow you would get from normal gate movement.
KK	Okay, so you have a sill in which the rails are situated. Do you call this a sill?
EX7	Yes, a sill. The undercarriage moves along the sill. The sill is recessed into the lock bottom, to protect the rails against vessels.
KK	Yes, so the rails are recessed into the bottom. Is it around 50 cm from the top of the rails to the top of the sill?
EX7	Yes, that sounds about right. Maybe even more. It deepens, starting from the lock bottom. You also have a radius, after which it deepens even more. I think at the deepest point it's 1-1.5 meter to the top of the sill.
KK	Okay. To seal the gates, do you use the difference in water level or cylinders?
EX7	Where would the cylinders be situated?

KK	On the gate itself.
EX7	No, at mitre gates you would need the cylinders to achieve a pressure against the difference in water level. With rolling gates, it seals on both sides. Due to the difference in water pressure, it seals on the right side. You have a complete seal of wooden beams against granite. We don't need external forces, solely the delta h of the water (resulting in a delta p), which seals the gate against the walls. I can't see the connection with siltation, but currently I'm looking at the density of the wooden beams. If the beams have wear or holes, it will leak. Delaying the levelling process. If the seal is tight, you have a fast levelling process. Again, I don't see the connection with siltation?
KK	No, you are right. I'm starting at zero with rolling gates, how are seals achieved, what kind of materials are used etc. So, that's why I ask these questions. A couple of short, practical questions. So, you seal with wood against granite. No plastics?
EX7	No, no plastics. Do they use plastics in The Netherlands?
KK	Yes, in the Northern Lock of IJmuiden and Meppelerdiep they use plastics.
EX7	Why?
KK	I'm not sure, but if I have to answer I think because of resistance against wear.
EX7	Yes, I have no knowledge of this. We use hardwood and I suppose in The Netherlands you are a bit more advanced with respect to durability. Personally, I think we use way too much hardwood and that's killing us. They are really heavy, so if they break loose, they sink to the bottom. Plastics should be able to float.
KK	Yes, they should.
EX7	However, so should wood.
KK	Back to the gate chamber, you said you have siltation at the back, and you clean it 1x per 8-10 year?
EX7	No, even less. Once per 10-15 years.
KK	Okay, so that's not really an issue. If I summarize your complete story you have issues on top of the air chamber and within the gate recess. Consequently, you have a system to manage the siltation on the air chamber. However, the siltation in the gate recess remains a problem.
EX7	Correct.
KK	Do you have deepened reservoir at the gate recess, or is it level with the bottom?
EX7	I'm searching for a photo, but we have no deepened reservoir. I personally would like to use that. To create a reservoir in front of the rails, in the bottom. However, you would also need to clean this after a while.
KK	Okay, so you would have to clean this. For such a cleaning operation you have several options. For instance, with the mobile compressor, or with the gate recess 4x per year. Could you give me a cost estimate? Would that be reliable?
EX7	Good question. I have done this in the past, maybe ask me this question again via e-mail. I cannot give a direct answer; if it's effective or not.
KK	I will ask again via e-mail. Previously I spoke with expert 2 and he mentioned an ingenious system with Venturi etc. in Port of Antwerp. It sounded like it would be situated at the back of the gate chamber, to suck up silt, but that's apparently not relevant. That's the system installed on the gates.
EX7	Yes, that's the principle of the airlift. The Venturi effect to transport (non hardened) siltation, at the front and back.
KK	Okay, maybe he described it incorrectly, or I misunderstood.
EX7	Yes, it's pretty ingenious because it's not used at other places. However, it's also pretty simple. You don't need pumps, it's venturi. I do have my doubts in the effectiveness. We could certainly use it, but it's not a system that could be used all the time. It's a manual method.
KK	Clear, it's quite an ingenious system. I believe the Kieldrecht Lock is relatively new?
EX7	Yes, it was completed in 2016.
KK	Am I right to assume these methods were designed/thought of in advance?
EX7	Yes, the airlift is from 1991 I believe and the mixers from the late 1990's. For us, it's not that innovative. However, if you realise that a gate (we have 24) is receiving a renovation every 10 years (at the earliest), you can imagine it takes a while to install all systems.
KK	Yes, exactly. You don't build a lock and say: let's see if we run into trouble. You think about positional problems in the design process.
EX7	Absolutely. We are very involved with the design process of new locks. To give an example, a lot of our knowledge is copied to the 5 locks in Panama. Furthermore, we were in contact with a lock in Sevilla. A firm just used the same principle as our rolling gates. Our knowledge is copied a lot. I have the luxury with my colleagues to retrieve data from this, but I can safely say I do not have the subject under control. It remains a grey matter. A theme with many parameters.
KK	Yes, I've noticed the same. I've only just started and do not know a lot, but just the number of different stories you hear. Problems at different locations. There is no absolute truth like: this is the problem, and this is how you fix it. Did you have real damage in the past? Are there certain components with fail and break due to the siltation, which need repairs?
EX7	That's a good question. Siltation means extra weight, which means an increase in power, which means an increased resistance on the driving mechanism. Until now, we have no real failures. We did however have 2 malfunctions, possibly related to that. Maybe a combination of increased weight with age and insufficient lubrication. We can monitor the weight of our installation and if we control it quite relaxed. Colleagues in Zeebruge did have some damage with rolling gates, due to increased weight. The undercarriage got damaged; the wheels were broken. This was a direct consequence of too much weight. You can prevent his in two ways: 1. Increase the amount of air in the air chambers, 2. Prevent siltation on the air chambers. I mentioned the shoulder joints, they contain load cells. In my opinion, they are not accurate enough. Since siltation is a really important parameter for the weight, you should improve the weight measurements as well. We have too much deviation. Why? A rolling gate has 2 load cells, which could measure 250 or 150 tonnes (dependent on the size of the gate), but this is the maximum limit. In the design we have several modes of operation. We call them 1,2 and 3. 3 is the limit with extremes load cases, which you use for your design. It means, such a situation could occur, and your load cells should be able to measure this. However, it also means that in low load cases you have a poor accuracy. A load cell with a high accuracy would fail in mode 3. Thus, I have a poor accuracy, and this is frustrating. I have not found a technical solution for better measurements, for a better control of the lock.

	So, do we have everything under control? Do we have costs due to too much weight? This is certainly a risk. If I would do a risk analysis I would have to say: yes, it's a risk. We feel quite secure since we have measures against this. I cannot look at the gate, how much siltation there is. Unless you perform an operation of 150.000 euros with which you drain the gate chamber, but you won't do this.
KK	Okay, because the load cell is situated on the top carriage?
EX7	Yes, 2. One on each shoulder joint. I'll show you some more pictures.
KK	A real quick question, do you use culvert for levelling?
EX7	Yes, correct. Here you can see the undercarriage and the sill. This is one undercarriage; the gate still has to be placed on top. This can only be achieved within water. The gate is able to float. So, this picture is still during construction, but it gives you an idea.
KK	The gate seals against the sill?
EX7	Yes, the gate. Not the undercarriage. Against the arduin (that's the type of stone).
KK	Okay, so the gate overhangs the undercarriage a bit?
EX7	Yes, correct.
KK	And you use a spring plate?
EX7	Yes, exactly. The gate will rest on the wheels over here and it has a guidance rod. So, it rests on here (rollers) and transfers the loads to the wheels, which run along the bottom. Let me also show the ploughs. Here you can see the wheels and the rails. There is little clearance between the ploughs and the rails. Be honest, is it really an issue if siltation will remain underneath the plough? No. We just have to move regularly. We cannot go lower, the wheels are prone to wear.
KK	Yes, that was my question.
EX7	Yes, it's also for safety. I think it's about 3 cm, the wheels won't wear out that much, but still. Here you can see the sill, your 50 cm was a good estimate.
KK	So, the gate is resting on the rollers. It's only fixated by weight?
EX7	Yes, correct.
KK	Okay, because the Krammer Locks use some kind of rubber cylinder. Due to the cylinder, the gate could move a bit sideways to create a seal.
EX7	What do you mean with a rubber cylinder? You are correct, the gate needs to move a bit sideways, but this can be achieved with the rollers. It's not really moving, but also not slanting. The gate needs to be vertical during movement.
KK	Are the rollers the only points of support?
EX7	Yes, it's a line contact. It's a good question, the weight cannot be too high, otherwise the wheels would be overloaded (and then the rails). If you look at the complete gate, we want a weight of 100 tonnes while submerged (the weight above water is 1500 tonnes). 60 tonnes on the undercarriage and 40 tonnes on the top carriage. That's the theory. So, 60 tonnes on the undercarriage means 30 tonnes left and 30 tonnes right. So, 15 tonnes per wheel. It could vary with the water level and siltation, but the 60 tonnes are what we aim for. So, 30 tonnes on 1 roller.
KK	Alright. Do you adjust the amount of air in the air chamber depending on the water level?
EX7	No, then you have to change it every 6 hours. The weight is the lowest during high tide. So, we make sure it still "sinks" during high tide. We once had to much air in the air chamber and the gate emerged during high tide. This cannot happen. So, we have to play with the contents of the air chambers. This a whole different subject: where do you put the air for stability? Left, right, front or back?
KK	Yes, there is so much to know.
EX7	Yes, these gates have 24 air chambers and other gates have 18. It's the principle of a submarine, you either fill it with air or you remove the air. I believe it's one of the most difficult subjects regarding a lock gate.
KK	Okay. Obviously, the design of a rolling gate is complex with numerous factors. If you take a look at the complete process, how important is the siltation problem? Should you consider this during the design process? Let me tell you why I'm asking this question. I asked the same question at the New Lock IJmuiden and they kind of ignored the siltation problem. It was not important enough during the design. So, they have no real measures against siltation, just a deepened reservoir and waterjets. That's it.
EX7	Where is the reservoir located? At the gate recess, similar to Meppelerdiep? They don't have enough space.
KK	Just before the gate recess. It's deepened and I think in between the rails. It's quite small and they also have a hole on the side. Do you have a picture of the sill in the longitudinal direction? (Expert 7 shows a picture of the sill) If you look to the left of the sill, it's also deepened over there.
EX7	Yes, but that's at the end of the lock?
KK	Yes, he said it runs along the entire width of the lock.
EX7	Yes, but after the last gate?
KK	Yes.
EX7	Yes, that's something different. That was one of my first questions: it is regarding the siltation of the lock, or the gates? That's an important difference. We have the same reservoir (along the width). This is for the overall siltation management. In the longitudinal direction the lock, you have a slanted line of salt and fresh water: a "slibtong" (Expert 7 points towards gates 1 and 2 as brackish water, Scheldt side, and towards gates 3-4 as fresh water, dock side). In theory it's a slanted line, which is heavier. The salt water will flow underneath the fresh water. That's why it will settle at the bottom. For this we have a method, in which I do not really believe. The siltation can accumulate in this reservoir AFTER the lock. These reservoirs are not installed on all locks, but on most. We should empty the reservoir frequently, with gravity. Maybe this is the ingenious

	system Arjen described. I'm not sure if it's within your scope, because it's not relevant for the gate. We already talked about the measures for the gates, but this is something completely different. It's also difficult to show. It's basically the "slibvang".
KK	I'm reading the interview with Arjen right now and I think you are right. It's the reservoir along the entire width of the lock. However, they also have a reservoir where the gates close. At the gate recess.
EX7	Can you show me?
KK	He didn't give any pictures, but I made a sketch which he confirmed. I will put it in the chat. The New Lock is not yet completed, so I based the sketch on The Northern Lock. The reservoir is on location 1.
EX7	I don't see anything, should I look in the chat?
KK	Yes.
EX7	So, on location 1?
KK	Yes, can you see it?
EX7	Yes.
KK	So, that's the reservoir. It's nothing advanced, just a simple "hole" which is around 0.5 m deep.
EX7	Okay, so that's just for the gate itself. Looking from the sea, is this the first or the last gate?
KK	The first. I'll have another look at the interview to see what they installed. Found it. So, the New Lock is only allowed 18 hours of downtime per year. Due to this high availability, they said no to complex systems since they can fail. That's why they chose to not install anything fancy. Then they concluded: we don't know what's going to happen. It can be better than expected, it can be worse than expected. Time will tell. Maybe they have major problems in 2 years, or none at all
EX7	Yes, I understand, but they could compare it with the Northern Lock.
KK	Well, that's also what surprised me. I thought they would work together with the Northern Lock, that's a big lock with rolling gates, but the collaboration was minimal. It's different parties.
EX7	Yes, they won the contract to build it.
KK	Yes.
EX7	I cannot find the animation, but I found a PowerPoint. I'm not sure about the principle. It works like this: at the back of the lock, you have a reservoir in which siltation will accumulate, which will be removed at low tide. We use the same channel to add water to the dock, since the water level is decreasing too much. So, we actually use the system for the opposite of what's it meant to do. It's an ingenious system, but not used for its purpose. But you didn't hear this from me.
KK	Okay, so it's located at the dock side, behind gate 4?
EX7	Yes, correct.
KK	I found something else. The New Lock does have a waterjet system on the undercarriage, which blows in front of the wheels. It blows during the closing of the gate.
EX7	Yes, they also have a system with hatches, they do not have culverts. So, they have a lot of current on the gate itself. It's totally different. Maybe they do have enough agitation for the siltation on the air chambers. I can only suggest they measure the weight of the gates sufficiently. I don't know if the have the tools for this.
KK	Me neither. I'm curious about the situation in a couple of years.
EX7	Yes, the 18 hours of downtime really did a number on them.
KK	Yes, because how much downtime do you have? Does it differ per gate?
EX7	We cannot go under a certain value of functioning, but we have more possibilities than the New Lock. Currently, we have a set 8 hour stop once per month. That's our average. If you calculate that, you have more than 18 hours. Way more. I already wished him good luck.
KK	Yes, I can imagine.
EX7	(Expert 7 shares his screen and plays a video) Can you see this?
KK	Yes.
EX7	(Expert 7 pauses the video) So, this is the principle. You can see the Scheldt side and silt rich water will fall down to the dock side (the back side). Here it will be sucked up with gravity and blown back to the front, to the Scheldt side. That's it. You can see a reservoir (at the back side) and the silt rich water (the Scheldt) and we use underground channels to redirect the water back to the Scheldt, parallel to the lock.
KK	Was this originally designed in Antwerp, or is it a standard for locks?
EX7	I cannot say. I have worked at Port of Antwerp for 10 years, and all new locks have one. It was designed in the 70's by a hydrodynamic laboratory. The principle is that the siltation will accumulate in the reservoir. We know we have a lot of accumulation and we use the reservoir as a drain. We go down there with divers and pressure washers and dredgers to force the silt to the reservoir. Next, we open the vents with low tide, to blow it back to the Scheldt. So, that's another manual action.
KK	They are not equipped with pumps?
EX7	No, never mention the pumps, please. We laugh about this, but people ask: where are the pumps. Everything is done with gravity. The difference in water level is also done with gravity. You make a connection between the reservoirs and it will level automatically. Due to the size, you see no variation. So, no pumps. Never.
KK	Because Arjen mentioned this system and said it does not work properly?
EX7	Here you can see the channels. So, this is the reservoir. I don't know why he says it does not work, that's not the case. It's a manual action and we do not do it often enough. As I said, the water level in the dock side decreases too quickly. So, we have to fill it with the channels. If there is siltation, we will push it further down. We only do this because we have to, to refill the dock side. During the design of the system, you assume you have sufficient water at the dock side, but that's not the case. So, now we use it to bring water into the dock side, meaning accumulated silt in the reservoir will be blown into the dock side. That's why I'm sceptical about this system, but we do use it. You can see the cherry pickers, of course the water is drained in the pictures, but in the meantime a lot of siltation has accumulated. If you agitate it with a dredging machine and drop it into the reservoir, you can remove it with the system in a

	coordinated action: so, we do use it for this. Depending on the urgency, we use it as a siphon. So, it's to remove the siltation from the edge.
KK	Okay, clear. It's not used to remove the siltation of the gate. It's used in general.
EX7	Yes, correct. I think we are done. I spoke a lot and you did to.
KK	Yes, almost 2 full hours. Very useful, I'm very happy with the results.
EX7	No headache?
KK	No, but I need to take some time to process the information. I do not know what to conclude right know.
EX7	Sure, if you have more questions send me an e-mail. I aim to answer them within 1-2 weeks. If you eventually publish something, let me know. I'm putting in my own time.
KK	Sure. Eventually I have to write a report and it looks like it will be open to the public, so I can send it to you. If I have more questions, I will send them to you. My last short question is: do you have scientific sources? I could not find a lot. I could only find there is more siltation in estuaries, but the information regarding siltation is limited. Do you have such information, studies or papers?
EX7	Well, no. I am not a theorist. I'm an engineer, I call it the application of the theory. I cannot tell you how a bridge works, but I can make it work. Furthermore, I'm working in an environment in which the reality is leading. It's a great advantage that I'm able to compare between the gates. It fascinating, but I haven't looked at the theory. For example, the salt levels. It's very difficult and hard to measure. I also have the feeling we need to measure if siltation is present on the gates. To answer your question, I do not have specific papers regarding rolling gates. I can recommend the hydrodynamic laboratory in Verkruizen, maybe they have some papers. However, they are more focussed on models of currents and not siltation. Herman Huitema of Nortek has measuring devices, which could measure sedimentation. They performed an extensive campaign in The Western Scheldt basin, I saw this on LinkedIn. He is Dutch. Those are the contacts that I know of. Such studies are more focussed on the intensity and density of the siltation, it's more within the chemical discipline. That's too theoretical for me. It's too difficult and it's also connected to the dredging industry.
KK	So, for you: there is siltation, but we don't care about the composition. How many sand particles etc.?
EX7	No, exactly. We need to make sure the gates will move, and that they are not too heavy. We need to remove the siltation. We can only determine: that gate has more silt and that gate less and we have the methods to remove it. However, we are not theorists who look deeper into the theory. It does not give us additional insights.
KK	Exactly, I had the same idea. I already noticed it's a difficult subject to find theoretical information. That's why I decided to speak with people with experience. There is so much knowledge, experience and information with those people. Way more useful than a paper, which only discusses half of it.
EX7	Yes, that's also my approach. I'm a Bachelor, so that's how I do it. Your question regarding the costs of siltation removal was a good one. I haven't looked myself within the bills. It's a 120-page file. I'm not sure, it will probably be a part of it. Walla.
KK	Thank you so much for all your time. I will send another email, but first I will process this information.
EX7	That's alright Kelwin!
KK	Thank you, enjoy your weekend and I'm sure we will speak again.
EX7	Alright, thank you and see you later.

Table 22. E-mail correspondence 03-08-2020 |10-08-2020.

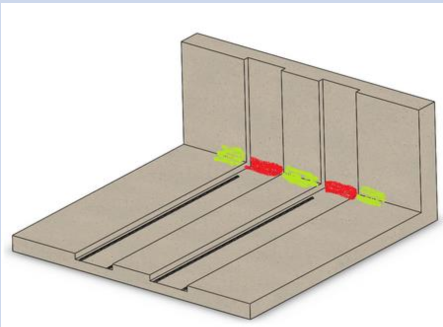
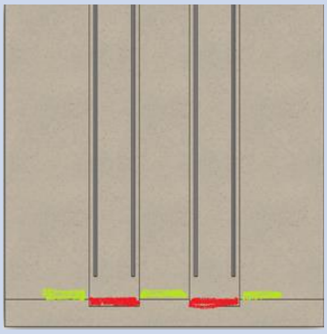
KK	Could I also use the pictures from the recorded interview?
EX7	If you let me know which ones you want to use, then I can see if I can give permission. If you use them mention that the pictures are protected and not the be copied without permission.
KK	Why is the gate open at the front? Just because it will increase the forces during opening and closing? Or because of an increased flow? I was wondering maybe you can fix the siltation problem in the gate by closing it.
EX7	A good thought. However: then we need to make the gate watertight up to the water level (also on top for rainwater etc.) because otherwise you would create a water basin in which the water will move around and create more weight. Furthermore, you will create an air reservoir with an upwards force which could make your gate too light. The current you create by moving of the gate will not be very strong, but you will create more waves. Perhaps earlier concepts did include a closed front?
KK	Do all gates in Port of Antwerp have air chamber? If not, do you have less problems with silt in those gates?
EX7	All gates have air chambers to reduce the weight on the carriages.

Table 23. Cost estimation provided by expert 7.

Component of one gate	Opex Of 1 intervention	Capex To equip one lock gate	Comments
Gate recess	1.250 €/year 2x per year =2.500 €/year	-	

Airlift (located on each corner of the gate)	650 € + depreciation compressor/each time 4x per year = 2.600 €/year	+-250.000 € (design life +- 20 j)	Gas and oil usage of compressor are not considered
Mixer (4 on each gate)	500 € 1x per year = 500 €/year	+-350.000 € (steel structure, electrical controls, components, …) (design life (+- 15 years)	Power usage of mixers

Table 24. Follow up questions and interview siltation of the gate recess 25-09-2020 – Microsoft Teams.

NOTE	Subsequent to the first interview (Table 21) email correspondence was completed with some sketches (shown in this cell). The main point was to further define the siltation problem in the gate recess. In the sketches red and green areas were noted with the following two questions: 1. I suppose the siltation is problematic in the red area, is this correct? 2. Could there also be siltation in the green areas? Expert 7 confirmed the sketches were correct and also mentioned the siltation does include debris (sections of wooden beams, car tires etc.).   The following interview was used to further clarify the situation.
KK	In the sketches of the gate recess, I made some marks where I thought the siltation would be problematic (in red) and asked if it would also be present in the green area. You then replied with a depth chart, in which I saw no siltation in the red area's
EX7	Don't get misled by those charts. They are kind of rough and are more an indication. The gate recess is actually not even included in the chart. A vessel is used to go back and forward in the lock (length wise), and it can not include the gate recess (since it can not go into those area's). So, it extrapolated the data from what it can measure. The resolution is rough so don't see it as a detailed analysis. Silt with reflect at a certain intensity, but this is difficult to get right.
KK	Okay so the sketch is correct, siltation at the red area is problematic. And eventually it will also flow to the green area's
EX7	Indeed. Red is problematic and it will also flow to the green area's, but this is no problem. It is allowed to accumulate in the green area's
KK	Okay so suppose I design a system which reassures the red areas are free of silt or push it to the green areas or the middle of the lock, that would be a great solution?
EX7	Yes, that would be the ideal solution. But if you push it to the other area's it will get back into the "dorpel", so it is not a permanent solution
KK	Yes of course, my goal is to get a solution to decrease the frequency of dredging. However, it will not be eliminated completely. Are the beams and other debris also a big problem, or is the silt the main problem?
EX7	It is a combination. The debris will increase the speed of siltation since silt can get stuck behind the debris.
NOTE	Expert 7 shows data which shows gate 3 is the most problematic in terms of closing (failures)
KK	In the red area, will the silt also go in the vertical direction? Upwards? Or is it mostly at the bottom?
EX7	Good question, I think at the bottom, but I have never been there.
NOTE	Expert 7 shows a high-resolution picture to show the siltation in the gate recess, which is accumulated at the bottom. Furthermore, you see the siltation in the green areas and some beams at the bottom of the lock.
KK	And the divers with high pressure washers are required to remove the silt?
EX7	Or a crane. That will be more efficient. The divers say they sometimes have to remove 1.5 meters of siltation. That is an enormous amount of silt.
KK	And does he also have a pump, or does he just blow it away?
EX7	Blown away. If you suck it up, you have to process it as debris, and we don't do that. With a crane we are able to get it and place it to the left and right
KK	How deep is the sill
EX7	Around 70 cm I think.

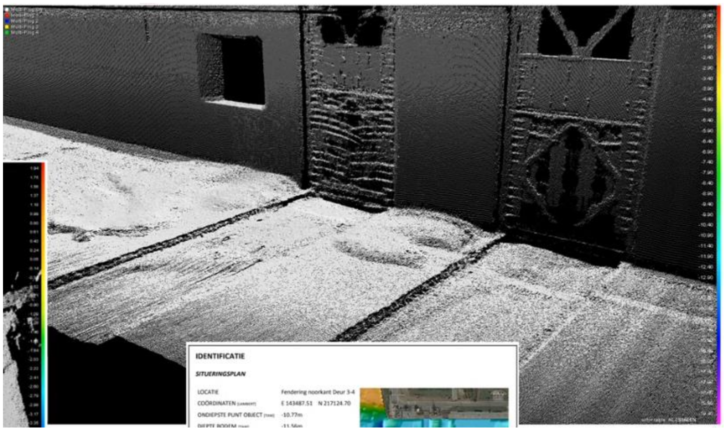
Note	Below several important pictures are screenshotted from the teams meeting (with permission) and will be used  

Table 25. Interview potential requirements expert 7 29-10-2020 – Microsoft Teams.

KK	In our earlier conversation you mentioned a crane was used in the past to clean the siltation, but you switched to divers. What was the reasoning behind this?
EX7	That was because of a very simple reason: the company that performed the cleaning for us did not have the crane anymore.
KK	You also mentioned you want to switch back again to the crane, why do you want to go back? What are the disadvantages of the divers?
EX7	There are huge amounts of siltation present and the divers do not really know where to start. The large amounts of silt are just difficult working conditions. It could easily be a silt layer of 10x2x1.5 meters. Furthermore, 1. the procedure is costly and 2. It puts pressure on our additional maintenance operations. We ask for 8 hours each month per lock to be out of order for maintenance. About half of the time, we have to send a diver down to the gate recesses. Which means: security, no movement allowed and no water flow. Thus, it puts a lot of pressure on the additional activities, since we might not be able to do those. This is separate from the costs.
KK	How long does a diver take for 1 gate recess?
EX7	We try to do 2 recesses on 1 day. Sometimes we succeed, sometimes not even close. On average it takes about 2-4 hours per gate recess. Note, we do not clean all the silt completely. Ideally you would take away all the silt with the high-pressure washers, which would take about 8 hours. We look if there is debris present and we take those away.
KK	Ah so you don't clean it completely. Suppose you would clean it completely; do you suspect you would not have to go down as often?
EX7	I don't know for sure, but I think so.
KK	Okay and back to the crane. Suppose the crane is back in business. How is the process controlled, do you still sent a diver down there to control? Or is it without control.
EX7	Sadly yes. We scoop out the silt but have no control over how clean it is. We do not check.
KK	Could you say: crane is cheaper, but with divers you have more control?
EX7	That is relative. The diver only has it hands to take out the debris. Are you thinking about an objective solution like a scanner or camera?
KK	Well, I'm still trying to determine the motivation for my system. What would be the added value of my system? Is it solely costs, safety, effectiveness etc.
EX7	Ah okay. I showed you the presentation in which it shows how often a gate is blocked due to siltation right? Did I send it to you?
KK	No, I made some screenshots. The third gate was blocked the most.

EX7	I will look it up, one moment.
KK	One more question about the divers, they go into the water alone?
EX7	Well, it is a whole crew of divers.
KK	Yeah, but per gate recess 1 diver is in the water and they rotate I suspect?
EX7	Yeah, that is correct
EX7	I cannot find the presentation right now. Anyway, to be honest costs are not the biggest issue. The main issue is reliability. If we need a gate and it does not close, that is a problem. Secondly, efficiency. As said if we need a diver, it puts pressure on the additional activities. The less we need to do this, the better. So those two are the main reasons. The costs are of course not negligible, but they are never the main motivation (as long as they are not absurdly high).
KK	Do you also get fines when the locks are not in use? This is the case in IJmuiden
EX7	No this is not the case; we have no fines. The situation in IJmuiden is quite difficult. I arranged about 6-7 years ago we have 8 hours per month per lock for maintenance. No fines or anything.
KK	Okay so if I would want to quantify costs you would look at loss of income from vessels? Because the lock is closed?
EX7	Yeah, they are delayed. That would be a method to quantify.
KK	Yeah, I looked into the income from vessels, but it is very difficult to find. Could you provide such information?
EX7	That is very difficult. Different vessels etc. I would not focus on this; I would focus on the reliability of the lock. Focus on the blocking of the gate due to the silt and debris in the gate recess.
KK	Great. Last time we also talked about the airlifts. Was the original purpose of the airlifts to clean the gate recess?
EX7	No, the purpose was to clean the rails, to spread the siltation. But as discussed, we now also try to use it a bit to clean the gate recess.
NOTE	Expert 7 gets a call and has to pause.
EX7	I'm back.
KK	I was thinking about what you said about just cleaning the debris instead of completely cleaning/emptying the gate recess
EX7	Yeah, that is something in which we limit ourselves. Ideally, we would clean it completely, but that is difficult.
KK	It takes to much time?
EX7	Yeah, plus we have no view on the situation. We only clean when the gate does not close anymore. We have no view on the condition of the silt. We do not see how much silt there is.
KK	And I can imagine it is difficult for the divers to just clean with there hands, they are limited.
EX7	Correct.
KK	Okay about the airlift. You use it kind of to clean the gate recess (the results were debatable you mentioned). Suppose it would work, would that be a good solution for you? Or are there disadvantages?
EX7	The problem is we need a mobile compressor which is logistically difficult. We need a large truck and a driver, which will go on top of the gate. All kind of activities which are not ideal. Better would be a for instance a mobile airlift installation in the gate recess.
KK	Okay. Because in my opinion you have several options: an integrated system which works 24/7 or a system which you need to operate manually, or which is even mobile and you need to install each time. So that's why I ask about the airlift. Suppose it would work great, would it be a great option despite the mobile parts etc? Or would a different system be better?
EX7	My choice would go to a mobile system which is applicable to all gate recesses (we have 24 in total). So, if you have a system which you can you use periodically instead of 24 systems in total (which you also need to maintain), that would be more realistic.
KK	Great that is valuable information. Because it was difficult for me to imagine what to choose since I have no experience with locks
EX7	I understand completely, so yeah a mobile option would be preferred. Something that can be moved by a crane or lorry for example. It would even better to have something in the gate recess. Now we have the airlift which sucks silt when the gate is in the recess itself, so the silt is basically sucked up and blown back into the gate recess. So, it is a closed circle of silt. It would be better to have a system which will work when the gate is not in the recess. You have a free space, and you will blow the silt into the direction of where you think there is water flow (because that is what you need, silt will compact if there is no water flow). Thus, such a system will be more efficient. Then you can also work with a combination of nozzles for instance. It will be more efficient than adding 24 systems to for instance the gates. Remember the gate movement is based on traffic, you can not move it freely when you need it. You need to wait for the gate. And the gate needs a closing movement, which means no vessel passage. When a lock has 4 gates, basically 1 is closed and you could use that time to clean the other 3 gates.
KK	Yeah, my idea was to have a requirement to have a cleaning operation under 60 minutes, since you said gates open and close around 12x per 12 hours. So, with the operation under 60 minutes, you would not delay the functioning of the lock.
EX7	Yes, that is a good idea!
KK	So, let me ask you the main question. What would be an ideal system? What would you require?
EX7	Mobile, cleaning under 60 minutes, look at what kind of volume you need to clean. Maybe not a mechanical system but air pressure or booster pumps with water. Robots would be a bit to far since you have a relatively simple area to clean. The system should also know the situation before and after. Some kind of feeler which knows okay I have been here, there was this much silt, and this is the result. That is important for me. It needs to be transportable, preferably on a "cabinette". Not a big truck
KK	What is a "cabinnete"? Like a forklift?
EX7	No, preferably not a forklift that close to water. We have several cabinettes up to 3.5 tonnes with two cranes of 1.5 tonnes. A floating system would not be ideal since you need to load it in and out with boats. It could be floating if you could load it in and out without ships, so easy manoeuvrable from shore. So yeah, that would be best, something you could load and operate from shore. Furthermore, I want to leave the options open for you. From this conversation I'm also getting some ideas. Maybe a frame with some nozzles and pressure so you could agitate the silt. It needs to be very sturdy (strong) though. It is a hostile environment. It needs to be able to withstand brute force.
KK	Okay like swinging back and forth?

EX7	Yeah, or even a collision with a rolling gate. It will probably not survive anyway. So, something robust and maybe we accept that it will be destroyed, but then it needs to be easily replaceable.
KK	Okay, besides the robustness are there additional conditions I need to consider? For instance, temperature?
EX7	Temperatures are not really an issue, salinity is more an issue. We have a lot of problems with components submerged in the water (corrosion wise). Sometimes we need anodes. Another option would be stainless steel. However, it is even an issue with stainless steel (the low-quality kind) so then you would end up in the high (costly) quality kind
KK	I am also thinking it needs to be easily replaceable or at least components because you will have corrosion one way or another. Or maybe even a cleaning function so you can clean it after use with for instance fresh water.
EX7	Reality tells me we would not clean it after use. You do need to design it without cavities, so the water won't get stuck. You need holes so the water can escape or design an open system. Because you're thinking about a system that you will use as a tool?
KK	I was still in doubt between a mobile system or an integrated system. Maybe even a system for new locks since you have more design freedom, but the applicability would be very limited. So, what I can already conclude from this conversation is that the preference is a mobile system. I already suspected this since an integrated system would probably be submerged at all times resulting in issues. But as you mentioned temperatures are not an issue. What can you tell me about design life? You sent the mixers and airlifts. I believe the mixers had a design life of 15 years, which I find quite short?
EX7	15 years is quite normal for electromechanical systems
KK	I also believe you have to inspect the mixers once each year. Is this above water?
EX7	Yes, I will show you a picture.
NOTE	Expert 7 shows pictures of the mixers.
EX7	The mixer is installed on vertical rails so we can take the mixer out when we want to inspect it.
KK	I was thinking about PIANC, you probably know this, in which I found some dimensions of the gate recess. Do you have some more details? Because in PIANC I could only find the gate width, but nothing about the recesses?
EX7	Did I already send you this? On 18 September? Because right now I am doing the same as one the 18th of sept?
KK	No, we had no contact on the 18th?
EX7	Okay then I sent it to someone else. Let me check
KK	It is not important I have dimensions up to a centimetre; I will not use the dimensions of Antwerp 1 on 1. It is important I know that there are for instant differences in dimensions between the recesses.
EX7	How detailed do you want it?
KK	The width is not that important, I can deduct it approximately from the gate width from the PIANC. The depth is more important.
EX7	Great, I have that information for you. I will send it to you.
NOTE	Shows a drawing
EX7	This drawing shows which zones we wanted to clear. So that would be a good reference for you to clean. It also shows an area to be cleaned in the gate chamber (blue, not red. In the red area we have stairs etc). So ideally your system would also be applicable to the area in the gate chamber.
KK	During our first conversation you mentioned the silt in the gate chamber is not really a problem?
EX7	Not really, there is a lot more space in which the silt can be "stored", the gate recess is a relatively small area so that's why there are problems.
KK	I have a couple of more quick questions. I will share my screen. You sent me the underwater echo picture and I see a difference between the front of the gates. Is there a reason for this?
EX7	Good question, I got the same from the company who made the picture, but I have no idea why there is a difference. The gates are exactly the same. So, if you know what the reason is for the difference in the picture let me know.
KK	Then I have a question about how far the gate (the front) hangs above the rails? I want to know this for the to "clean" area. Because if the gate hangs above the rails I don't have to clean underneath the rails. Because then the gate will just slide across that layer. And if the gate hangs either 2 cm or 30 cm above the rails the "not to clean" layer will differ.
EX7	I understand. Let me look up some drawings.
NOTE	In the rest of the conversation Expert 7 shows me different drawings in which we try to find how far the gate hangs above the rails. In the beginning it is not quite clear what I mean but in the end we conclude the gate hangs a couple of centimetres above the rails, just above the ploughs. So, the ploughs could be seen as the lowest point to the rails. The lowest point of the gate is approximately collinear with the beam of the under carriage: 

	We end by saying he is more than happy to help. If I want to have a meeting I should you sent a proposal for a meeting via teams instead of a mail asking for a meeting.

Appendix B7: interview expert 8

Content	Interview with *expert 8* (Table 26), contact at a diving company, regarding the process of siltation removal underwater and the process of diving in the civil industry.
Attendees	K. Koets – interviewer (KK) | Expert 8– interviewee (EX8)
Date	8-11-2020 | 16:00-17:00 | Mobile phone call
Remarks	The interview was a mobile phone call. As a result, the interview was not recorded. The answers were written down during the interview. The interview was performed in Dutch. Subsequently, the interview was translated.

Table 26. Interview expert 8.

KK	What can you tell me about silt removal at locks?
EX8	The main thing they remove is growth of e.g. cockles and for that they sometimes use pneumatic gear to remove the growth from concrete. We also do a lot of inspections and cleaning with airlifts. We often use the airlift instead of a pump since a pump could get stuck. We then dump the silt just outside of the lock, which will be further removed by a dredging vessel. You must be aware to keep the silt under water, once it is above water you need to discard the silt (e.g. with trucks) which will result in additional efforts and costs
KK	What does the process of going underwater look like?
EX8	First, we have a conversation with the lock master, for our own safety. The lock master has to turn off all automatic features and controls. You could say everything needs to be done in an alert way. The lock master also needs to sign a declaration he will not touch any controls unless we say so. Then we always dive at the low water side of a lock. Which could mean that once we are done at the low side we go out of the water, the lock will level to change low water side and we enter the new low side to continue our work. This could be difficult with tidal locks since the low water side is also changing due to the tide. So, we watch this as well as the lock master.
KK	Why do you always need to stay on the low side?
EX8	You have height differences and with sea locks also tidal differences. Suppose there is a leak in a gate, or it doesn't close properly, the water pressure will result in a flow from high level to low level. By remaining on the low water side, the worst case is that you get blown away. Suppose you where on the high level, you would get sucked into the leak like you would be a plug for the leak. I believe in the last 10 years 5 divers died in The Netherlands, all while diving in locks. The difference in water pressure is really dangerous. In the best case you would get stuck and they could open a vent to equalize the water level to get you loose. But with tidal differences you cannot achieve this so it would mean you get stuck for a very long time. It could even mean you get pressed through the leak. That is why you ALWAYS dive at the low side.
KK	Okay so that is quite dangerous. Would that be one of the main disadvantages of diving at locks?
EX8	Yes, it is very dangerous and you should be aware of that. With respect to silt, you really need to think what you will do with the silt. As I said, once it is above water you cannot put it back into the water so you need to discard it. It is not directly our responsibility since we are the just performing the assignment. But the danger (also during normal inspections) is the main disadvantage
KK	So, on top of the "dive at the low side rule", are there additional safety protocols
EX8	Yes we always dive in teams of 3, that is according to the law. One is the actual diver in the water and the other 2 are above water. While you are diving you have an air supply (high pressure as backup and low pressure connected to a compressor and tank) connected to your helmet. Suppose something would go wrong while you have 2 divers in the water, they are still connected to the same air supply. You cannot share a helmet like you would do with a mouthpiece of normal diving. Meaning for the safety 2 divers in the water does not add something: you cannot really help each other. Per diver in the water, you have 2 people supporting above water. One is responsible for communication (diving time, air regulation, depth control etc). The second assisting in tasks. E.g. handing new welding electrodes, pulling a pump in a certain direction and more. In case of emergency the second person is also a backup diver.
KK	Is the backup diver already prepared in a suit?
EX8	No, but at sea he is. Then he is dressed in his suit with his helmet near by, this is according to law. In inland waters this is not obligated.
KK	Back to the silt removal, could you tell me more about this process?
EX8	So, I will tell you about different methods we use. I mentioned the airlift. That is a large metal tube connected to a compressor with a large volume. 10 cm above the bottom entrance you blow the air into the tube and due to the venturi effect you take water and silt, sand or other stuff with the flow. Under water we have a valve to open the airflow. This should be done slowly, otherwise the tube will fill with air at once and act like a floatation device. You want something that is easy to control
KK	Do you control this alone?
EX8	Depends on the size. Sometime a really large one is supported by a crane and the diver is there to guide the tube. The dive coordinator is in contact with the crane driver. So, if the diver says to the coordinator: move the tube 5 meters south, the coordinator will forward this to the crane driver to move the tube.

	But with regard to the airlift, an electrical pump is better suited for silt removal. The motor and pump are located on a floatation device. The suction hose runs to the bottom and is moved by the diver and this hose is easier to control. Sometimes when the hose is heavy someone helps to control it via rope from shore. The hose which secretes the silt could be aimed towards a different location in the water or to shore. Depending on the situation. We used this as well in Germany (Lingen) at a new lock under construction. These used some kind of polymer in the water. This would act like a bonding agent to silt, which would then sink with the silt to the bottom. We would suck this up with the pump into a porous container. The container would let the water run out, but retain the silt and polymer. This would then be later discarded once in a while I think.
KK	What does the floatation device look like?
EX8	I can only speak from experience. Our pump is a quite standard build with a motor that could go under water. We build a frame around it with left a right a plastic barrel (like an oil barrel) to provide floatation. It is a 14- or 16-kW pump I believe.
KK	Are there difficulties with sucking up the silt?
EX8	A pump could stop working, which is annoying but not a real problem or dangerous. When we are in the water, the lock cannot function. Meaning it would just take longer before the lock is back in function. It could be that a pump would get stuck. I once dropped the suction hose and it sucked itself 2 meters into the sand. Meaning I had to dig it out by hand under water, which did not go smoothly.
KK	Can a pump get stuck? Do you ever get a pump stuck?
EX8	Not really. There is a grate in front of the suction hose. If something does get stuck, you can turn of the pump to take it out of the hose. Then you can dump it a bucket if needed. Depends on the situation. In a lock chamber you cannot just throw it back on the bottom so then you place it in a bucket. Once the bucket is full, they pull it on shore and empty it.
KK	I know they also use high pressure washers to remove siltation. Are you familiar with this?
EX8	We have high pressure washers of around 300-1000 bar, but 1000 bar is more used to destroy concrete. Suppose we have to do a video inspection and we see a lot of growth (cockles etc) then we use the 300-bar pressure washer to clean. For siltation we would what we call a low-pressure washer, I don't know how much bar. It uses a large fire hose with a 14-kW pump. The hose also uses a retro thruster, which blows backwards and forwards, so it lays neutral underwater. So, we use that hose to blow away silt and upwards. The retro thruster then blows it away one more time when the silt settles down and thus it is transported. We use these often to clean slots and grooves etc.
KK	Are the hoses difficult to work with?
EX8	Sometimes they are difficult to direct, the hose is quite stiff and doesn't really bend. You could use second person to help direct the hose behind you.
KK	Is the hose also placed on a floating device?
EX8	No, it just lays on the bottom.
KK	And the pump?
EX8	The pump lays on shore. With a fire hose it is easy to reach places. The width of the lock determines the length of the hose. The pump is placed on a pallet and can be moved with a pallet cart. Maybe in Antwerp they have a fixed pump system. I can imagine that they want to remove the divers in Antwerp because a) it is expensive, b) it is dangerous and c) the lock is out of order. An hour of downtime can become expensive.
KK	How long does a normal cleaning operation take?
EX8	Totally depends on the operation. Something we often do is silt removal during the pouring of concrete. Once concrete enters the water is has a silt like consistency, but it is a bit thicker and heavier. So, the concrete pushes the silt away. However, in a corner the silt cannot be pushed away and you get silt inclusion. You can't have this since it will lower the strength of the concrete. So, before the concrete is poured we try to remove as many silt as possible. Then during the pouring we zigzag in front of the concrete "front" to remove the last silt. We suck this up. How long it takes is influenced by how large the project is etc. Also, for locks it depends. In my experience it never takes to long (video inspection), sometimes an hour. Depends on if we have to do 1 door, 2 or more.
KK	How long are you able to stay underwater?
EX8	There is not straight answer, depends on e.g. the depth. The absolute max is dictated by low for people working under pressure and that is 8 hours. However, normally you don't stay that long underwater. Especially in the cold you want to get out of the water after half an hour to an hour. Also, dehydration is an issue that makes you want to get out of the water. So often you dive for about 1.5 hour and then you get out.
KK	Earlier you also said you could communicate, how is this achieved?
EX8	The helmet is closed of and equipped with a microphone and speaker. Also, power for our head torch.
KK	I can imagine the torch is quite important. How is the vision underwater?
EX8	Really depends. For instance, in the canals in Amsterdam you sometimes have 2 meters vision. Which is a lot and is perfectly fine to work in. However, once you turn on the hose to remove silt the vision is reduced to 0. You cannot see anything at all. Sometimes you don't even see your own head torch.
KK	How do you get power for your equipment? Is there a power source or do you take a generator with you?
EX8	Both. In Lingen there was already a power source. They had a huge pump with suction hoses. Also, on construction sites there is often a power source. If we go to a lock, we communicate before if there is a three-phase power source. If not, we take a generator with us.
KK	How do you transport all this equipment?
EX8	We have a big MAN bus and also an Iveco truck with container on the back. We also have 8 ft and 10 ft sea container with build in equipment. For a long job these are brought by truck and they remain on the site until the job is complete.
KK	Regarding costs, how much would it cost to hire a team of divers?
EX8	Standard price, meaning we haven't done anything, is 300 euros for a team of 3 per hour. You have to pay for a minimum of 4 hours, so even if we have to do something for 10 minutes you pay for 4 hours. Then we also have call-out charges and costs

	for equipment. The standard price is just for the normal diving equipment. Silt pumps or pressure washers are all additional costs.
KK	Suppose I would design a system to remove the silt, meaning you won't have to go underwater, what would be important to you. What would make your job easier?
EX8	For a lock the important thing would be that it is user friendly. You would want to eliminate divers completely. If you still need 1 diver, you still need a full team of 3. The bill we sent remains the same, so I would be better to have somebody else operate the system e.g. from the municipality or the lock itself. Suppose you do keep the divers, then a system which makes it easier for the divers. Maybe the low-pressure washers connected to some kind or robot arm which moves with guidance on a rail. This way the diver only needs to control the operation. The use of camera's is not useful since the vision is zero once you start the siltation removal. Also be aware of debris, there are all kinds of debris at the bottom. Cans, pieces of wood and more.
KK	What about maintenance, is this also important to consider?
EX8	We have pumps in which a fan rotates in a cone to create suction. With sand and silt this will wear down, but is also designed to wear down. Furthermore, we also have maintenance to the motor and bearings. We don't do this ourselves, we send it away. So, you should keep in mind that parts need replacement.
KK	Do you also clean your equipment after a job, for instance after salt water?
EX8	Yes, after saltwater operations we clean everything with freshwater. Also, if we know we won't use the pump for a while we flush it with antifreeze to prevent rust.
KK	So, these are things I should also keep in mind for my system
EX8	Yes, is should be easy to maintain. For instance, pipes of stainless steel. Also have reservoirs with freshwater present so you can flush the pumps after use. You can connect the pump to such a reservoir and flush the water through the pump into the lock. Also, use antifreeze or something similar if you can, to prevent rust.

Appendix C: concept selection

Appendix C1: selection based on discussion and intuition

Table 27. First discussion regarding concept screening

Concept	Main arguments to discard concepts	Assessment
Advanced	- Complex system with multiple actuators and controls. - Permanently installed, meaning an individual complex system per gate recess. - Extensive contact (e.g. hydraulic and controls) with water, leading to increased maintenance. - Risk of oil leakage in water due to extensive contact with water. - Different design per gate since rolling gates differ per lock. Furthermore, the inside could be filled with e.g. structural members which significantly increase the complexity of realising the system.	Continued with alterations
Invisible	- Permanently submerged underwater, meaning complex maintenance. - Installation underneath the gate requires expensive drydocking. - Low movement speed of the gate result in low rotation speed of the sweepers unless e.g. gears are used. Which increase the complexity and required maintenance. - Constant contact between the wheels and the sill is difficult to maintain due to wear and external influences.	Discarded
Ingenious	- Heavy system actuated by a winch is fragile and susceptible to e.g. wind and waterflow. - Dependent on the weight of the system to go and stay down. - Different design per gate since rolling gates differ per lock. Furthermore, the inside could be filled with e.g. structural members which significantly increase the complexity of realising in the system. - Replacement of the winch by e.g. hydraulic rotary actuators is difficult due to large range of motion and high loads on the actuators due to the heavy system.	Discarded
Embedded	- Identical disadvantages as concept **ingenious.** - Main difference is reduction in complexity, however the weight is further increased due to the scoop and resulting forces of dragging the siltation out of the recess.	Discarded
Long	- Identical disadvantages as concept **ingenious** except the necessity to be customized per gate since the system is transportable from gate to gate. - Even though the system is transportable, due to the size transport and installation per cleaning operation is difficult.	Discarded
Submerged	- Permanently submerged underwater, meaning complex maintenance. - Limited range of motion due to available space and low movement speed of the gate (actuator) results in minimal loosening of the siltation. - Vulnerable to external influences. Blocking of the seesaw (debris) will obstruct gate movement.	Discarded

Appendix C2: selection criteria

Table 28. Selection criteria based on the primary needs.

Primary need = selection criteria	**Secondary need interpreted from interviews (grouped)**
Non-interference of lock function	The system can be used without divers The system is proactive The system can reduce the interval of large cleaning operations The system functions when the gate is not in the gate recess The system will not interrupt vessels The system will not interrupt the functioning of the gate The system will not take the lock out of function
Ease of use	The system is not labour intensive The system is simple to operate/control The system can be used frequently The system can be used frequently to prevent hardening of siltation
Maintainability	The system is rust resistant The system is easy to inspect The system is minimally exposed to water to prevent rust The system minimizes underwater components The system can be easily cleaned The system can be maintained easily
Ability to remove siltation	The system removes all siltation from the gate recess The system assures siltation transport is underwater The system can transport the siltation to the lock chamber
Ease of construction	The system is easy to replace The system can operate without vision The system is simple in construction
Mobility	The system can be used on multiple gate recesses The system preferably does not required boats The system is easy to transport
Reliability	The system can operate on external power sources if needed The system can function with small debris present The system is robust The system can withstand the surrounding environment
Costs	The system is relatively low cost The system is low in energy consumption The system has low operating costs

Appendix C3: concept scoring stage 1

Appendix C3.1: weight factors

Compared to → / Importance of ↓	Non-interference of lock function	Ease of use	Maintainability	Ability to remove siltation	Ease of construction	Mobility	Reliability	Costs	Score	Weight [%]
Non-interference of lock function		1	1	1	1	1	1	1	7	25
Ease of use	0		0	1	1	0	1	0	3	11
Maintainability	0	1		0	1	0	1	1	4	14
Ability to remove siltation	0	0	1		1	1	1	1	5	18
Ease of construction	0	0	0	0		0	1	1	2	7
Mobility	0	1	1	0	1		0	0	3	11
Reliability	0	0	0	0	0	1		1	2	7
Costs	0	1	0	0	0	1	0		2	7
							Total score		28	

Figure 58. Pairwise comparison matrix expert 3.

Compared to → / Importance of ↓	Non-interference of lock function	Ease of use	Maintainability	Ability to remove siltation	Ease of construction	Mobility	Reliability	Costs	Score	Weight [%]
Non-interference of lock function		1	1	1	1	1	1	1	7	25
Ease of use	0		0	1	1	1	0	1	4	14
Maintainability	0	1		1	1	1	0	1	5	18
Ability to remove siltation	0	0	0		1	1	0	1	3	11
Ease of construction	0	0	0	0		0	0	1	1	4
Mobility	0	0	0	0	1		0	0	1	4
Reliability	0	1	1	1	1	1		0	5	18
Costs	0	0	0	0	0	1	1		2	7
							Total score		28	

Figure 59. Pairwise comparison matrix expert 6.

Importance of ↓ / Compared to →	Non-interference of lock function	Ease of use	Maintainability	Ability to remove siltation	Ease of construction	Mobility	Reliability	Costs	Score	Weight [%]
Non-interference of lock function		1	1	0	0	1	0	1	4	14
Ease of use	0		0	0	1	0	1	1	3	11
Maintainability	0	1		0	1	0	0	1	3	11
Ability to remove siltation	1	1	1		1	1	1	0	6	21
Ease of construction	1	0	0	0		0	0	0	1	4
Mobility	0	1	1	0	1		1	1	5	18
Reliability	1	0	1	0	1	0		0	3	11
Costs	0	0	0	1	1	0	1		3	11
								Total score	28	

Figure 60. Pairwise comparison matrix expert 7.

Importance of ↓ / Compared to →	Non-interference of lock function	Ease of use	Maintainability	Ability to remove siltation	Ease of construction	Mobility	Reliability	Costs	Score	Weight [%]
Non-interference of lock function		1	1	1	1	1	1	1	7	25
Ease of use	0		0	0	0	1	1	1	3	11
Maintainability	0	1		1	1	1	0	1	5	18
Ability to remove siltation	0	1	0		1	1	0	1	4	14
Ease of construction	0	1	0	0		1	0	1	3	11
Mobility	0	0	0	0	0		0	1	1	4
Reliability	0	0	1	1	1	1		1	5	18
Costs	0	0	0	0	0	0	0		0	0
								Total score	28	

Figure 61. Pairwise comparison matrix expert 9.

Compared to → Importance of ↓	Non-interference of lock function	Ease of use	Maintainability	Ability to remove siltation	Ease of construction	Mobility	Reliability	Costs	Score	Weight [%]
Non-interference of lock function		1	1	0	1	1	0	1	5	18
Ease of use	0		1	0	1	1	0	1	4	14
Maintainability	0	0		0	1	1	0	1	3	11
Ability to remove siltation	1	1	1		1	1	1	1	7	25
Ease of construction	0	0	0	0		1	0	0	1	4
Mobility	0	0	0	0	0		0	0	0	0
Reliability	1	1	1	0	1	1		1	6	21
Costs	0	0	0	0	1	1	0		2	7
							Total score		28	

Figure 62. Pairwise comparison matrix expert 10.

	Expert 3	Expert 6	Expert 7	Expert 9	Expert 10	Mean	Median	Mode	Weight (mean)	Weight (median)	Standard deviation
Non-interference of lock function	7	7	4	7	5	6.0	7.0	7	21	25	1.4
Ease of use	3	4	3	3	4	3.4	3	3	12	11	0.5
Maintainability	4	5	3	5	3	4.0	4	5	14	14	1.0
Ability to remove siltation	5	3	6	4	7	5.0	5	N/A	18	18	1.6
Ease of construction	2	1	1	3	1	1.6	1	1	6	4	0.9
Mobility	3	1	5	1	0	2.0	1	1	7	4	2.0
Reliability	2	5	3	5	6	4.2	5	5	15	18	1.6
Costs	2	2	3	0	2	1.8	2	2	6	7	1.1
Total	28	28	28	28	28	28	28		100		

Figure 63. Summarizing table - weight factors.

Appendix C3.2: data concept scoring stage 1

Concept scoring S1		**Concept 1: Mobile**		**Concept 2: Quick**		**Concept 3: Simple**		**Concept 4: Exchangable**		
Selection criteria	Weight [%]	Score	Weighted score	Score	Weighted score	Score	Weighted score	Score	Weighted score	Ideal score
Non-interference of lock function	21	1	0.21	1	0.21	1	0.21	1	0.21	0.86
Ease of use	12	2	0.24	1	0.12	1	0.12	3	0.36	0.49
Maintainability	14	2	0.29	1	0.14	1	0.14	2	0.29	0.57
Ability to remove siltation	18	3	0.54	1	0.18	1	0.18	3	0.54	0.71
Ease of construction	6	3	0.17	1	0.06	2	0.11	2	0.11	0.23
Mobility	7	3	0.21	2	0.14	3	0.21	3	0.21	0.29
Reliability	15	3	0.45	1	0.15	2	0.30	2	0.30	0.60
Costs	6	3	0.19	2	0.13	2	0.13	3	0.19	0.26
	Total score	2.31		1.14		1.41		2.22		4.00
	Percentage	58		28		35		56		
Expert 3	Rank	1		4		3		2		

Figure 64. Concept scoring S1 matrix expert 3.

Concept scoring S1		**Concept 1: Mobile**		**Concept 2: Quick**		**Concept 3: Simple**		**Concept 4: Exchangable**		
Selection criteria	Weight [%]	Score	Weighted score	Score	Weighted score	Score	Weighted score	Score	Weighted score	Ideal score
Non-interference of lock function	21	4	0.86	4	0.86	4	0.86	4	0.86	0.86
Ease of use	12	2	0.24	2	0.24	2	0.24	4	0.49	0.49
Maintainability	14	1	0.14	1	0.14	1	0.14	3	0.43	0.57
Ability to remove siltation	18	2	0.36	4	0.71	2	0.36	2	0.36	0.71
Ease of construction	6	3	0.17	3	0.17	3	0.17	2	0.11	0.23
Mobility	7	2	0.14	2	0.14	2	0.14	2	0.14	0.29
Reliability	15	2	0.30	2	0.30	2	0.30	3	0.45	0.60
Costs	6	2	0.13	2	0.13	2	0.13	3	0.19	0.26
	Total score	2.34		2.70		2.34		3.03		4.00
	Percentage	59		68		59		76		
Expert 6	Rank	3		2		3		1		

Figure 65. Concept scoring S1 matrix expert 6.

Concept scoring S1		Concept 1: Mobile		Concept 2: Quick		Concept 3: Simple		Concept 4: Exchangable		
Selection criteria	Weight [%]	Score	Weighted score	Score	Weighted score	Score	Weighted score	Score	Weighted score	Ideal score
Non-interference of lock function	21	3	0.64	3	0.64	3	0.64	2	0.43	0.86
Ease of use	12	2	0.24	3	0.36	3	0.36	1	0.12	0.49
Maintainability	14	3	0.43	4	0.57	2	0.29	2	0.29	0.57
Ability to remove siltation	18	3	0.54	3	0.54	1	0.18	3	0.54	0.71
Ease of construction	6	1	0.06	3	0.17	2	0.11	1	0.06	0.23
Mobility	7	3	0.21	3	0.21	3	0.21	1	0.07	0.29
Reliability	15	2	0.30	3	0.45	2	0.30	2	0.30	0.60
Costs	6	1	0.06	3	0.19	2	0.13	2	0.13	0.26
	Total score	2.49		3.14		2.23		1.93		4.00
	Percentage	62		79		56		48		
Expert 7	Rank	2		1		3		4		

Figure 66. Concept scoring S1 matrix expert 7.

Concept scoring S1		Concept 1: Mobile		Concept 2: Quick		Concept 3: Simple		Concept 4: Exchangable		
Selection criteria	Weight [%]	Score	Weighted score	Score	Weighted score	Score	Weighted score	Score	Weighted score	Ideal score
Non-interference of lock function	21	4	0.86	4	0.86	4	0.86	4	0.86	0.86
Ease of use	12	3	0.36	3	0.36	2	0.24	1	0.12	0.49
Maintainability	14	2	0.29	3	0.43	1	0.14	1	0.14	0.57
Ability to remove siltation	18	3	0.54	2	0.36	2	0.36	3	0.54	0.71
Ease of construction	6	3	0.17	3	0.17	1	0.06	1	0.06	0.23
Mobility	7	3	0.21	3	0.21	3	0.21	2	0.14	0.29
Reliability	15	2	0.30	3	0.45	1	0.15	1	0.15	0.60
Costs	6	3	0.19	3	0.19	2	0.13	1	0.06	0.26
	Total score	2.92		3.04		2.15		2.07		4.00
	Percentage	73		76		54		52		
Expert 9	Rank	2		1		3		4		

Figure 67. Concept scoring S1 matrix expert 9.

Concept scoring S1		Concept 1: Mobile		Concept 2: Quick		Concept 3: Simple		Concept 4: Exchangable		
Selection criteria	Weight [%]	Score	Weighted score	Score	Weighted score	Score	Weighted score	Score	Weighted score	Ideal score
Non-interference of lock function	21	1	0.21	1	0.21	2	0.43	1	0.21	0.86
Ease of use	12	3	0.36	2	0.24	3	0.36	3	0.36	0.49
Maintainability	14	3	0.43	2	0.29	4	0.57	3	0.43	0.57
Ability to remove siltation	18	3	0.54	3	0.54	1	0.18	3	0.54	0.71
Ease of construction	6	3	0.17	3	0.17	3	0.17	3	0.17	0.23
Mobility	7	4	0.29	4	0.29	4	0.29	2	0.14	0.29
Reliability	15	2	0.30	2	0.30	3	0.45	2	0.30	0.60
Costs	6	2	0.13	2	0.13	2	0.13	3	0.19	0.26
	Total score	2.43		2.16		2.58		2.35		4.00
	Percentage	61		54		64		59		
Expert 10	Rank	2		4		1		3		

Figure 68. Concept scoring S1 expert 10.

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	2.5	2.25
Variance	0.666667	0.858974
Observations	40	40
Pearson Correlation	0.338837	
Hypothesized Mean Difference	0	
df	39	
t Stat	1.5711	
P(T<=t) one-tail	0.062119	
t Critical one-tail	1.684875	
P(T<=t) two-tail	0.124238	
t Critical two-tail	2.022691	

Figure 69. Results T-test concept scoring S1

Appendix E: dimensions scale model

Table 29. Dimensions scale model gate recess..

Scale: 1:16.25		
Description	Dimensions scale model [mm]	Real dimensions [mm]
A: length wall	1180	19180
B: height wall	845	13730
C: length gate recess	338	5500
D: length sill	700	11380
E: width gate recess and slot 1	80	1300
F: height gate recess	43	700
G: slot 3	185	3000
H: water level	550	8940
Slot 2	130	2112

Appendix F: concept scoring stage 2

Concept scoring S2		Expert 3				Expert 6				
		Concept 1		**Concept 2**		**Concept 1**		**Concept 2**		
Selection criteria	Weight [%]	Score	Weighted score	Score	Weighted score	Score	Weighted score	Score	Weighted score	Ideal score
Non-interference of lock function	21	3	0.64	2	0.43	3	0.64	3	0.64	0.86
Ease of use	12	4	0.49	2	0.24	3	0.36	3	0.36	0.49
Maintainability	14	4	0.57	2	0.29	3	0.43	2	0.29	0.57
Ability to remove siltation	18	1	0.18	4	0.71	1	0.18	3	0.54	0.71
Ease of construction	6	4	0.23	1	0.06	2	0.11	2	0.11	0.23
Mobility	7	3	0.21	1	0.07	3	0.21	1	0.07	0.29
Reliability	15	4	0.60	3	0.45	3	0.45	2	0.30	0.60
Costs	6	4	0.26	2	0.13	3	0.19	2	0.13	0.26
	Total score	3.18		2.38		2.59		2.44		4.00
	Percentage	79		59		65		61		
Expert 3 & Expert 6	Rank	1		2		1		2		

Figure 70. Concept scoring S2 matrix expert 3 and expert 6.

Concept scoring S2		Expert 7				Expert 9				
		Concept 1		**Concept 2**		**Concept 1**		**Concept 2**		
Selection criteria	Weight [%]	Score	Weighted score	Score	Weighted score	Score	Weighted score	Score	Weighted score	Ideal score
Non-interference of lock function	21	4	0.86	3	0.64	3	0.64	4	0.86	0.86
Ease of use	12	4	0.49	2	0.24	4	0.49	2	0.24	0.49
Maintainability	14	3	0.43	3	0.43	3	0.43	2	0.29	0.57
Ability to remove siltation	18	3	0.54	2	0.36	2	0.36	2	0.36	0.71
Ease of construction	6	4	0.23	2	0.11	3	0.17	2	0.11	0.23
Mobility	7	3	0.21	2	0.14	4	0.29	2	0.14	0.29
Reliability	15	3	0.45	3	0.45	2	0.30	3	0.45	0.60
Costs	6	3	0.19	2	0.13	3	0.19	2	0.13	0.26
	Total score	3.39		2.51		2.86		2.58		4.00
	Percentage	85		63		72		64		
Expert 7 & Expert 9	Rank	1		2		1		2		

Figure 71. Concept scoring S2 matrix expert 7 and expert 9.

Concept scoring S2		Expert 10			
		Concept 1		Concept 2	
Selection criteria	Weight [%]	Score	Weighted score	Score	Weighted score
Non-interference of lock function	21	1	0.21	1	0.21
Ease of use	12	3	0.36	2	0.24
Maintainability	14	2	0.29	2	0.29
Ability to remove siltation	18	4	0.71	3	0.54
Ease of construction	6	4	0.23	2	0.11
Mobility	7	4	0.29	4	0.29
Reliability	15	3	0.45	2	0.30
Costs	6	3	0.19	2	0.13
	Total score	2.74		2.11	
	Percentage	68		53	
Expert 10	Rank	1		2	

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	3.075	2.275
Variance	0.737820513	0.563461538
Observations	40	40
Pearson Correlation	-0.072575621	
Hypothesized Mean Difference	0	
df	39	
t Stat	4.284033284	
P(T<=t) one-tail	5.80364E-05	
t Critical one-tail	1.684875122	
P(T<=t) two-tail	0.000116073	
t Critical two-tail	2.02269092	

Figure 72. Concept scoring S2 matrix expert 10 (left), results T-test concept scoring S2 (right).