Standardization of mitre gates

Standardizing steel mitre gates within existing navigation locks in the Netherlands

Illustration of steel mitre gates

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September, 2018

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Master Thesis report
September 2018

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Acknowledgements

By writing these acknowledgements, I am finalizing my master thesis. Writing this thesis was a challenging journey and could not have been done without the help of my graduation committee. Each member of the committee managed to help me in their own way and I would hereby like to thank them individually.

Firstly I would like to thank Sander van Alphen and Jos Vorstenbosch (Movares & Rijkswaterstaat) for helping me out on the technical in depth problems encountered during my thesis. Both were great sparring partners for who I could seek out for help whenever I felt was necessary.

Secondly I would like to thank Erik-Jan Houwing and Mark Voorendt for helping me structure my research. Both have motivated me and guided me through the different stages of my research, continuously reviewing and helping me to improve my work.

Finally, I thank thank Bas Jonkman for his broad perspective and feedback during the committee meetings.

Marc Levinson

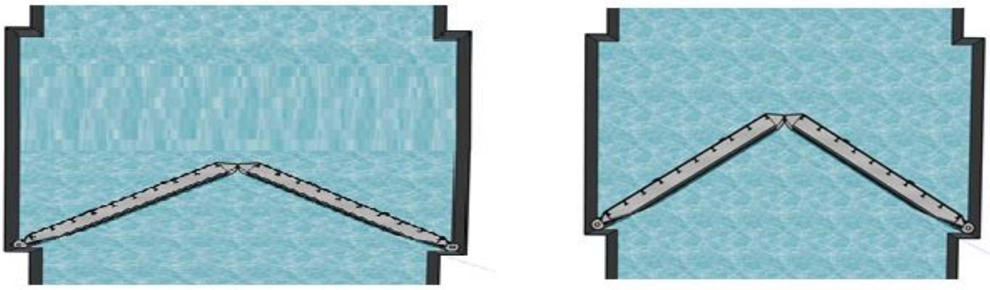
Summary

The Dutch Ministry of Infrastructure and Water Management (Rijkswaterstaat) currently manages 137 navigation locks. Most of them have been constructed during the 20st century and were considered as unique projects. This led to a great variety in their designs and characteristics. Currently, 52 locks are reaching the end of their technical life span and require significant renovation and renewal.

Almost all locks are different and this variety complicates their management and maintenance. These complications cause several problems concerning sub-optimal availability, unpredictable reliability and high life cycle costs. Rijkswaterstaat performed several studies, indicating that the standardization of lock gates could potentially solve these problems. However, how to standardize these lock gates is still unclear. This research investigates the standardization possibilities with the aim of reducing the variety found in lock gates, focusing on the mitre gates present in 37 of the 52 locks requiring large renovation and renewal. Focus is put on mitre gates as these are the most common gate type used in Dutch navigation locks.

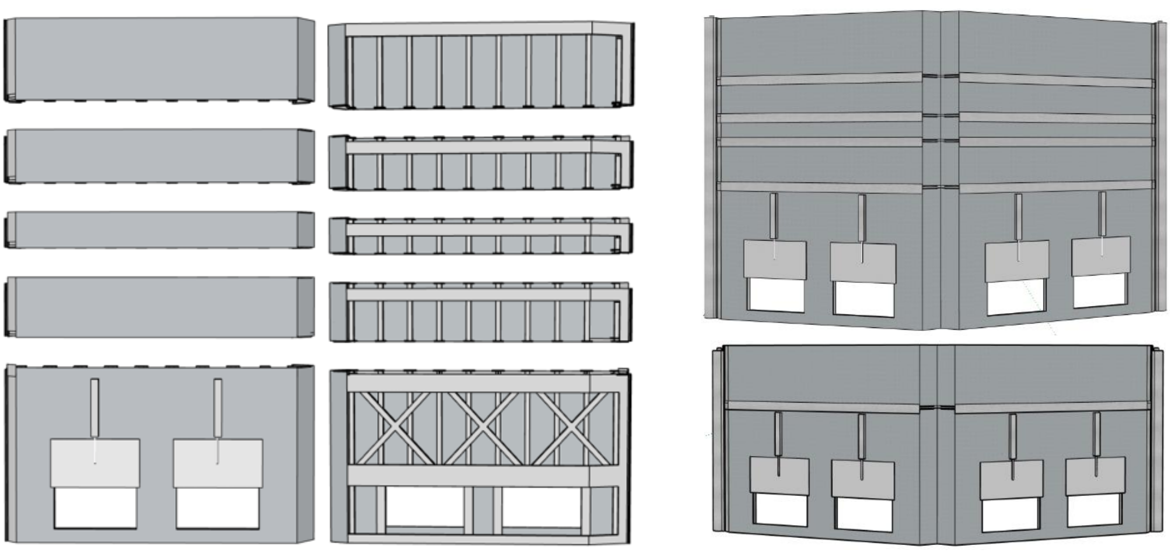
The approach of reducing the variety in the lock gates is based on the creation of clusters, in which one standardized gate is applied. The clustering of the mitre gates is based on the widths and required door heights of the considered locks.

To tackle the problem of standardizing gates in locks with different widths, it has been decided to vary their angle of closure. The degree to which the angle of closure can vary is dictated by physical boundaries, indicating the limit with respect to stability requirements.



Lock gate placed in locks with different widths by changing the angle of closure

Consequently it was chosen to modularize the doors so that they can be scaled up or down to the desired height, solving the problem of applying a standard door in locks with different retention heights.



Left: Conceptual design of a modular door (front and back) Right: Possible module combinations for different gate heights

To grasp the effects of standardization, the over-dimensioning is approximated by using estimates for the amount of material required for the gates. To determine the optimum cluster configurations, a clustering program has been developed, taking into account both over-dimensioning and physical boundaries.

The clustering program encompasses the study of 37 locks. This study shows that the gates of these locks can be grouped into a minimum of five clusters. Due to a modular gate design and fewer spare components, excessive over-dimensioning is prevented. A conceptual design and a comparative analysis indicated that the gates can best be grouped into eight clusters, potentially leading to improved management and a € 7.100.000 cost reduction.

This research included several assumptions and starting points. The following steps should be taken in order to deepen and enhance the current research:

- Assess the influence of the determining aspects on the **costs** of a lock gate instead of the material required.
- Better approximation of over-dimensioning by using a more complex and accurate model for the estimation of the required material.
- Perform a study on the amount of spare components required for each separate gate cluster.

Table of Contents

1 Introduction

This chapter introduces the topic of this report by first addressing the importance and functioning of Dutch river locks, and their current situation. The gate components are addressed, with attention to their dependencies.

1.1 Motivation of research

Research on the standardization of navigation locks has indicated that standardization has great potential for improving reliability, availability and life cycle costs. The optimal application of standardization for Dutch locks is yet unknown and is still to be discovered.

1.2 Background information

The Netherlands are known as the Waterlands and it has this name for a reason. About 18% of the country's area consists of water, while 26% of the land is situated below mean sea level and a total of 59% of the land is susceptible to flooding (Leefomgeving, 2017).

Apart from the dangers and damages brought by the water, water has been a very close ally and forms a crucial component to the national economy. The Port of Rotterdam and the Port of Amsterdam are Europe's largest and fourth largest ports respectively and have a combined European market share of 45,6% (Havenbedrijf Rotterdam, 2018). The main function of these ports is to act as large transport hubs, where cargo is handled from one transportation mode onto another. The modal split of a port indicates how the different transport modes (sea transport, inland waterways, rail and road) relate to each other. The current modal split for the container terminal Maasvlakte 2 of the port of Rotterdam indicates that 70% of the incoming container continue their journey to the hinterland. From here 47% is transported by road, 40% by inland waterways and 13% by rail. Due to environmental concerns the port aims to decrease the traffic by road and therefore increasing the traffic by inland water ways and rail .Due to the increasing demand on the usage, the provision of sufficient inland water ways capacity is key. The Dutch waterways have a total combined length of 6257 km, of which the main transport waterways cover 1448 km (Centraal Bureau voor Statistiek, 2017). The connection with the sea and areas with different elevations can cause several complications for navigation and call for the implementation of hydraulic structures. A navigation lock with a water leveling system is the most common type of structure enabling navigation over elevation differences and is the only type applied for that purpose in the Netherlands. The Netherlands counts a total of 250 of these structures, with 137 under the management of Rijkswaterstaat. Fifty-two of the locks that are under the management of Rijkswaterstaat are attaining the end of their life cycle as these were built around 90 years ago (Multiwaterwerk, 2015) . The aging and outdated locks slowly start to fail to the capacity requirements and are reaching the end of their life cycle. These locks require a vast number of operations to conform once again to their functional requirements and extend their life cycle. Figure 1 shows two lock gates severely requiring maintenance, being at the end of the life time or not conforming to their requirements with regard to water retention.

Figure 1: Two lock gates at exceeded life time and in need of maintenance and renovation: Left: seepage through centre seal between mitre gate doors. Right: corrosion leading to overall seepage (Buildiww, 2018)

Most of the locks which were built around the 1930s were designed separately by different parties using different design methods and techniques which lead to a large variety of locks. Apart from the interesting aspect of having such a diverse lock portfolio, this approach also lead to several difficulties. The absence of a certain uniformity in the designs often causes problems guaranteeing the reliability and the availability of the locks. Many replacement components have to be held aside and the knowledge of all the individual systems had to be maintained. The project Multi Water Works (MWW) has been initiated to investigate the approach for the renovation methods for the 52 locks. It aims at the determination and implementation of re-design, adaptation, renovation construction and management of its locks. The goal of MWW is to obtain a better reliability and availability, lower Life Cycle Costs and a more predictable estimation of the construction cost and time (Multiwaterwerk, 2015).
The main approach for MWW to achieve its goals is by performing a standardization research for its lock arsenal. Creating standards for the locks has several advantages and disadvantages. The required material would for instance increase due to an overall increase in robustness, leading to higher material usage. However, standardization also has the potential to enable economies of scale, resulting in lower cost decrease (Verslag, 2000). The evaluation and quantification of the interplay between the pros and cons of standardization is crucial in the decision-making of what to standardize and what not.

1.3 Navigation locks

This section gives a brief explanation on how navigation locks work, which elements they consist of and what variety can be found amongst them.

In order for vessels to move upstream to waters with a higher elevation level, the downstream gate of a lock is opened such that the vessels can navigate into the lock chamber. The upstream gate is closed in order to retain the high upstream water level.

Once the vessel is in the lock chamber, the downstream gate closes such that the it finds itself in an enclosed basin between two closed gates. By allowing water to flow into the closed basin the water level increases up to the desired level.

When the water level reaches the same height as the upstream water level the upstream gate can be opened and the vessel can sail out of the lock. In case a vessel is moving downstream the same process takes place but then the other way around.

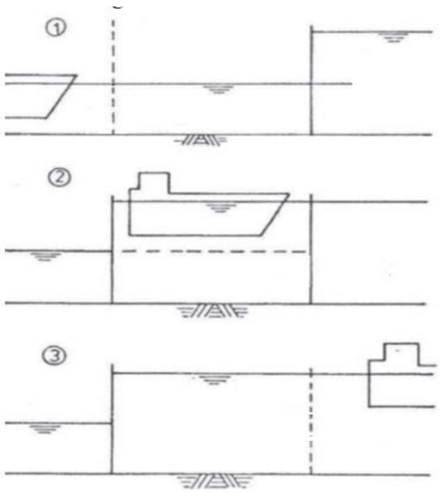


Figure 2: Process of leveling vessels (Molenaar, 2011)

A navigation lock generally consists of the following components:

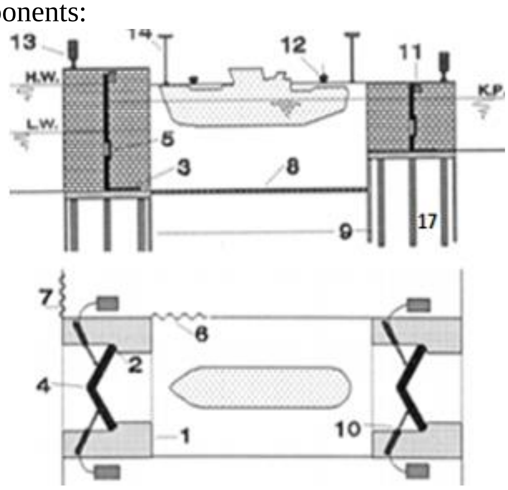


Figure 3: Lock components (Van der Toorn, 1993)

1) Upper and lower heads
2) Turing points (pivots and collar)
3) Stop
4) Gates
5) Means of leveling
6) Lock walls
7) Bank protection
8) Bottom protection
9) Cut-off walls
10) Movement mechanism gates
11) Movement mechanism leveling system
12) Bollard recess and bollards
13) Navigational signals
14) Lighting
15) Control panel
16) Lock control room
17) Lock foundations and earth works

Even though navigation locks often contain the same elements and functionalities, they may vary greatly from one another. Figure 4 illustrates a small navigation lock in an English canal, in use for recreational navigation having a width of approximately 4m. On the right one of the largest locks to be built is shown, namely the "Nieuwe Zeesluis" in IJmuiden. This lock will only be in use for commercial shipping and will have a width of 70m.

Figure 4:Left: Small lock in recreational water way. Right: Large sea lock in commercial water

Figure 4 illutrates the designers' choice for these components may vary greatly from lock to lock. This choice mainly depends on the boundary conditions and functional requirements of the lock.

1.4 The project Multi Water Works (MMW)

MWW has been set up with the objective to increase the reliability and availability, decrease the life cycle costs and reduce the uncertainties in construction time and costs of navigation locks. To reach these objectives the approach of MWW comprises of three elements: research, development and implementation.

The research phase: studies the feasibility of standardization for the locks in order for MWW to achieve its goals: lower life cycle costs, higher availability and reliability, better estimation of construction time and costs. This phase has already been completed and several reports have been composed.

1.4.1 Research

In the following section three research reports are discussed.

- *Assessment lock elements*

Recently IV-Infra b.v. conducted a research into which lock elements relate best to the specific MWW goals. The research consisted of a data analysis and the collection and evaluation of expert opinions. Unfortunately due to an insignificant amount of data no proper data analysis could take place, therefore the report is entirely based on expert opinions. The collection of the expert opinions took place according to the Roger Cooke method, where each opinion is calibrated with respect to the knowledge of the expert on the specific component. The MWW goals were divided into four different sub-goals. All lock components have been assessed with respect to these sub-goals and the ones that have the largest influence per sub-goal are listed below (Markus, 2015):

1. Reduction uncertainty construction costs
   - Foundation
   - Lock head
   - Lock chamber walls
   - Culverts
2. Reduction uncertainty construction time
   - Foundation
   - Lock head
   - Lock chamber floor
3. Reduction Life Cycle Costs
   - Gates
4. Increase Reliability and Availability
   - Energy supply
   - Drive mechanisms gates

- *Standardization in river locks*

In 2013 the student Slijk investigated what objects, elements or parts of a river lock are most suitable for standardization, based on financial benefits. Slijk figured that in order to quantitatively assess the financial benefit of standardizing the various components, it would be important to split up their costs into various cost types. Argument has been made that different cost types behave differently towards the potential financial benefits of standardization. He came up with the following financial dependencies:

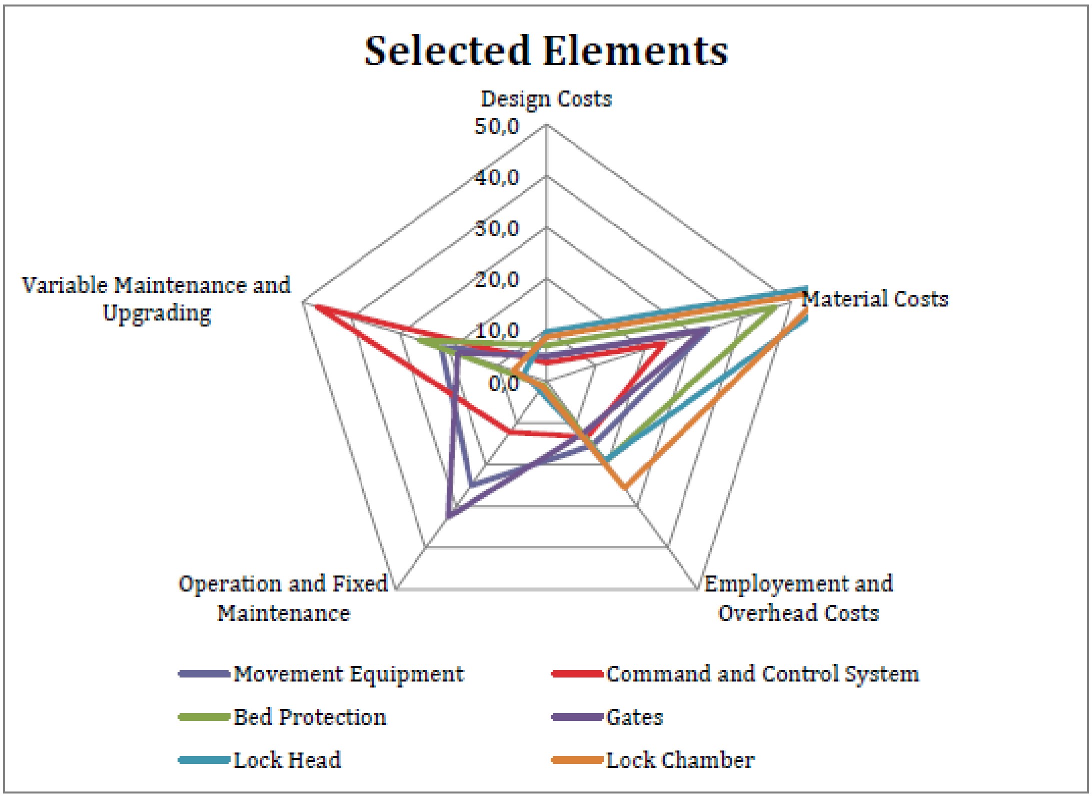


Figure 5: Cost type distribution per component (Slijk, 2013)

Slijk argued that standardization would have a different impact per cost type. For instance, standardization has a much lower impact on the material costs for a component than for the maintenance costs.

Having estimated the various costs for the elements and how these relate to standardization, R. Slijk ranked the components according to their suitability for standardization. Figure 6 illustrates the final result of his thesis, indicating the elements that are most suitable for standardization on the left side of the standardization spectrum.

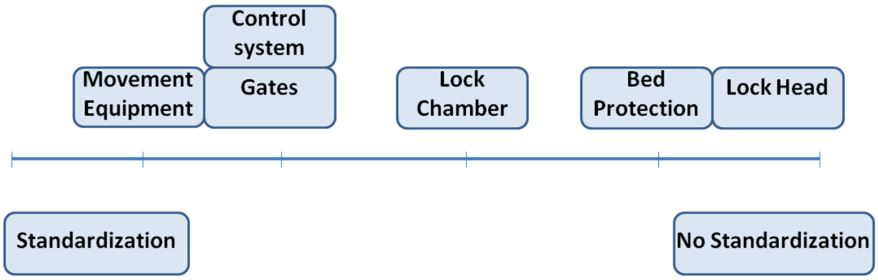


Figure 6: Scale of most suitable elements for standardization (Slijk, 2013)

- *Modularization and standardization of navigation locks in the Netherlands*

T. Wilschut from TU Eindhoven identified 72 lock components by studying the entire lock arsenal of Rijkswaterstaat. A modularity investigation of the lock components was performed with the application of the Dependency Structure Matrix technique to see how these components relate to one another. Once the dependencies between the different components became clear, each dependency was evaluated with regard to their effect on the locks' life cycle costs and reliability and availability. The dependencies were quantified accordingly using expert opinions.

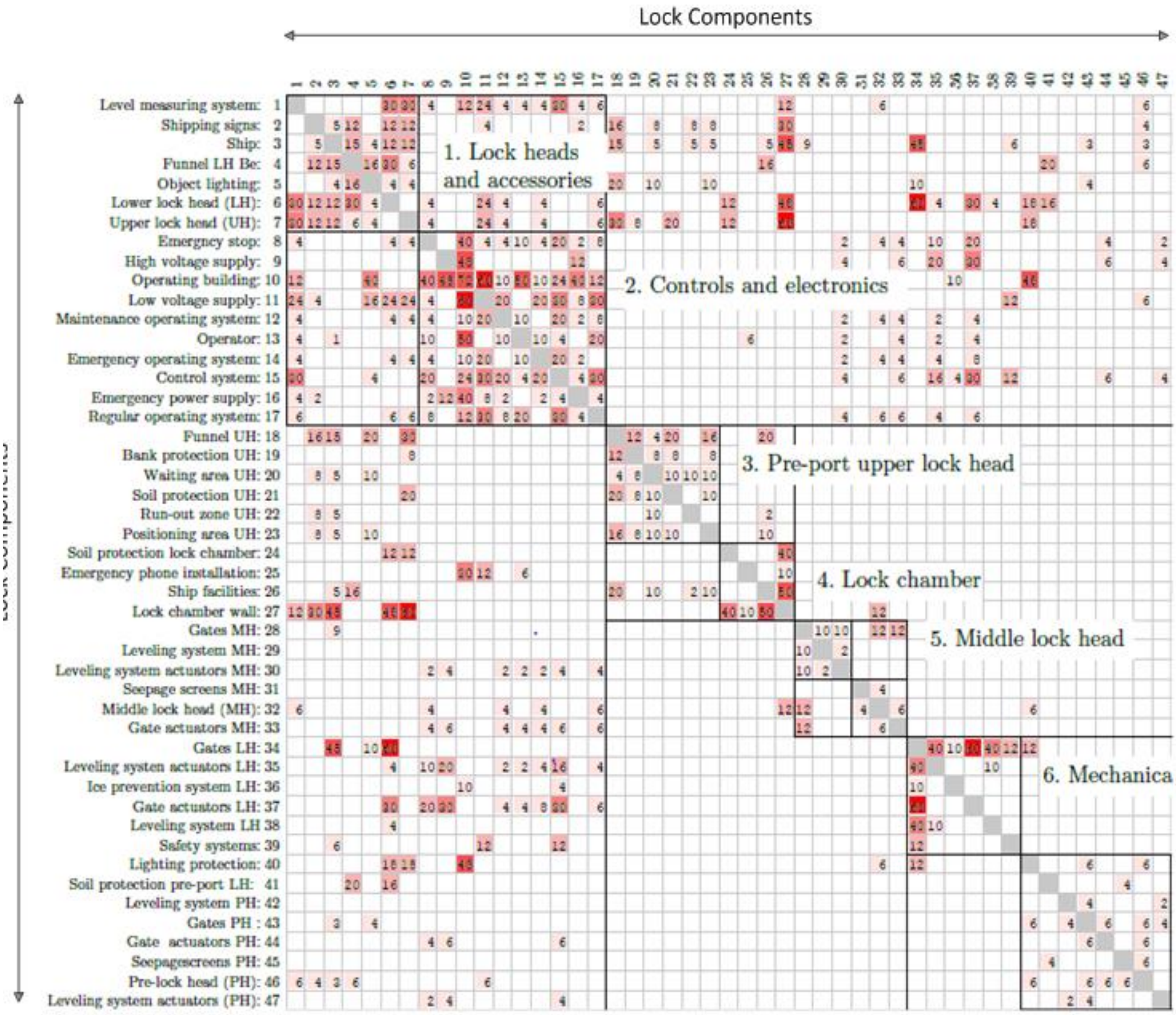


Table 1:Part of the Availability projection matrix (Wilschut, 2017)

Table 1 shows one of Wilschut's matrices, namely the Availability Projection Matrix. In this matrix the components are numbered and the y and x axis are identical, with the same list of components. The dependency between two components occurs when their axis meet, so cell 34:6 defines the dependency between the lower head lock gates and the lower lock head. If there is a dependence the cell is given a color and a grade. The grade is given accordingly to the significance the dependency has on the availability of the lock.

From this availability projection matrix it can be concluded that the controls and electronics, the gates, the gate actuators and the lock chamber walls have the biggest impact concerning the availability of the lock.

It is interesting to note that the lock chamber walls have not been identified in the previous two research reports. Wilschut managed to include the uncommon occurrence of an exceedance of bollard forces caused by the leveling the vessel in the locks. If the allowed bollard forces are exceeded the bollard can be pulled out of the lock chamber wall, leading to notable damages and very time consuming repairs. Even though this event has a relatively low occurrence, its consequences are very significant.

After the assembly of several of these matrices, namely one for the availability, reliability, construction, maintenance, renovation and life cycle costs (combination of the construction, maintenance and renovation costs) Wilschut finally concludes that:

- Mechanical components and lock gates of both upper and lower heads (Cluster 6 and 9) have great potential for standardization as these contribute significantly to the life cycle costs and the availability and reliability of the lock.
- Control and electrical components (Cluster 6 and 9) have high impact on the reliability and renovation costs of a lock. However, full standardization may not be beneficial due to the fast developments within the electronica industry and the new standard may soon be outdated.
- Standardization of the major civil components (Cluster 1 and 4) can increase the efficiency of the construction process and reduce the construction costs. It can also help to prevent (re)occurring construction errors that have a big impact on the construction costs and construction time

(Wilschut, 2017)

1.4.1.1 Conclusion of previous research

This section has covered the three research reports conducted in the assignment of MWW. Although the approach of each of these reports strongly differs the conclusions are very similar.
From these three investigations the conclusion can be drawn that the gates and mechanical components have a large impact on the life cycle costs, reliability and availability of the lock and that these components are very suitable for standardization. Therefore, these components match the wishes of MWW best, namely increasing the availability, reliability and LCC's of a lock through the implementation of standardization. This research will focus on the lock gates and will briefly address the drive mechanisms as part of the entire closure system.

1.5 Lock gate arsenal

The MWW locks are situated all across the country, in various navigation corridors. Figure 8 gives the approximate locations of the locks.
Appendix A gives the complete list of the MWW locks along with their characteristics and exact locations. Focusing on the gates it is found that mitre gates are the most common gate type followed by vertical lift gates and rolling gates, see Figure 7. Appendix B includes more information about these gate types, the choice of material and the mechanisms that drive the gates.

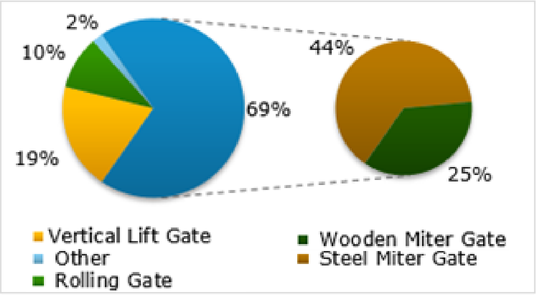


Figure 7: Gate type distribution

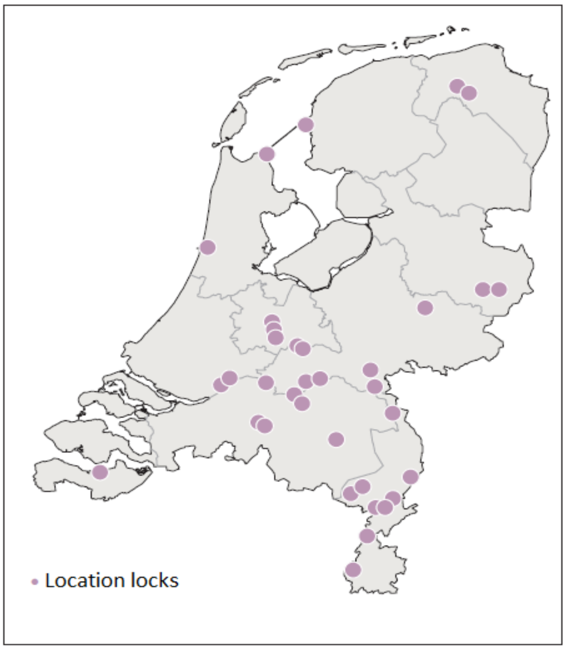


Figure 8: Location MWW locks (Van Erp, 2017)

2 Research description

This chapter clarifies the problem definition of this research. Several sub-research questions have been set up in an attempt to answer the main research question and find a solution to the problem.

2.1 Problem definition

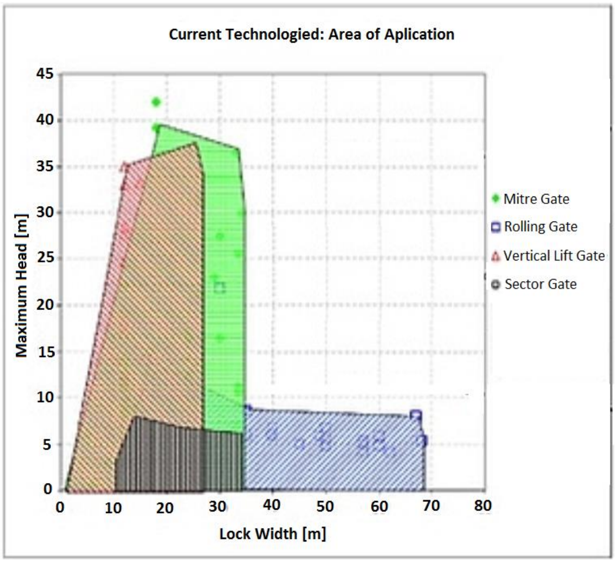
There is a very large variety in the design of navigation locks within the Netherlands. This variety hugely complicates their management and maintenance leading to a sub-optimal availability, reliability and life cycle costs. From recent studies it appears that the standardization of lock gates has great potential in optimizing the locks' availability and life cycle costs. However, how to apply this standardization and exploit its potential is still unknown.

2.2 Scope

This section briefly discusses the gate type, material, pivot system and load transfer considered in this research, leading to a reduced scope of the main research question.

2.2.1 Gate type

In 2012 Jan Doeksen performed a research into the applicability of four different lock gates types. Doeksen considered the applicability of these gates by addressing their presence in locks with various widths and retention heights. By studying a wide range of existing projects he collected the data of all these locks and put them into a plot shown on the left in Figure 12.



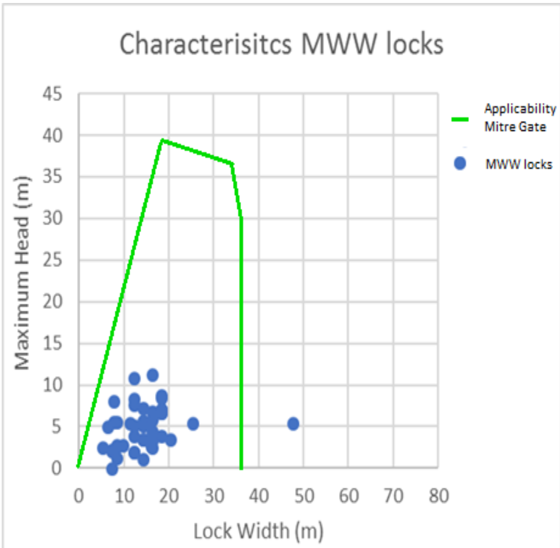


Figure 9: Left: Area of Application of Gate Types (Doeksen, 2012); Right: Positioning of MWW locks

Using the lock data from Appendix A, the MWW locks can be positioned in the very same plot. From the right plot of Figure 9 it can be noticed that, based on the two variables lock width & maximum head, almost all MWW locks fall under the applicability curve of mitre gates and vertical lift gates. Considering the wide applicability range of mitre gates and the large presence this type of closure has in the Dutch waterways, it is chosen to focus this research on the standardization of this specific gate type. Due to the fact that vertical lift gates and rolling gates are usually only applied when mitre gates cannot, this research does not consider the locks containing either of these. This leaves us with not 52 locks for which the gates have to be standardized with mitre gates but 37.

2.2.2 Material

There are various materials that can be used for the design of a mitre gate, the conventional steel and wood and the upcoming composite and concrete gates. Steel is found to be the governing material as can be seen Figure 7. This is due to the fact that it can be applied for all lock widths whereas wood has a limit due to its lack of strength and ability to withstand large loads. Due to the wider range of applicability of steel, this research limits itself to steel mitre gates. Figure 10 illustrates the distribution of the materials used in the mitre gates of the MWW locks. It is assumed that all gates in Figure 10 hold the same design principles.

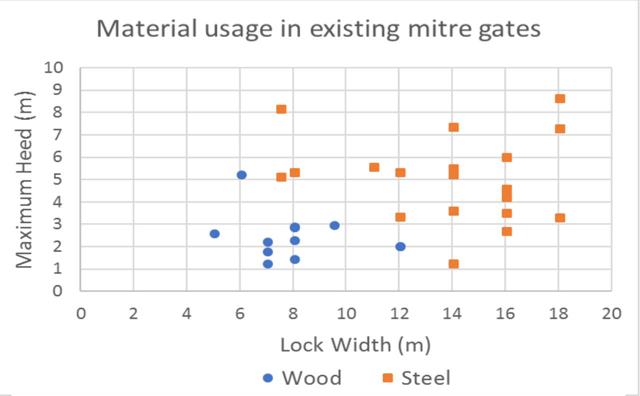


Figure 10: Material distribution of lock width and maximum head

2.2.3 Pivots

A crucial component of mitre gates are the pivots. There are two main types of pivots, pivots with clearance and pivots without clearance. The choice of pivots with or without clearance has a large impact on the sealing mechanism and load transfer of the gate.

When closed and under hydrostatic pressure, pivots with clearance enable the doors to be pushed against the lock head over the entire height of the door, sealing off the space in-between and relieving the pivots. The occurring load transfer in the doors is mainly horizontally towards the lock head.

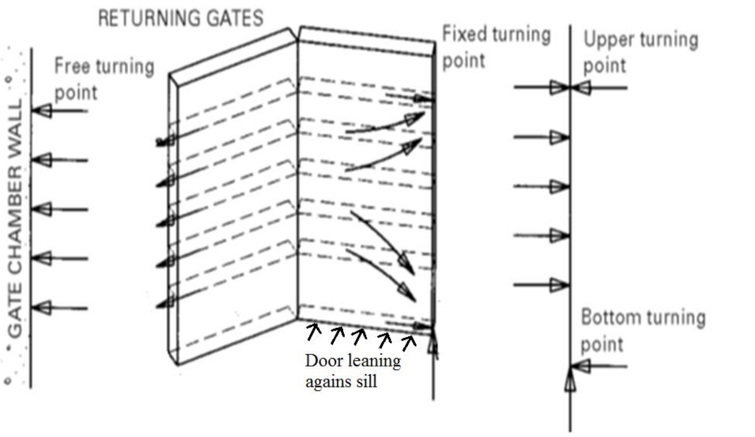


Figure 11: Load transfer in doors with varying pivot mechanism; Left: With clearance; Right: Without clearance (Vrijburcht, 2000)

In case of pivots without clearance, the loads are fully conveyed and concentrated on the pivots. To seal off the space between the doors and the lock head additional measures are required. To relieve the pivots it is possible to calibrate the sill such that the doors lean against it, acting as a distributed support along the bottom of the door. In this case the load transfer in the doors is both horizontal as vertical. The load transfer in the doors when supported with pivots with clearance (left) or without clearance (right) is illustrated in Figure 11.

This load transfer has a significant impact on the design of the doors and direction of the main girders. Figure 12 illustrates the direction of the main girders corresponding pivot types.

Figure 12: Left: Doors with main horizontal girders and pivots with clearance; Right: Doors with main vertical girders and pivots without clearance (Gibson, 2002)

A mayor disadvantage of pivots without clearance is the complexity in sealing off the space between the doors and the lock heads and the sill. The additional measures to ensure proper sealing increase the vulnerability to sedimentation and obstacles, disabling proper closure of the gates. Another setback is that doors supported by pivots with clearance are less labor intensive to install and require less maintenance (Vrijburcht, 2000). However, the vertical load transfer does have the benefit of enabling mitre gates to locks with larger widths as the distributed support along the sill helps to reduce the large bending moments in the doors. From the theoretical background on the pivot system it is clear that the loose pivots containing clearance are more practical concerning installation, and the visions of MWW.

To summarize:
This report considers the standardization of mitre gates with steel gates, suspended by pivots with clearance resulting in main horizontal load transfer through the doors.

2.3 Research questions

Main question:
How to standardize the MWW navigation lock gates with steel mitre gates to reduce their variability?

RQ1: What design determining aspects should the standardization of the lock gates be based on?

To determine how to apply standardization amongst the MWW locks it is initially important to understand why the locks differ from one another. Lock gates, like any functional structure, are designed to conform to certain functional requirements and boundary conditions, these can be seen as the design determining aspects. For each lock, the design determining aspects are different, hence the wide range of different structures. This research question aims at exploring the aspects that determine the design of a lock gate and evaluate their relevance to this research.

RQ2: What standardization method could be applied amongst the MWW lock gates?

Standardization comes in many forms and there are several ways to adapt a standardization method. This question aims at determining the most feasible method for standardizing the MWW lock gates.

RQ3: What are the structural effects and physical boundaries of the standardization method?

When standardizing, it is often inevitable that a certain degree of over-dimensioning occurs. How much over-dimensioning is unknown and must be investigated. Along with the over-dimensioning there might also be physical limitation to the chosen standardization method. It is crucial to determine the degree of over-dimensioning and the physical boundaries to investigate its feasibility.

RQ4: How does the standardization method relate to the clustering of the lock gates with regard to over-dimensioning, physical boundaries and variety reduction?

Based on the over-dimensioning and physical boundaries, the MMW locks can be clustered into categories for which a standardized gate can be applied.

RQ5: What would the design of a standardized mitre gate door look like?

This question focusses on the practicality to this rather theoretical research, considering the design and implementation of standardized lock gates. An attempt is made to include the main components of a lock gate and figure out how these would fit in the design of a standardized gate.

RQ6: How does the standardization/clustering of the lock gates compare to the situation where no standardization/clustering is applied?

The answering of the previous research questions results in a certain standardization strategy. This question aims at comparing this strategy to the case where no standardization would be applied. Comparing the cases should reveal which approach is most suitable for the renovation of the lock gates considering the MWW goals of improving the life cycle costs, availability and reliability.

2.4 Method

This section shortly explains the approach used to answering the various sub-questions.

RQ1: What aspects should the standardization be based on?

To answer this question a literature study is done. This study reveals which boundary conditions and functional requirements play a role in the geometry of the gate and loads acting upon it. Consequently the aspects will be classified as significant or non-significant for this research by evaluating their degree of influence on the dimensioning of a lock gate, with focus on the use of material. This classification takes place in a quantitative or qualitative manner.

RQ2: What standardization method could be applied amongst the MWW lock gates?

First the MWW goals are assessed along with a theoretical solution how these could be achieved through standardization. From here starting points will be set up, providing a basis for the determination of the standardization method. Based on the most significant design determining aspects and starting points, suitable standardization methods are determined.

RQ3: What are the structural effects and physical boundaries of the standardization method?

Structural calculations are performed to compute the effects and limitations of standardization. Concerning the over-dimensioning, the help of a finite element software SCIA Engineer is used. This software is used to estimate required amount of material needed in the design of mitre gates. Comparing the estimated amount of material needed the over-dimensioning can be determined. Because of initial unfamiliarity with the software, hand calculations are provided as a check.

RQ4: How does the standardization method relate to the clustering of the lock gates with regard to over-dimensioning and the physical boundaries?

Once the structural effects and limitations of standardization are known, these can be linked to the data for the MWW locks in order to create feasible, standardized lock gate clusters. Due to the complexity around the standardization possibilities a program is made to determine the optimal clustering of the lock gates based variety reduction and over-dimensioning.

RQ5: What would the design of a standardized mitre gate door like?

From the determined clusters, one cluster will be chosen to serve as an example of how the design of a lock gate can be determined for a range of locks with different dimensions. Initially the main questions around the conceptual design are listed followed by the setup of starting points which are to be taken into account. Treating the main characteristics of a mitre gate it's *conceptual* design is determined one step at a time. The design principles developed during the conceptual design of the gate within one cluster are assumed to hold for all other clusters.

RQ6: How does the chosen standardization strategy compare to the situation where no standardization is applied?

Having determined certain standardized cluster configurations and design principles for the lock gates, a comparison is made between the case for which standardization is applied and for which it isn't. For comparison, a direct building cost estimation is made, this estimation will be based on the figures and values supplied by interviewing senior cost advisors working for the Ministry of Infrastructure and Water Management. Finally, the effects standardization has on the availability and reliability are discussed.

Figure 13 illustrates the dependencies between the research questions and the chapters to come by means of a flowchart:

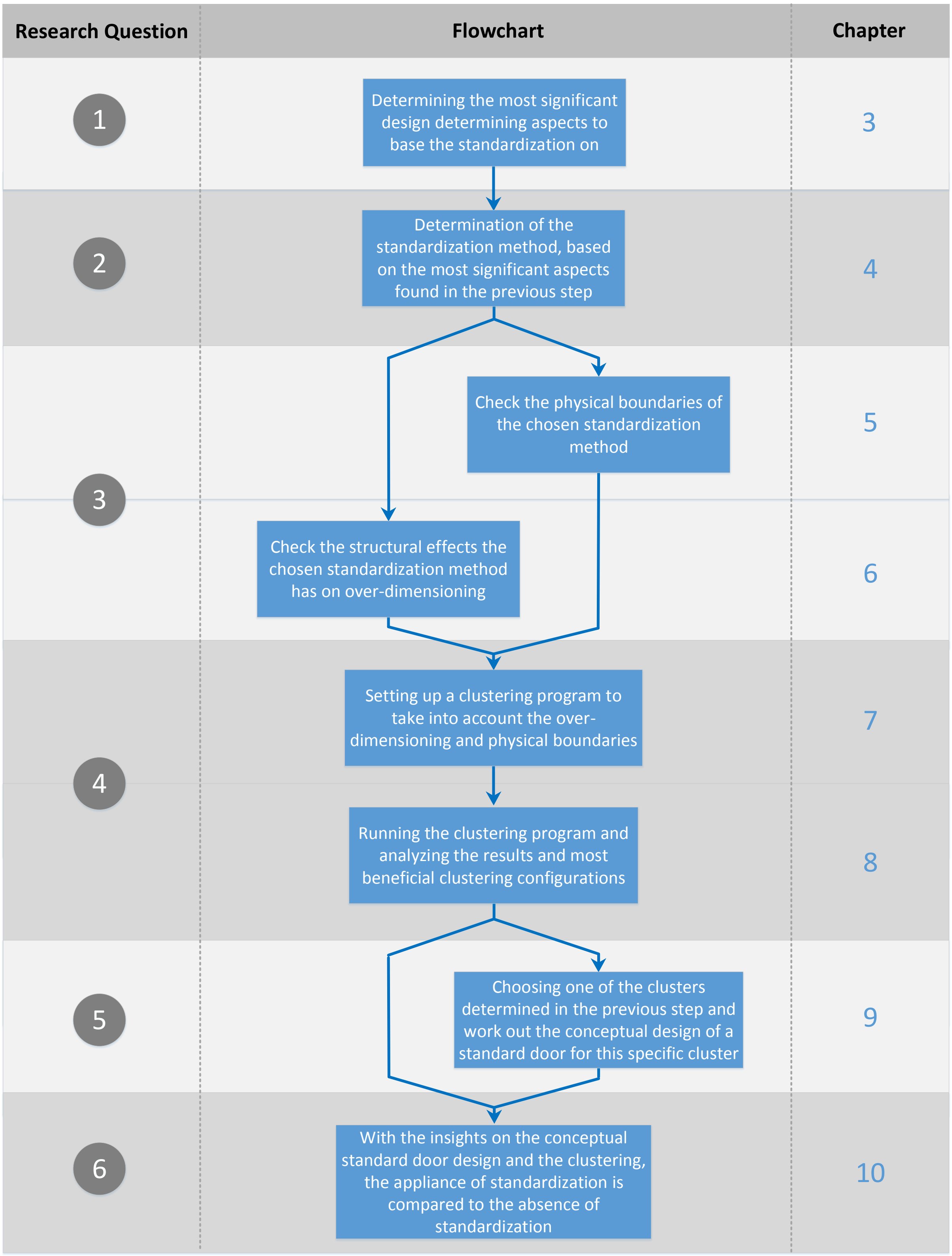


Figure 13: Flowchart

3 Design determining aspects and significance

To determine how to apply standardization amongst the MWW locks it is initially important to understand why the locks differ from one another. Lock gates are designed to conform to certain requirements and functionalities which may differ from lock to lock. This chapter is dedicated to identify the different functionalities of locks regarding water retention, the varying geometrical aspects a gate must have and the various loadings a lock gate can be exposed to. These aspects combined can be seen as the design determining aspects. Each of these aspects have an influence on the design of a lock gate. This chapter aims to discuss the most common design determining aspects and filter out the most significant ones in the context of this research, answering RQ 1.

3.1 Functional requirements regarding water retention

From the lock data in Appendix A it can be noticed that the 37 contain a total of 98 mitre gates, meaning each lock averagely contains 2.7 gate sets. This section briefly explains how the number of mitre gates is determined with respect to the locks' functionality requirements regarding the retention of water.

3.1.1 Unidirectional and steady water level differences

The traditional lock is a lock with two sets of gates, one set per lock head. It is usually found in the separation between two canal reaches with different water levels or in a canalized river next to a weir or barrier. One starting point for a traditional lock is that the water retention is always one-sided, meaning that the water level on one side of the lock is always higher than the water level on the other side of the lock. The Figures 14 and 15 illustrate such a traditional lock:

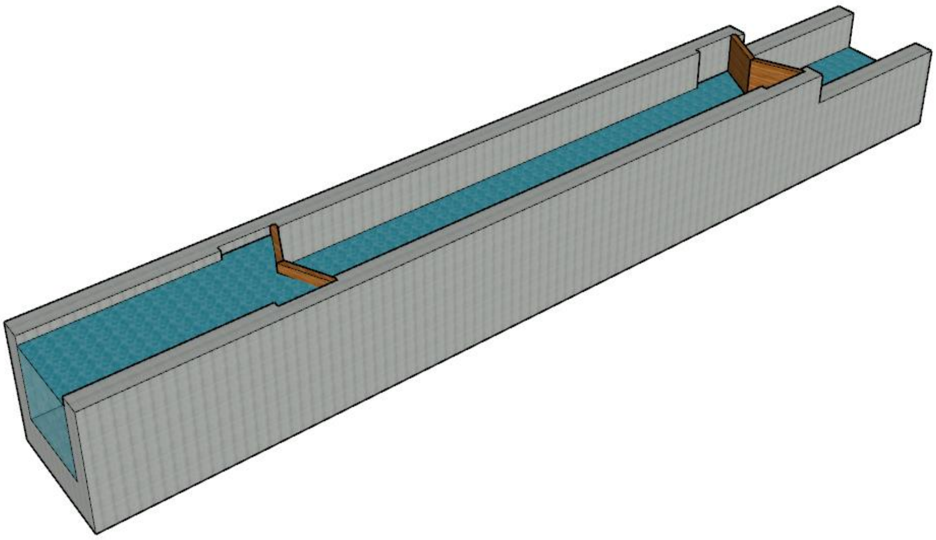


Figure 14: Standard lock with mitre gates

The longitudinal cross-section below gives a clear indication of the lock heads, water levels and gates/doors. The illustration shows a lock with a sill in the outer lock head. The choice whether to implement a sill or not usually originates from a financial tradeoff between the sill or a more expensive outer head door. The lock is also drawn such that it would always be open for navigation as the minimum shipping water level is always maintained.

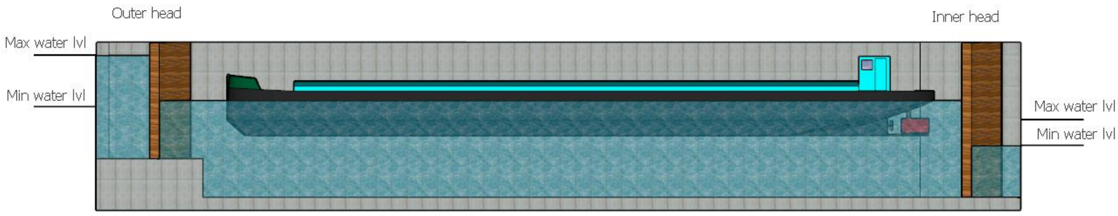


Figure 15: Cross-sectional view standard lock

3.1.2 Lock as part of flood defense

If a navigation lock is part of a flood defense, the safety requirements are more strict than in case of a traditional lock. The gates of the lock being part of a flood defense can be considered as the weak link, therefore some severe requirements are set for the reliability of closure. The requirements on reliability of closure are usually obtained by applying two gates capable of withstanding the highest possible water levels for which the structure is designed. A traditional lock as shown in figures 14 and 15 could suffice for a lock being part of a flood defense, however, the extreme water levels occur at a relatively low frequency and in this case the entire lock must be built according to the highest possible water level. From a financial point of view it is beneficial to only raise the outer lock head and add a spare gate set (Molenaar, 2011). This type of lock is considered as a lock with double retention and is shown in the figure below.

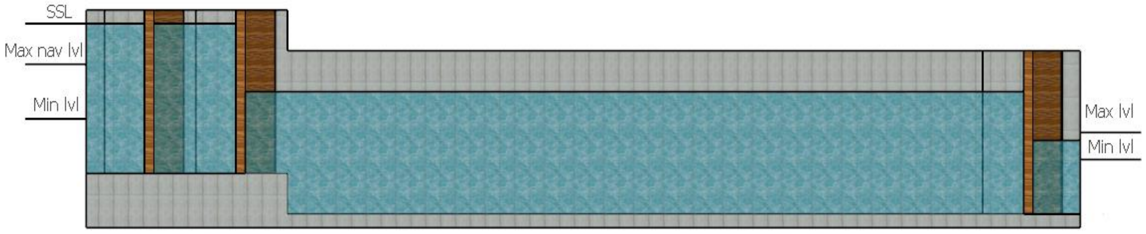


Figure 16: Cross-sectional view lock as part of flood defense

The economic benefit comes from the fact that in this case only the outer lock head needs to be built for the corresponding design water level (SSL). The rest of the lock can be built for a lower water level corresponding to the chosen maximum water level to enable navigation. If the outer water level exceeds the maximum navigation level, the lock closes for navigation. Figure 17 indicates the trade-off for the lock structure. The lock contains either the red part or the yellow part, depending on which solution has a higher economic feasibility. When adding a set of gates in the upper head (red part) one should also take into account the economic loss of unavailability to navigation when the maximum navigation level is exceeded.

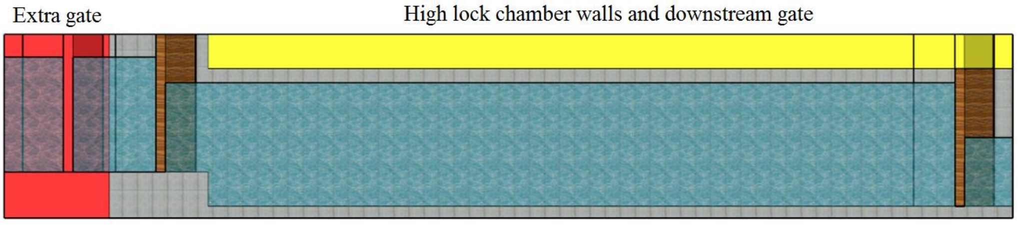


Figure 17: Optimization trade-off

3.1.3 Two-sided retention

In some cases the water levels on the outer head may have mayor fluctuations, such as for locks in coastal areas. If the lowest water levels in the outer head are lower than the lowest allowed low water level in the inner head, the lock will have to be able to retain water from two sides. For most other gate types than mitre gates, two-sided retention does not form an issue. For mitre gates however, two sided retention means an extra set of gates is required (this is due to the closure mechanism of mitre gates, the water pressure is used for closure).

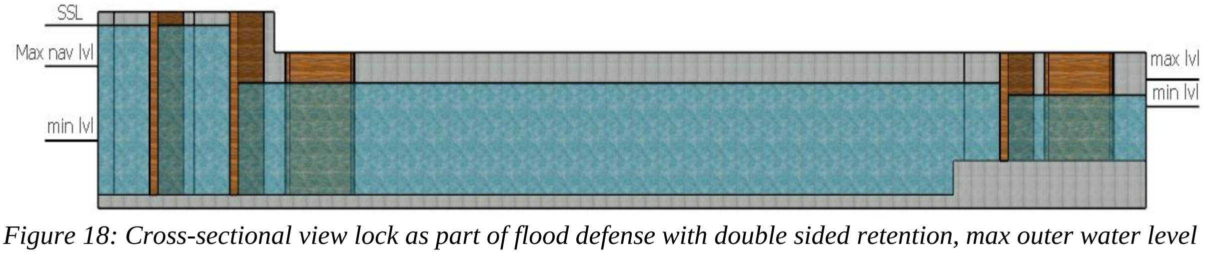


Figure 18: Cross-sectional view lock as part of flood defense with double sided retention, max outer water level and min inner water level

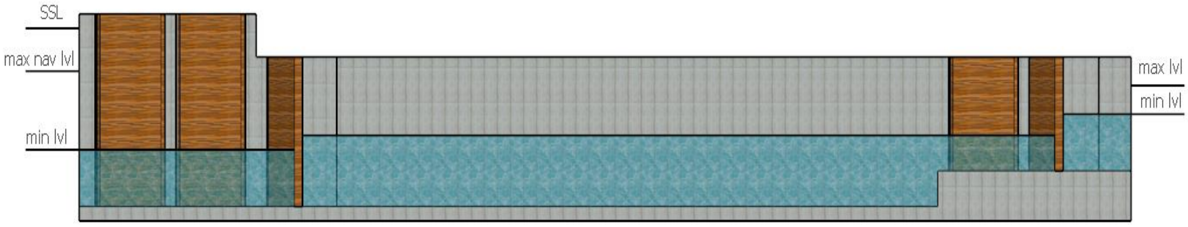


Figure 19:Cross-sectional view lock as part of flood defense with double sided retention, min outer water level and max inner water level

Figures 18 and 19 indicate the different situations in which the lock may find itself, retaining water from the outer head during a storm surge (upper illustration) and retaining water from the inner head during low tide (bottom illustration).

3.1.4 Middle lock head

In some conditions it is chosen to construct a lock with an extra lock head in the middle of the lock. The purpose of this extra lock head is to reduce the operation time of the lock when small vessels have to pass through the lock by reducing the effective length of the lock to approximately half its total length. This measure thereby reduces the amount of water that has to be leveled and therefore the total locking time. The middle lock head can be performed with either one or two mitre gates depending on whether the lock enables one sided or two sided retention.

3.1.5 Full retention

In some cases the gates of a lock have to be designed to withstand a maximum water retention with no opposing water pressures. An example of such situation is when the lock requires maintenance or repairs and needs to be set dry. In this case there are no favorable inner water pressures, reducing the resultant water loads. Another occurrence for full retention is when calamity occurs on a downstream retaining structure causing a drop in the water level. The hydraulic loads are further assessed in section 3.3.1.

3.2 Geometrical aspects

A mitre gate can be seen as a three dimensional slab with a certain length, height and thickness required to retain water. This section identifies the governing aspects determining the geometry of a mitre gate and explains how the optimum dimensions are determined.

3.2.1 Lock width

So far most of the loads have been determined as kN per meter door length, which implies that the length of the door is a governing variable concerning the loads acting on it. The required door length is directly proportional to the lock head width. This width is usually determined by the width of the largest ship passing through the belonging waterway. The length of the doors depends on the width of the lock and the angle at which they close. Figure 20 illustrates a lock head, indicating the described variables. The optimum angle of the doors is determined such that the load transfer and the use of material is the doors can be optimized. According to Vrijburcht (2000) this angle is at 18.4^{o} (1/3). Due to the fact that there is little information about how this optimum is obtained a small research into finding this angle is done below. Note that “optimum” stands for the angle for which a minimum of material is required.

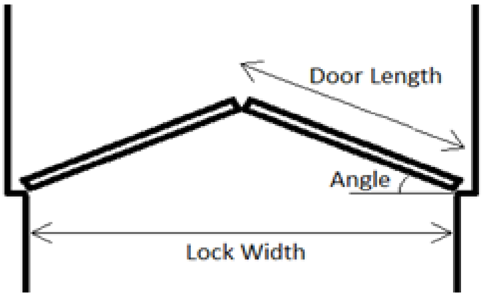


Figure 20: Lock width, door length and angle of closure

- *Determination of model*

The door of the gate is modeled as a single beam, the lock head as a hinge in which all displacements are fixed and only a rotation around the z-axis is permitted. The middle of the gate, where the doors meet in closed position is modeled as a hinge allowing displacement in the x-direction and rotation around the z-axis only. It is important to note that the difference between a beam in the door and a singular beam is that the beam in the door is supported vertically by vertical girders, these would prevent buckling in the z-direction. For this reason the single beam is modeled with a uniform support along its length, preventing displacements in the z-direction. The figure below illustrates the coordinate system with respect to the gate on the left, the right image shows the beam representing one of the beams in the door.

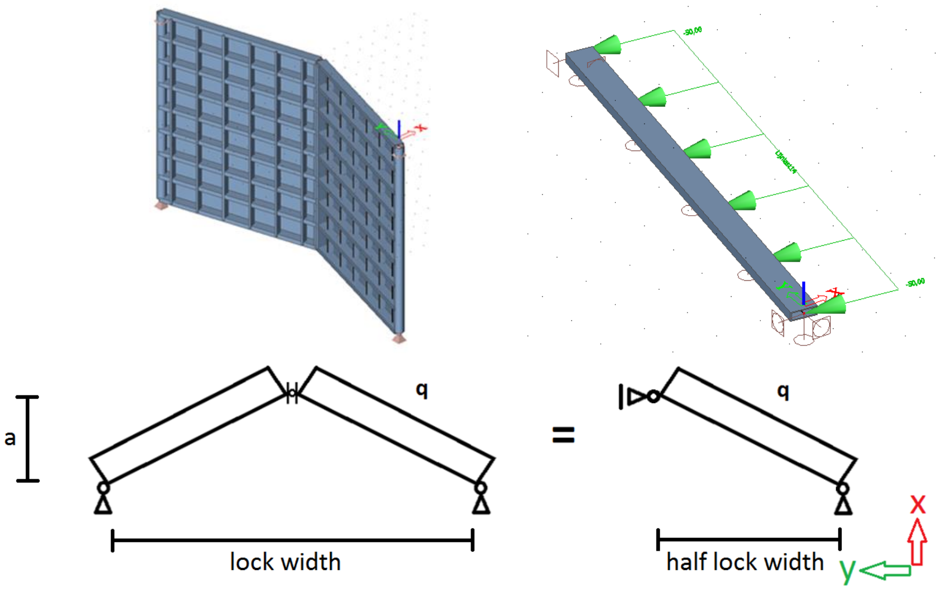


Figure 21: Upper: SCIA Engineering model; Bottom: Hand model; Left: lock gate; Right: modelled horizontal beam

In this schematization only the horizontal beams contribute towards the horizontal stiffness of the door (as is the case for doors supported by loose pivots) and the beam is loaded with a uniformly distributed load of q = 50kN/m. This would load represents the load on a horizontal beam found at a depth of 5 m with a beam center to center distance of 1m. The width of the lock is taken at 20 m and the slope of the doors is varied by varying “a”. The slope of the door is given by a divided by half the lock width (a/10).

3.2.1.1 Internal forces and bending moments

To figure out the internal forces in the beam the support reactions must be determined first. This can be done by taking the sums of bending moments around the hinges and applying the concept of force equilibrium.

Taking a sum of moments around the lower hinge: $F_{V_{upper}} = \frac{\frac{1}{2}\sqrt{10^2+a^2}^2 q}{a}$

Horizontal force equilibrium: $F_{H_{lower}} = 10q$

Vertical force equilibrium: $F_{V_{lower}} = F_{V_{upper}} - a\,q$

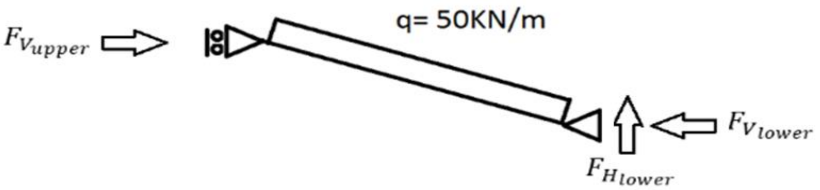


Figure 22: Support reactions on modeled beam

The maximum occurring normal force, shear force and bending moment are given by the following expressions:

Normal force: $N = \frac{10}{\sqrt{10^2+a^2}} F_{V_{upper}}$

Shear force: $V = \frac{a}{\sqrt{10^2+a^2}} F_{V_{upper}}$

Bending moment: $M = \frac{1}{8} q(10^2 + a^2)$

Solving the equations above for “a” being equal to 3 results in the following support reactions and bending moments:

Force/Load	$F_{v,upper}$	$F_{h,lower}$	$F_{v,lower}$	N	V	M
Value	908.3	500.0	758.3	870.0	261.0	681.3
Unit	kN	kN	kN	kN	kN	kNm

Having set up the model in SCIA Engineer, the following forces have been determined (see Figure 23. Fortunately the forces coincide with the forces determined by the hand calculations above proving a proper set up of the model. Further calculations of this kind are now computed with the help of this finite element program.

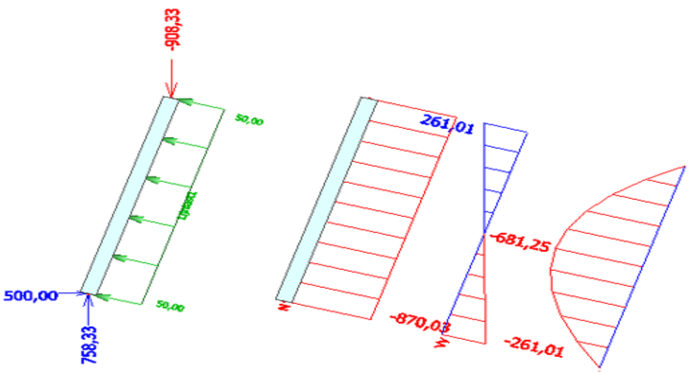
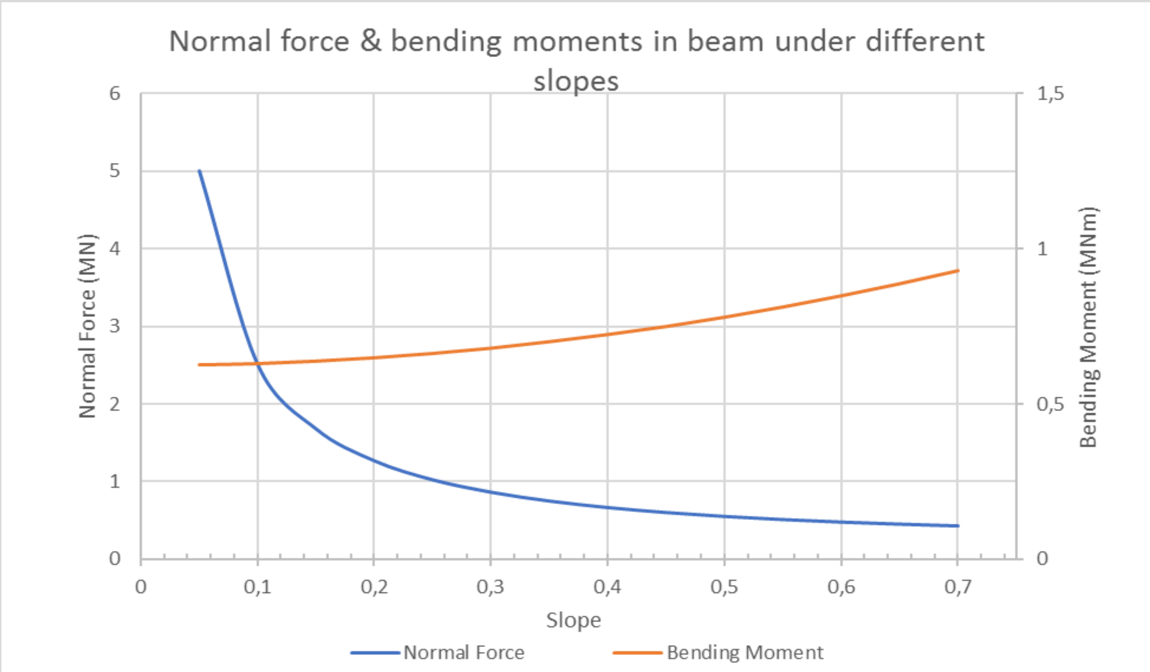


Figure 23: SCIA calculations

Graph 1 illustrates the relation between the bending moments and the normal force in the beam when placed under a varying slope. The slope of the beam is varied between 1:20 to 14:20 in steps of 1:20. The shear force is not displayed due to its relative minor presence.



Graph 1: Normal force and bending moments in beam under varying slopes

It is interesting to observe the rapid decline of the normal force in the beam as the slope is increase from 1/20 to 1/5. The bending moments only seem to increase very mildly with an increase in slope, this can be explained through the fact that with an increasing slope the length of the beam increases. Since the bending moment is proportional to l^2, with l being the length of the beam, it exponentially increases with it.

3.2.1.2 Required steel profile

According to the Eurocodes, a loaded beam must be able to meet certain strength and stability requirements for it to be able to bear the forces acting upon it. Such requirements are given in the table below:

	Strength requirements			Stability requirements		
Checks	**Normal force**	**Bending moment**	**Shear**	**Normal force and bending moment**	**Normal Buckling**	**Combined bending and axial stress**
Eurocode	EN 1993-1-1, 6.2.4	EN 1993-1-1, 6.2.5	EN 1993-1-1, 6.2.6	EN 1993-1-1, 6.2.1(5)	EN 1993-1-1, 6.3.1.1	EN 1993-1-1, 6.3.3
Formula / Unity check	$\frac{N}{N_{c,Rd}} \leq 1$	$\frac{M}{M_{c,Rd}} \leq 1$	$\frac{V}{V_{c,Rd}} \leq 1$	$\frac{N}{N_{c,Rd}} + \frac{M}{M_{c,Rd}} \leq 1$	$\frac{N}{N_{b,Rd}} \leq 1$	$\frac{N}{\chi_y N_{c,Rd}} + k_{yy} \frac{M_y}{\chi_{LT} M_{c,Rd}} < 1$

*Buckling due to bending (kip) is not taken into account as the beam is continuously vertically supported in order to prevent this failure mechanism.

Basically, what each of the formula means is that the resistance of the beam, to for instance the normal force ($N_{c,Rd}$), must be greater or equal to the occurring load (N). If this is the case the unity check $N/N_{c,Rd}$ must be smaller or equal to 1.

The resistance terms are all dependent on the characteristics of the beam. These characteristics include the shape of the cross-sectional profile, the amount of steel in the profile and the length of the beam.
It can be said that the more steel the profile contains, the larger its resistance is. Taking this into account, the optimum profile would result in a maximum unity check (as close to 1 as possible).

To determine this optimum profile it is possible to choose one based on an estimation. This profile can consequently be checked with the Eurocodes and its outcome is greater than one the amount of steel in the profile can be increased, whereas if the outcome is smaller than one the amount of steel can be decreased. As can be expected this is a very iterative procedure where the profile is adjusted and checked each time.

Fortunately the engineering software SCIA Engineer is capable of performing this iterative optimization by itself. After having set up the model and given the beam a certain profile SCIA changes the profile such that the unity checks get as close to 1 as possible. SCIA also allows the user to set certain beam characteristics as fixed variables and others as varying. To investigate the effect the slope of the beam has on the required steel in the beam, a beam with the following dimensions is chosen:

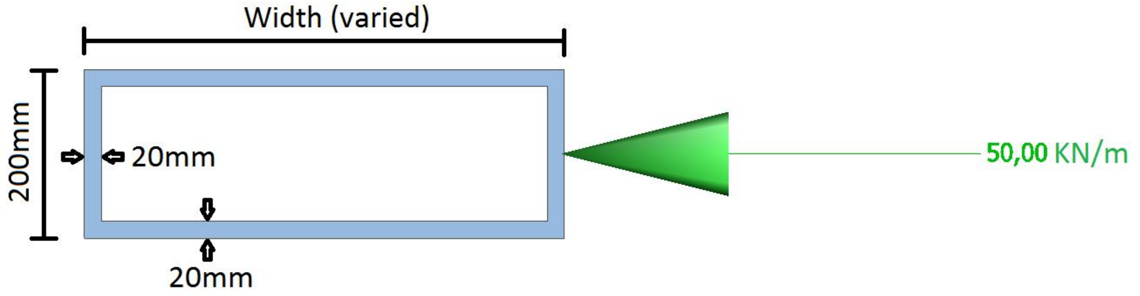


Figure 24: Optimization of profile

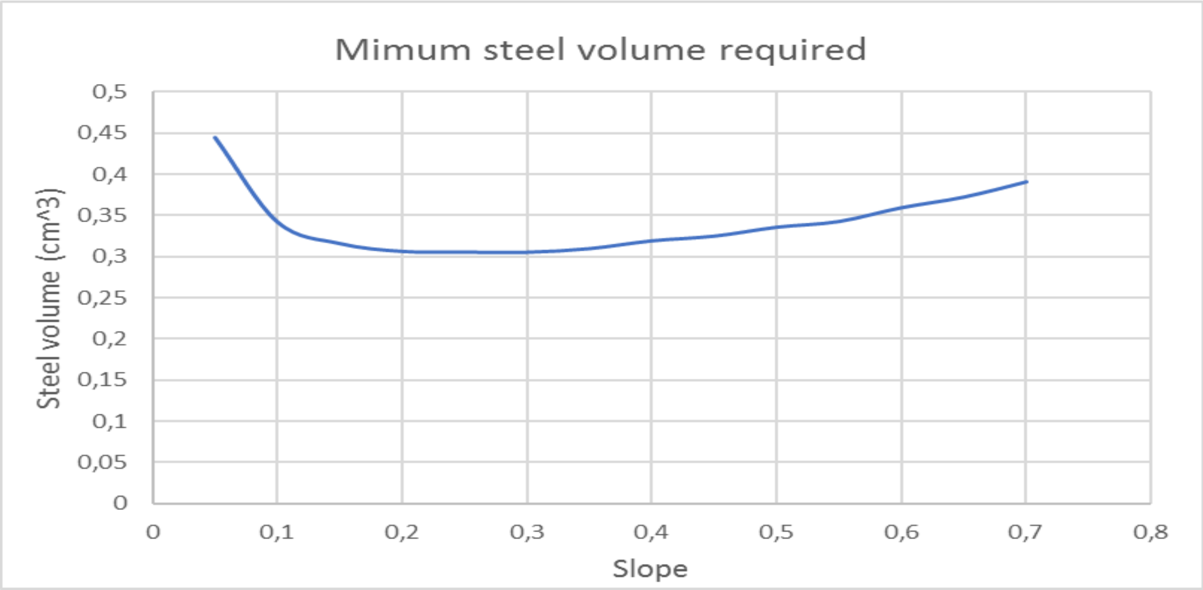
In this case the thickness of the steel plates and the height of the beam are kept constant, 20 mm and 200 mm respectively. With width of the beam is varied in steps of 10 mm such that the beam meets the requirements for the loads occurring at varying beam slopes. Also the following beam characteristics are set:

- Steel type S235
- Profile classification 3
- Partial factors:
  - Resistance of all cross-sections $\gamma_{M0} = 1{,}00$
  - Resistance of elements concerning element stability $\gamma_{M1} = 1{,}00$
  - Resistance of cross-section in tension until failure $\gamma_{M2} = 1{,}25$

If we were to investigate the beam in the condition where it is placed under a slope of 3:10 the minimum width of the profile becomes 570 mm, leading to a total steel volume of 0.3 m^3. The table below gives the corresponding unity check values according to the Eurocodes.

	Strength requirements			Stability requirements		
Checks	**Normal force**	**Bending moment**	**Shear**	**Normal force and bending moment**	**Normal Buckling**	**Combined bending and axial stress**
Unity Check	0.13	0.76	0.21	0.88	0.16	0.94

The unity checks above are checked by hand in order to make sure the model input is correct and SCIA performs the right calculations. These hand calculations can be found in Appendix C: Eurocode Checks. From the unity checks it appears that the stability requirement concerning combined bending and axial stress is governs the dimensioning of the profile. Graph 2 illustrates how the required steel volume changes when the beam is placed under a varying slope.



Graph 2

From this graph it becomes clear that the optium slope under which the beam can be positioned lays somewhere between 2:10 and 3:10 as the high normal forces domintate the required profile for mild slopes whereas the bending moments dominate the required profile for steeper slopes.

Before jumping to the conclusion that this optimum slope holds as a universal truth it is decided to see if this optimum also holds for beams in different conditions such as:

- Varied profile shape
- An eccentrically supported beam
- Half the lock width

These are elaborated in Appendix C. Taking these varying conditions into account the overall optimum is found to be at a slope of 3:10. Since this optimum slope of closure of the doors remains constant in varying conditions, amongst a changing lock width, varying profile shape and eccentrically supported beams it can be said the width of the lock and the length of its doors are always directly proportional. The proportionality is given by:

$$Door\ length = 1.044 * \ Lock\ width$$

3.2.2 Retention height

The height of a door depends on the minimal water level required for navigation and the maximum water level for retention. The bottom slab of the lock is located such, that when the minimum water level for navigation is reached, the lock still provides enough water depth for vessels to navigate through the lock. The required height of the door can therefore be determined by the following relation:

$$Door\ Height = minimum\ depth\ for\ navigation + retention\ height + wave\ height + clearance^{1}$$

[1] Takes sea level rise, settling and setting during the plan period, rise in water level due to wind action and rise in water level due to seiches, rain oscillations and surges into account (Vrijburcht, 2000).

Figure 26 illustrates how the variables add up to determine the required door height (h_w stands for wave height).

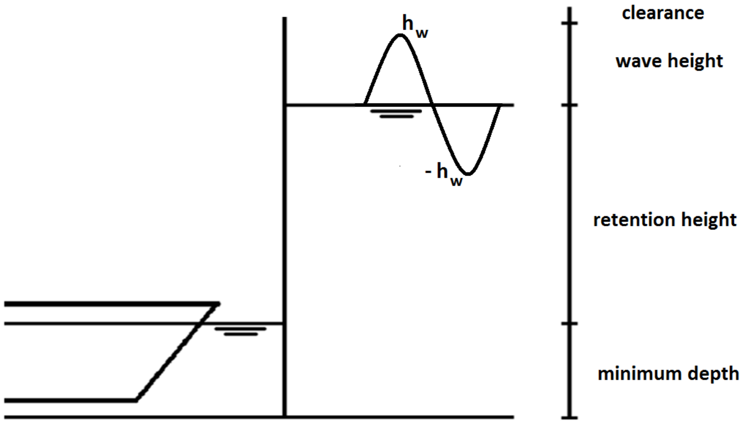


Figure 25: Illustration of door height

In some cases the minimum water depth is lower than the minimum required water depth for the locking of vessels. This is mainly due to an economic tradeoff where this situation is found to be so rare that it becomes economically beneficial to have a slightly higher bottom level in the lock. It's possible to determine the door heights for most of the MWW locks using the Appendix A data.

3.2.3 Door thickness

The required door thickness is a result of a vast amount of things. The door thickness is representative for its strength and should therefore be determined by assessing the occurring stresses in the door. The stresses are caused by the loads and the length of the door being described at the start of this chapter. Under a constant load, the local stresses in the door automatically reduce when the doors' thickness (thickness of the girders) are increased. The maximum allowed occurring stress is material dependent, therefore the door thickness also relies on the material chosen. It is clear that the door thickness is more a calculated outcome than a design determining aspect. For a renovation project however, there might be limitations to the door thickness applied, if the door thickness is increased, it may not fit in the existing gate recess.

3.3 Load aspects

A lock gate has to be designed such that it can bear the loads acting upon it. The loads are caused by several causes. This section treats the governing ones and explains the effects they have on the loads the doors have to bear.

3.3.1 Hydrostatic water pressures

The hydrostatic loads are caused by the water pressures acting on the gates. When the water levels are the same on either side of the gate, the hydraulic pressures are equal and thus the resultant pressure is zero. With different water levels on either side of the gate, one pressure dominates the other and a resultant water pressure develops. Figure 27 illustrates the hydrostatic loads caused by a water level difference over a lock gate. The left figure shows how the course of the hydrostatic pressures on either side of the gate whereas the right figure indicates the resultant pressure.

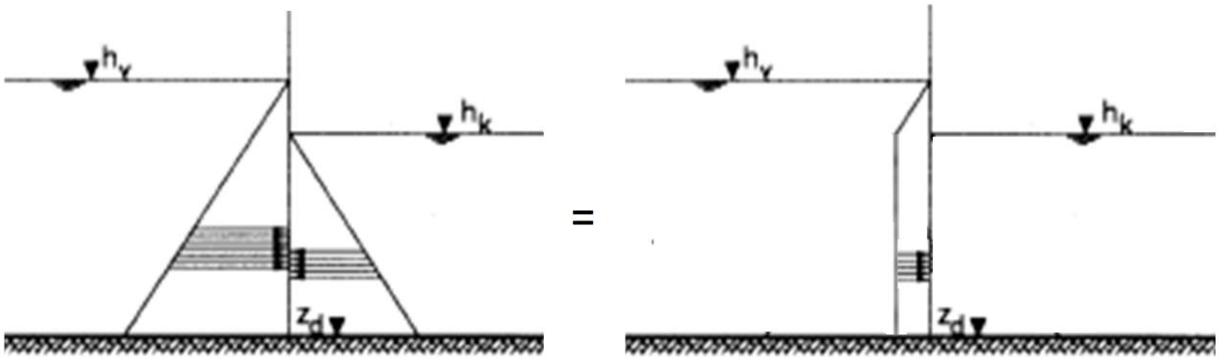


Figure 26: Hydrostatic load on lock gates; Left: water pressures; Right: Resultant water pressure

When considering equal water densities on either side, the governing hypostatic loads are very closely linked to the required door height as will be explained in section3.3.2. The resultant horizontal force of the hydrostatic water pressures can be given by the following relation:

$$F_h = \left(\frac{1}{2}\rho g(h_v - z_d)^2 - \frac{1}{2}\rho g(h_k - z_d)^2\right)$$

Where :

F_h	= total horizontal force on door per meter width	N/m
ρ	= volumetric weight of water	kg/m^3
g	= gravitational constant	m/s^2
h_v	= outer water level	m
h_k	= inner water level	m
z_d	= bottom of door	m

From the illustrations and the formula above it becomes clear that the horizontal force on a door is directly dependent on the water head difference $(h_v - h_k)$. From the available data about the MWW locks (Appendix A) it can be noticed that a lot of data is missing concerning the water levels. From the available data it is found that the retention heights go up to 8.2 m (Sluis Panheel). The minimum water depth inside the lock during this head difference is 2.7m.

Filling these values into the formula results in a resultant horizontal force of 557.6 kN//m.

Considering the case described in section 3.1.5, where the doors are loaded under full retention, the hydrostatic loads only act upon one side of the gate as the other side is set dry. Such situation is shown in the figure below.

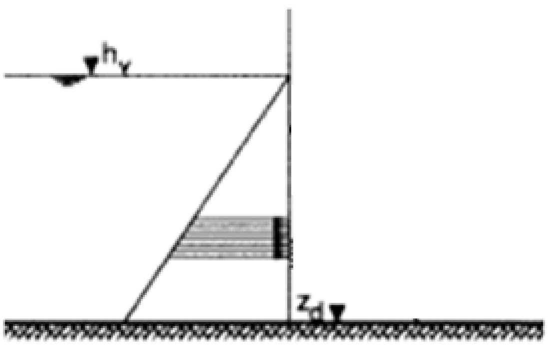


Figure 27: Resultant hydrostatic loading on gates without opposing water level

In this case the resultant horizontal force becomes 594.1 kN/m. For locks with low retention heights the relative change in the resultant horizontal force become more significant when comparing full retention versus partial retention (where there's water on both sides of the gate).

3.3.2 Wave loads

Waves cause changes in the water level and can cause significant loads on lock gates. The figures below illustrate the varying water pressures corresponding to the crest (left) and the trough (right) on a wave hitting a vertical wall. In the figures, the solid straight line represents the hydrostatic water pressure if no waves were to be present.

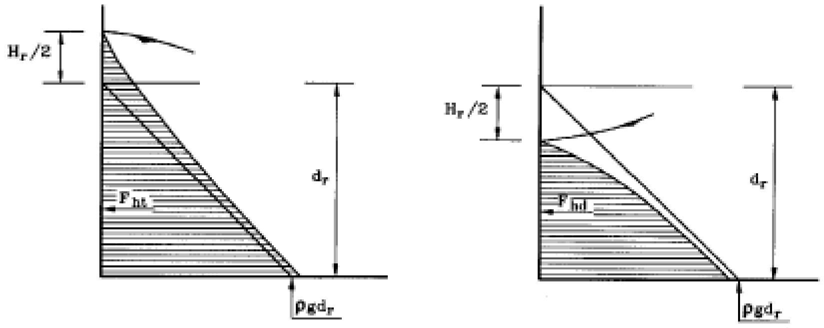


Figure 28: Water pressures induced by wave loading (Vrijburcht, 2000)

As a primary estimate it is possible to use a simple rule of thumb for the determination of wave loads. This rule of thumb considers a wave to cause a net increase in water level, this increase in water level can then be used to be added up to the average water level. From this total water level a hydrostatic water level can be determined using the method as described on the previous page.

According to this technique the maximum wave pressure against a wall is given by the following relation (Voorendt, 2016):

$$F_{max} = \frac{1}{2}\rho g H^2 + d\rho g H$$

Using this relation is the same as adding the maximum occurring wave height to the outer water level and applying the same formula for hydrostatic water pressure as on the previous page. It should be noted however that this is an over estimate of the actual combined load of water pressure and wave loads.

If we consider the fact that a lock gate should be designed to withstand the maximum occurring head difference and occurring waves (applicable for coastal locks in case of a storm surge) the height of the gate is such that it remains above maximum water level plus the maximum wave height. Using the approach as described above, the height of the doors can be used to give a conservative estimation on this combined loading.

Amongst the MWW locks the door heights vary between 3.9 m and 12.7 m, assuming the locks were to be set dry this would result in a combined loading of $76kN/m$ and $806kN/m$ respectively. Figure 29 indicates how the pressures add up to form the relevant combined loading on the gates.

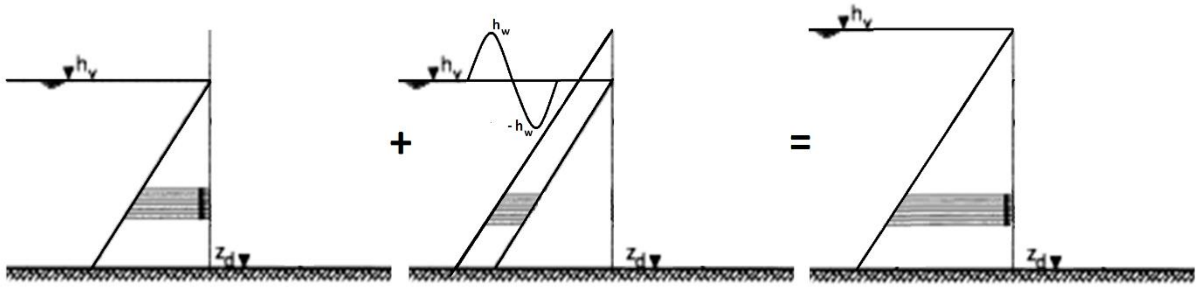


Figure 29: Addition of hydrostatic pressures and wave loads

3.3.3 Ship impact

Another mayor load on the gates can be caused by ships colliding with the gates. When addressing ship impact loads, the governing situation is found when a vessel travelling downstream enters a lock and collides with the downstream lock gate. The significance of this situation is due to the fact that the hydraulic water pressures act in the same direction as the ship impact loads, such situation is illustrated in the figure below.

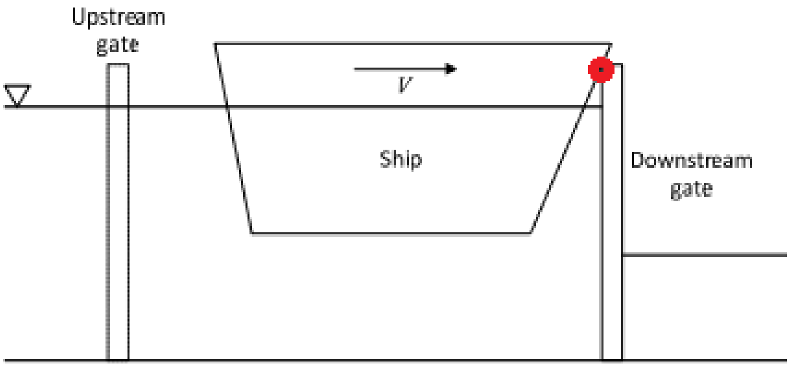


Figure 30: Least favorable ship impact scenario

Ship impact loads can be treated as extreme accidental loads and there are several ways to deal with these when designing the lock gates and lock heads.

3.3.3.1 Ship impact prevention

In some situations it is chosen to implement ship impact prevention measures which protect the lock gates against the threat of ship collisions. These would be placed at the location of the red dot in the figure above. An example of ship impact prevention measures are the placement of a restraining cable or a shock absorber beam. These are shown in the figures below.

Figure 31: Ship impact prevention measures. Left : restraining cable. Right: shock absorber beam (InCom_Working_Group_151, 2014)

The measures described above imply an extra lock chamber length of 5m, longer operating times of the lock and additional construction and maintenance costs. The choice whether to add preventive ship impact measures is therefore made based on the determination of the consequences resulting from a ship collision:

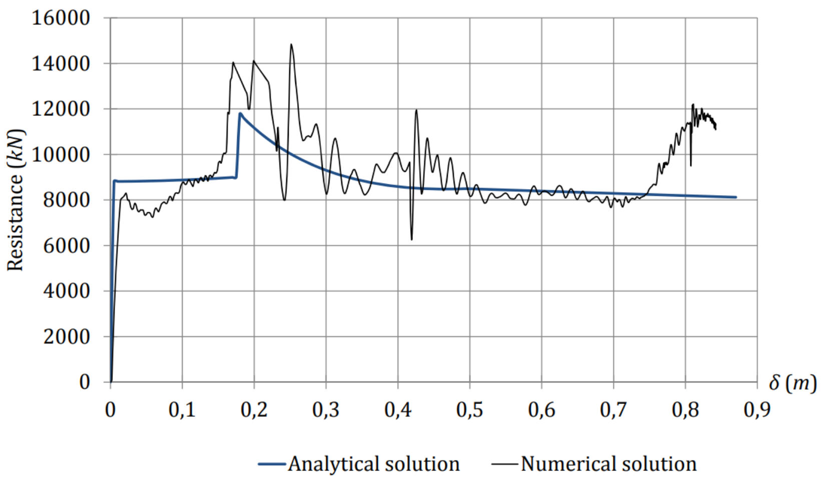
- Drop in upstream water levels and emptying of upstream waterway
- Stranding of vessels
- Potential flooding of downstream area

When these events can lead to the substantial risk of loss of life, injury and/or social and economic costs the ship impact prevention systems are to be applied (InCom_Working_Group_151, 2014) .

3.3.3.2 Ship impact acceptance

Ship collisions should preferably be avoided but in most cases it is a risk the designer is willing to accept, this is mainly if the conditions for ship prevention systems are not met (see previous section). The probability of a vessel colliding with a lock gate and the lock gate entirely losing its retaining function is then estimated to be small enough. This can be due to the fact that the approach of the lock is such that chances of collision at significant ship velocities are negligible or that the lock gate is calculated to be strong enough to withstand the ship impact loads. Another reason could simply be that if the gate were to fail the consequences would not be too severe.

The loads lock gates have to withstand during ship collisions depend on two aspects, namely the kinetic energy of the approaching ship and the resistance displacement ratio of the lock gate. The graph below shows the resistance of a mitre gate when a 4000 ton vessel collides with it at a speed of 2m/s.



Graph 3:Resistance of mitre gate during ship collision (InCom_Working_Group_151, 2014)

In this case it can be observed that the kinetic energy of the ship $\frac{1}{2}mv^2 = 8\ MJ$ is entirely absorbed by the gate (the area underneath the line seems to be equal to 8 MJ).

3.3.3.3 Ship impact absorption

In case the design of the gate is too weak to be able to withstand the ship impact loads it can be chosen to upgrade its impact resistance by adding a shock absorber to the door. This mainly increases the structural deformation range and therefore helps the gate to absorb more impact energy.

Figure 32: Ship collision absorber (InCom_Working_Group_151, 2014)

It is interesting to notice how minor the effect of such measure is on the design of the lock gate/head as the absorption structure is placed at a slightly higher lever then the lock head. This means that when implementing this structure no changes need to be made to the gate recess (where the doors are stored while the gates is open).

3.3.4 Ice loads

Ice loads come in two forms, namely horizontal ice loads and vertical adherent ice loads.
Horizontal ice loads are caused by the expansion of volume when water freezes into solid state. Being confined in boundaries a normal force develops. A linear distributed load of 400 kN/m must be applied for quay walls in fresh water. When considering salt water this value drops to 250 kN/m (CUR_166, 2008).

As water freezes on the gate, adherent ice loads add to the weight of the structure. The added weight imposes a vertical force on the gates leading to larger resultant forces in the pivots and the diagonal elements of the gates. An approach to take into account the loads imposed by the adherent ice a vertical force of $0.1kN/m^2$ can be applied on the doors (Vrijburcht, 2000).

Figure 33: Adherent ice on mitre gates (Johnson, 2017)

In several cases ice formation is prevented by adding electric thermal heating systems, low volume air bubble systems or propellers to the gate. High volume air bubbler systems can be applied in the gate recess in order to ensure that the gates can recess entirely, this system serves more as a debris mover (Johnson, 2017).

3.3.5 Driving loads and blockage by obstacles

In order to operate the doors of a mitre gate are driven by drive mechanisms as explained in Section XXX. The normal opening time of a mitre gate is about 120 seconds for which a certain average angular velocity is required. The force required to open or close the doors is dependent on their weight, wet area (water displacement) and opening time. The point of attachment find is usually located upon the top of the door at 1/3 of the door length. Due to the eccentric positioning along the height of the door, this creates a torsional moment in the door. Another important factor in determining the maximum driving load is the type of drive mechanism used.

During the operation of opening and closing the door the governing situation concerning the drive loads is when an obstacle is trapped between the door and the gate recess or sill causing the door to block. This especially become problematic when the obstacle finds itself close to the bottom pivot. Concerning electro mechanical systems this is even more of a problem as these are displacement driven and blockage becomes less noticeable.

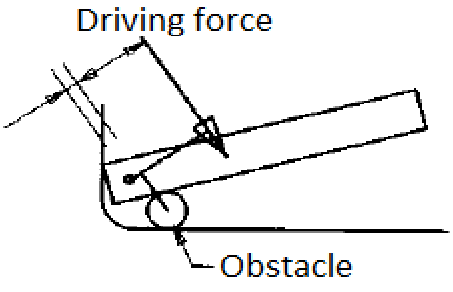


Figure 34: Obstacle between door and lock head, preventing proper opening of the gate (Vrijburcht, 2000)

3.3.6 *Water densities*

In addition to the discussed hydrostatic pressures, there might be a presence of varying water densities. The figure and relation below indicate a possible situation of varying water densities and how the resultant load on the gate would be determined.

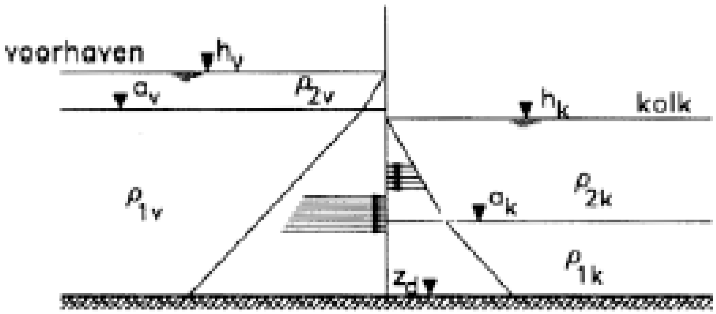


Figure 35: Development of hydrostatic loads in case of varying water densities (Vrijburcht, 2000)

$$F_h = \left(\frac{1}{2}\rho_{2v}g(h_v - z_d)^2 + \frac{1}{2}(\rho_{1v} - \rho_{2v})g(a_v - z_d)^2 - \frac{1}{2}\rho_{2k}g(h_k - z_d)^2 - \frac{1}{2}(\rho_{1k} - \rho_{2k})g(a_k - z_d)^2\right)$$

Where :

ρ_{1v}	= volumetric weight of salt water outside of the lock	kg/m^3
ρ_{2v}	= volumetric weight of fresh water outside of the lock	kg/m^3
ρ_{1k}	= volumetric weight of salt water inside the lock chamber	kg/m^3
ρ_{2k}	= volumetric weight of fresh water inside the lock chamber	kg/m^3
a_v	= level of the boundary layer outside of the lock	m
a_k	= level of the boundary layer inside the lock chamber	m

In the case of varying water densities the governing situation would be where the high water would be entirely salt and the low water entirely fresh. Taking into consideration that fresh water has a density of $\rho = 1000\ kg/m^3$ and for salt water $\rho = 1025\ kg/m^3$ the density difference contributes 2.5% of the total water load induced by the head difference.

3.4 Significance of aspects for standardization

To determine the significance of the various design determining aspects it must be recalled what is meant by the word significance. In this case the significance relates to the significance of this research, namely to standardize mitre gates. In the method section 2.4, it is mentioned that the standardization will take place based on estimates of amount of steel used as these give an approximate value for over-dimensioning when standardization is applied. Hereby an aspect is considered as significant if it largely contributes to the amount of steel required in the gate. From this starting point it can be concluded that:

- Functional requirements of a lock considering flood protection mainly contribute to the amount of door sets in a lock. The specific design of a particular door is hardly effects in case of either double retention or the presence of flood gates (extra set of doors). However, if the lock gates have to be able to withstand full one sided retention (only water on one side of the gate) the loads on the doors may significantly increase (section 3.1.1)

- It comes without saying that both the required door height and door length play a crucial role in the determination of amount of required steel. The door length proves its significance as it directly relates to the stresses in the door resulting in the required stiffness, thus profile dimensions. Also longer doors require more steel due to the additional length, both profile dimension as length determine the volume of steel. Concerning the door height, this variable mainly depends on the maximum water head and the occurring waves, hereby door height, hydrostatic & wave loads considered as the very same determining aspect. The combined load considered is shown in Figure 29.

- As we saw in section 3.2.1, the loads acting on a gate have direct influence on the amount of steel required in a door. One very large potential load could be the ship impact loads and the horizontal ice loads. These loads however, largely depend on a various amount of conditions and can be prevented or reduced by additional measures. Also the loading is very local and thus taking this into account in the design of a door would not result in a significant increase in required steel. This also holds for blockage loads due to obstacles.

Taking the above points into consideration, this standardization research will be based on the required height and length of the lock gate doors.

4 Standardization method

The previous chapter identified the various design determining aspects of a mitre gate and put emphasis on the most significant ones. In this chapter, an attempt is made to figure out how these most significant aspects can be clustered to create specific categories. The idea is that each formed category will require one standardized door design. The goal of this chapter is to identify the optimum standardization method having the potential to cluster the lock gates. The first section of this chapter sums up the data of the lock gates, indicating the wide spread of the gate characteristics and listing the starting points based on which the standardization will be based. The second section discusses the options for standardizing the lock gates according to the variety in lock widths and required door heights. This chapter gives the answer to RQ2.

4.1 Lock gate characteristics

The main and most governing design determining aspects of a mitre gate are the required door heights and door lengths. For this research it is chosen to base the standardization purely on these two aspects of the lock gates. Table 2 indicates the variance found in the door heights and lock widths amongst the corresponding MWW lock gates. The door heights and lock widths have been rounded off to their closest integer. The number inside a cell indicates the amount of lock gates with that specific combination of values for the aspects, this table for instance tell us that there exist six lock gates within a 8 m wide lock with door heights of 6m.

Amount of lock gates		Door height									
		4	5	6	7	8	9	10	11	12	13
Lock width (m)	5		3								
	6					3					
	7	5	3								
	8		4	6		4			2		
	9										
	10			2							
	11				1		1				
	12			9	1	1	2				
	13										
	14		2	6	7		3	10			
	15										
	16			1	2	4	5	2			
	17										
	18			1	2	2			3		1
Total		98									

Table 2: Lock gate characteristics

4.2 Starting points

From Table 2 it can be observed that the lock gate characteristics are widely spread. In order to come up with a standardization method the following starting points have been set up:

4.2.1 Spare components

The non-availability of a lock gate is closely linked to its reparation time during maintenance. It is evident that the reparation time for a lock gate is much quicker with the presence of spare gates/components. For this reason the availability of spare components is considered as a primal requirement. If there are several identical lock gates within a cluster they may share the same spare gate as this spare gate would be compatible for each of them.

4.2.2 Minimum adaptation to existing civil structure

MWW is a project concerning the renovation of existing structures. It is assumed that the gates of the MWW will have to be replaced without significantly adjusting the existing concrete structure. The gates should therefore be designed to be compatible within the existing locks. In this case the most important factor is the variety in the lock widths which is assumed to remain unchanged during the renovation and maintenance process.

4.2.3 Variety reduction

The main goal of this research is to apply standardization to achieve variety reduction amongst the MWW lock gates. The reason for striving for variety reduction is in order to optimize the maintainability of the lock gates and encounter fewer problems concerning the availability and reliability.
Another mayor advantage of variety reduction standardization is to attain economies of scale, reducing the cost per piece as production becomes cheaper. Also taking into account the first starting point, less variety leads to the requirement of fewer spare components, leading to potential benefits concerning the overall usage of material.

4.3 Standardization approach

Designing a standard door for several locks with different lock widths and retention heights brings up two options. The first option is to design a door that's suitable for the locks with the largest dimensions and try to fit it into the other smaller locks. The second is to design a door that can be downscaled by taking off certain components to make it more suitable for the locks with smaller dimensions. The concept of a structure that can be adapted by adding or removing certain components or modules is further referred to as modularization.

4.3.1 One size fits all

This section discusses the possibility and the consequences of applying a "one size fits all" lock gate to several locks with different dimensions.

- Lock width

Applying the "one size fits all" for gates in locks with different widths without changing the widths, it would be necessary to adapt the angle at which the gates close. Only this way doors with the same length can be applied in locks with different widths without adjusting them. Applying lock gates with different lengths and closure angles implies that some changes will have to be made to the existing civil structure. The changed angle of closure implies that the sill will have to be extended in order to properly seal the bottom of the gate. Also, the longer doors will require more space for the gate recess in the lock head.

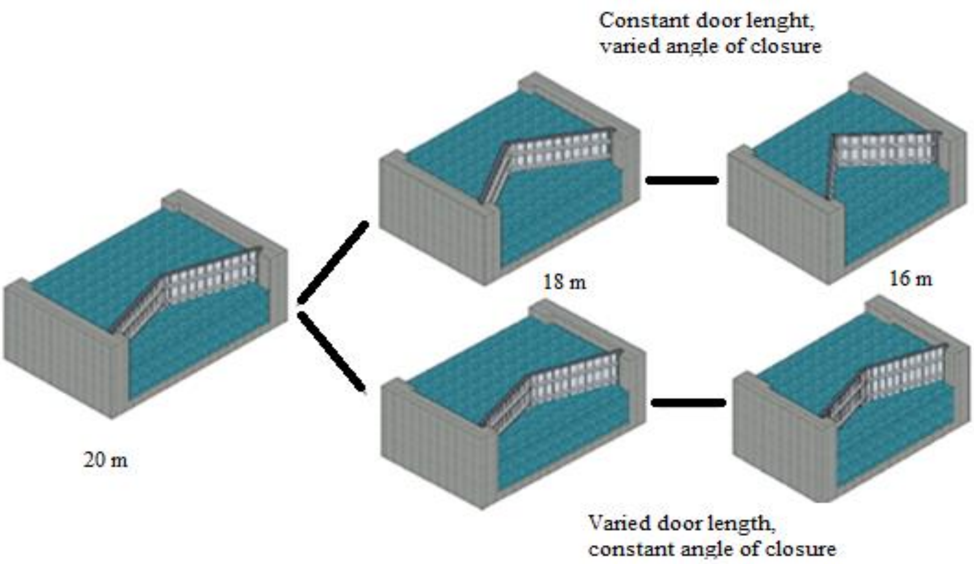


Figure 36: One size fits all: lock widths

The top path in Figure 36 illustrates the appliance of a standard door length in locks with different widths and the corresponding change in angle of closure. The bottom path serves as a reference for when the length of the doors is designed according to the width of each lock, maintaining the optimal angle of closure.

- Door height

In case a door with a fixed height is to be implemented in locks with different door height requirements the door will exceed the lock head. The exceedance of the lock head may result in many structural complications. The extra height of the door will greatly contribute to the dry weight of the door, increasing the loads on the pivots. Another consequence of the exceeding door height is that the upper pivot would most likely require to be relocated and elevated to the same level as the door.

The combined effect of implementing a "one size fits all" type of lock gate is illustrated in Figure 37. The left image displays a lock gate in its governing situation. The design of this gate is optimized and the door lengths and heights are determined without exceedance. The right image illustrates this very same door when applied in a lock with a smaller width and lower retention height.

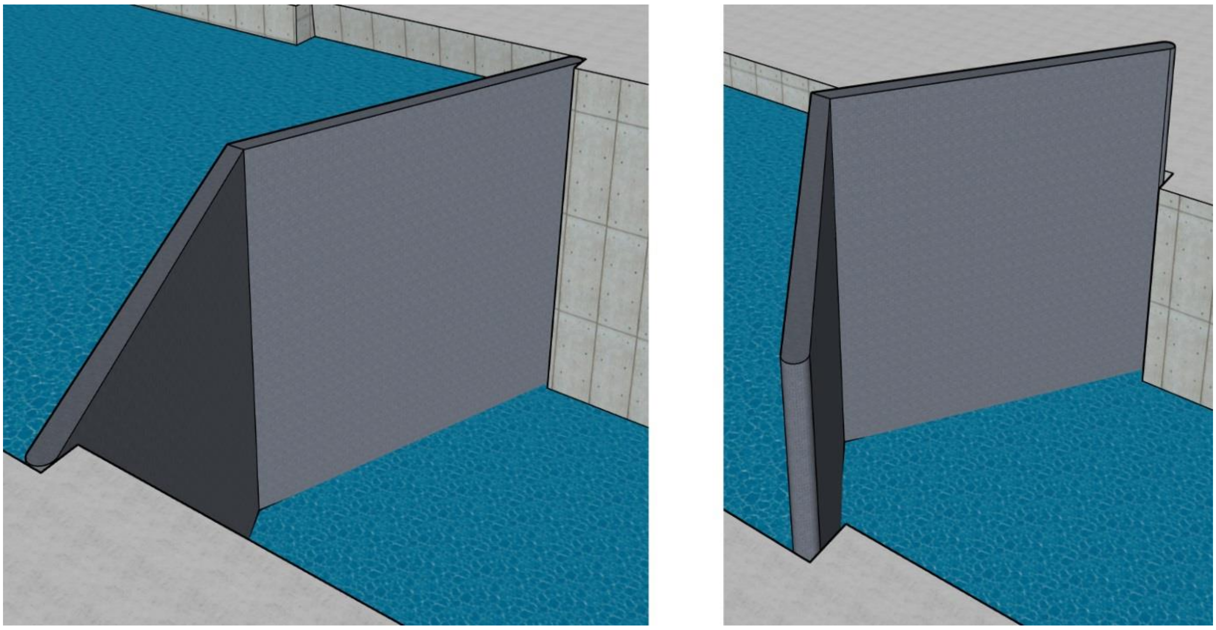


Figure 37: Combined effect of One Size Fits All; Left: Optimized door design for lock with largest width and retention height; Right: Implementation of same door is smaller lock with lower retention height

It is expected that the applicability of the "one size fits all" is limited when addressing the wide range of the MWW lock gate characteristics.

4.3.2 Modularization

Broadly speaking, modularity is the degree to which a system's components may be separated ad recombined, often with the benefit of flexibility and variety in use (Merriam-Webster, 2018).

- Door length

As mentioned in the scope, this research considers the main load transfer within the gates to be horizontal and thus along the main horizontal beams. Being capable of separating and recombining the doors along their length requires a strong connection capable of withstanding these loads. Creating a proper connection between the modules would be very challenging, especially when one has to consider the fact that the maximum thickness of the door is limited by the space offered in the gate recess.

- Door height

The main horizontal load transfer makes modularization more beneficial concerning the door height. In this case a door design should be made for the lock head that requires the highest door. This door can then be subdivided into various modules that can be subtracted in order to create door heights more suitable for other locks.

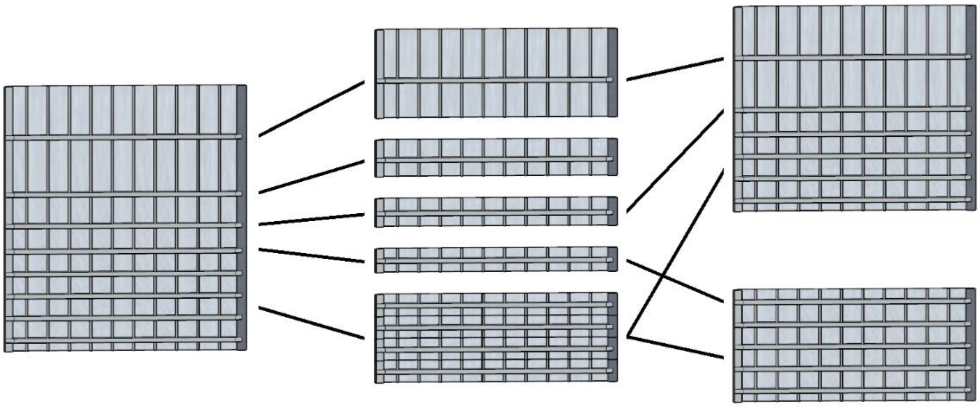


Figure 38: Standardization procedure lock height

Figure 38 illustrates how a large door can be subdivided into various modules with which other doors with smaller heights can be formed. It is expected that the design of such modularized doors is challenging and may result in many complications concerning torsional forces and the connection between the modules.

4.3.3 Conclusion

Due to the horizontal load transfer, it seems unfavorable to apply modularization along the length of the doors, therefore this is not considered as an option and is excluded from this research. The horizontal load transfer does however seem favorable to enable the modularization of the height of the doors. From this point two standardization methods will be researched and compared to one another: door with a fixed length - fixed height and doors with a fixed length – modular height.

The upcoming two chapters investigate the physical boundaries and overall effects on over-dimensioning caused by the appliance of a door with a constant length in locks with different widths.

5 Physical boundaries to standardization

The previous chapter described the two standardization options that are to be considered further in this research. This chapter investigates the physical boundaries occurring if a door with constant length is applied in locks with different widths. This chapter initially discusses a number of starting points concerning the characteristics of the doors. Consequently it describes the model used to evaluate the stability of the door. At the end an example is worked out on how the determined relationship between the loading and the maximum allowed slope of the doors is further applied in this research. This chapter gives the answer to the first part of RQ 3.

5.1 Starting points

In the research into the physical boundaries the following starting points are maintained:

- Pivots with clearance

The gates are suspended through pivots with clearance instead of fixed pivots. The reason is explained in section 1.5.5, discussing the various advantages and disadvantages of the each support type. The choice of heaving pivots with clearance leads to the requirement that the lock gates must always be pushed into the lock head by the hydraulic loads acting upon them. The figures below illustrate the support reactions the mitre gate encounters during closure, these reaction forces must always be positive according to their corresponding direction.

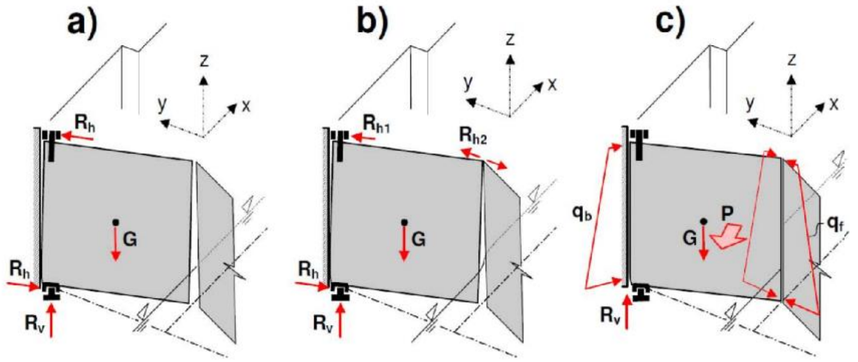


Figure 39: Support reactions for pivots with clearance during different closure situations (Ryszard, 2017)

- No aid by lock sill in SLS

There are various ways to seal off the bottom mitre gates. The seal often contains a rubber element that is squeezed against the sill of the gate. Choice can be made to elevate the sill above the bottom level of the door so that the doors can “lean” against it during closure. Such sills cause very careful adjustment and the slightest obstacle or inaccuracy between the door and the sill can prevent the gate from closing properly resulting in leakage. It is chosen to only consider a sill type that does not help the gates to transfer to loads to the surrounding concrete lock structure due to the enhanced simplicity. The figures below show two of these kind of sills:

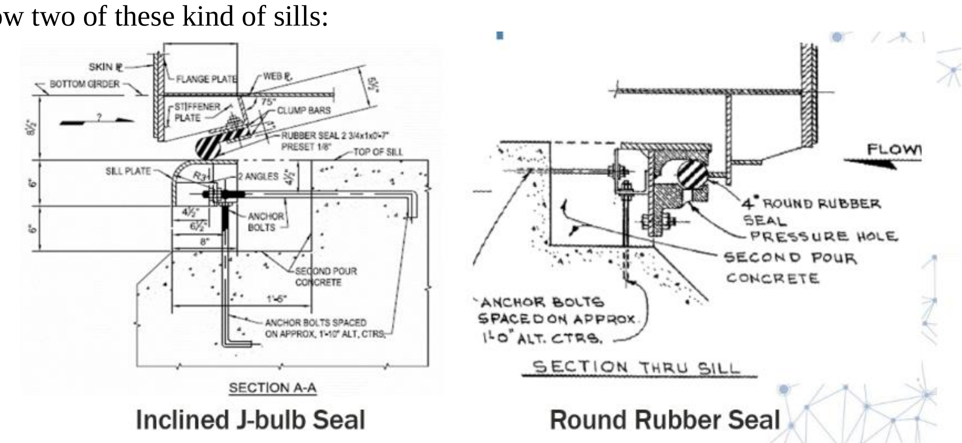


Figure 40: Different sill seals without sill aiding in supporting the gate (Johnson, 2017)

- In this research two seal types are investigated:

The friction based seal between the two mitre gate doors consists of a seal that is being squeezed in-between the doors due to the water pressures' resulting normal forces (spatkrachten). At the point of contact, normal forces as well as shear forces might occur. In case of the presence of shear forces, it is important for there to be enough friction at the contact surface to prevent sliding of the doors. This is further explained in the next section.

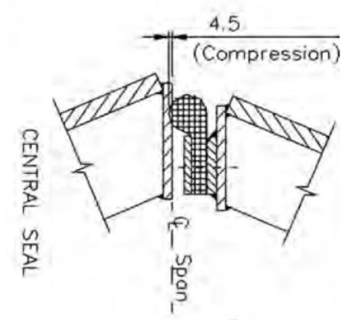


Figure 41: friction based seal (Vrijburcht, 2000)

Another type of seal is the type that is applied in the German standardized locks. This mechanisms more or less locks the gates together preventing possible sliding, creating a very stable intersection between the doors.

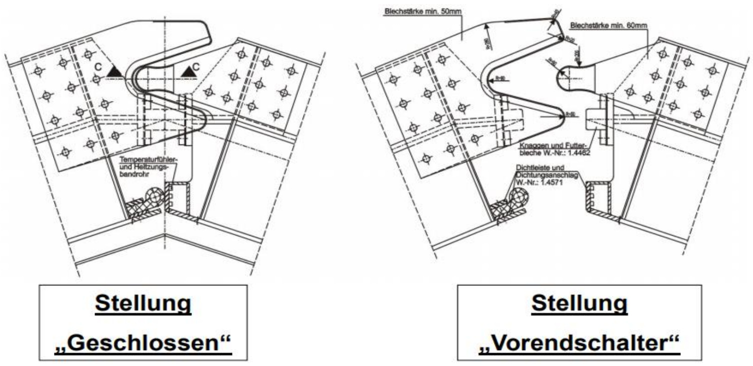


Figure 42: Normal force based central seal (Jander, 2015)

This research investigates the effect the seals have on the physical boundaries and the stability of the doors under a varied slope of closure.

5.2 Loads

The loads on the gate are purely considered as resultant hydrostatic loads. In case of perfectly still water, the water pressures are completely identical for both doors of the gate. To assess the stability of the gates however, one should take the occurrence of waves into consideration and the corresponding, least favorable scenario. In this case it is assumed a wave obliquely enters a lock head and that the wave crest approaches one door while the wave trough the other, resulting in a net water level difference over the doors. If at the same time a vessel inside the lock departs the lock, it may result in an additional forcing on one of the lock gates. The figure on the right illustrates this least favorable scenario. In this case it is assumed the wave height is 1 m with a rounded water level differences over the gate of 1m. The forcing on the door caused by the bow thrust of the departing ship is estimated to be equal to a 0.5

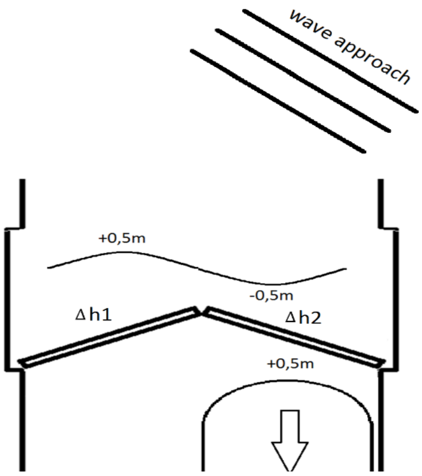


Figure 43: Governing condition causing asymmetrical loading on doors

m water level rise. According to the figure on the right $\Delta h_1 = \Delta h_2 + 1.5$.

5.3 Gate schematization

With the gate and hinge mechanisms as described in the starting points, the gate is schematized as beams supported and connected to one another with a hinge. This schematization is used to evaluate the stability of the gate. Figure 44 illustrates the schematization along with the variables. Since the distributed load per meter on a lock gate is more or less directly proportional to the water head difference, Δh_1 and Δh_2 are replaced by the distributed loads q_1 and q_2 respectively, the exact relation between Δh_1 and Δh_2 and q_1 and q_2 is explained in Appendix D. The specific purpose of this schematization is to determine the minimum allowed degree of symmetric loading (q_2/q_1) for a varied slope (a/b). The largest possible degree of symmetric loading considered is when $q_1 = q_2$ and the minimum for $q_1 = -q_2$.

<u>Variables:</u>

Slope	a/b
Symmetric loading factor	$\frac{q2}{q1}\left(\approx \frac{\Delta h_1}{\Delta h_2}\right)$

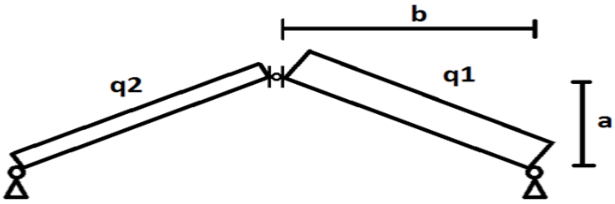


Figure 44: Schematization for asymmetric loading assessment

5.4 Stability assessment with regard to asymmetric loading

There are various forms at which instability may occur for the lock gates. This section describes these instability modes and how these result in stability requirements. For these requirements to be met a relation is found between the slope of closure and the symmetric loading factor.

5.4.1 Stability in the lock head

Since we consider pivots with clearance it is important that the gates are always being pushed into the lock head, sealing of the gaps in-between the gate and the concrete structure. In other words, the normal force of the gate “spatkrachten” have to be pointing outwards, therefore the reaction forces in the lock heads must always be positive in the directions given in the figure below.

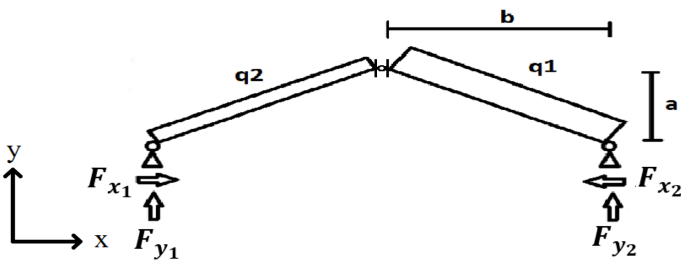


Figure 45: Required direction of support reactions

This leads to the following requirements:

$$F_{x_1} > 0 \;\;\&\;\; F_{x_2} > 0$$
$$F_{y_1} > 0 \;\;\&\;\; F_{y_2} > 0$$

The support reactions can be determined by the following set of equations:

Sum of forces in x-direction:	$F_{x1} + F_{x2} = q_1 b + q_2 b$
Sum of forces in y-direction:	$F_{y1} - F_{y2} = -q_1 a + q_2 a$
Sum of moments right side:	$F_{y1} b - F_{x1} a = \frac{1}{2}(b^2 + a^2) q_1$

Sum of moments left side: $F_{y2}b - F_{x2}a = \frac{1}{2}(b^2 + a^2)q_2$

Writing the equations in matrix notation leads to the following equation:

$$A * X = B$$

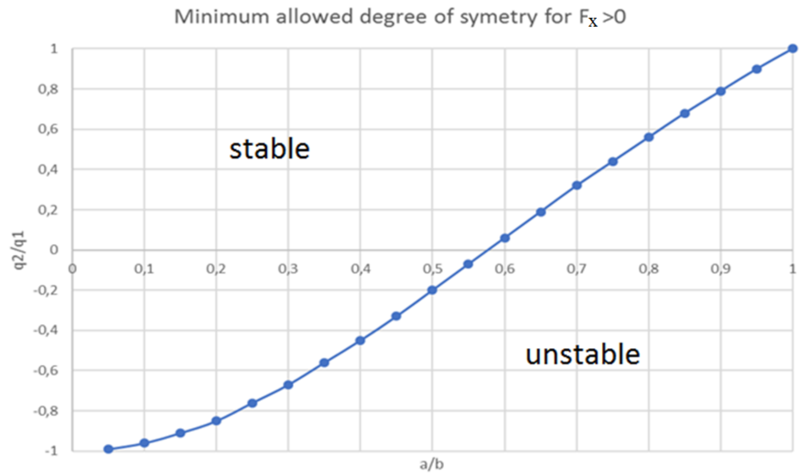
With

$$A = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & -1 \\ b & 0 & -a & 0 \\ 0 & b & 0 & -a \end{bmatrix}, \quad X = \begin{bmatrix} F_{y1} \\ F_{y2} \\ F_{x1} \\ F_{x2} \end{bmatrix}, \quad B = \begin{bmatrix} q_1 b + q_2 b \\ -q_1 a + q_2 a \\ 1/2\,(b^2 + a^2) q_1 \\ 1/2\,(b^2 + a^2) q_2 \end{bmatrix}$$

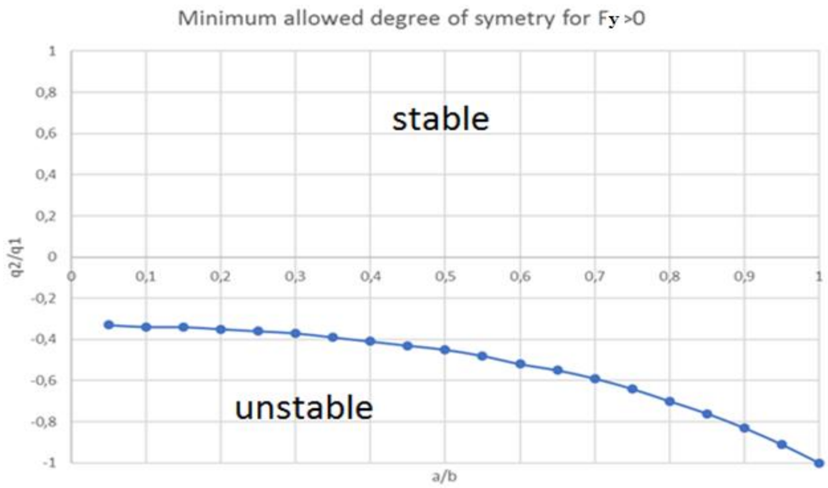
To solve for X:

$$X = A^{-1}B$$

Varying the ratios a/b and q2/q1 such that F_{y1}, F_{y2}, F_{x1} and F_{x2} remain larger than 0 results in the following relations:



Graph 4: Stability relation for $F_x > 0$



Graph 5: Stability relation $F_y > 0$

The graphs above tells us what the minimum symmetric loading factor can be for a gate with doors positioned under a varying slope, whilst complying to the requirement that F_x *and* $F_y > 0$. So if the doors are positioned at a slope of 1:1, no asymmetry in the loading can take place (q2/q1<1) or the doors would become unstable. The area above the line represents all the stable situations, whereas the area below the unstable situations. It appears that the maximum slope of closure is dominated by the requirements that $F_x > 0$.

5.4.2 Stability in centre seal

The centre seal between the gates can be modelled as a hinge, allowing rotation and being capable of bearing normal and shear forces. Since the actual closure point isn't really a hinge, the loading acting upon it must comply to certain requirements for it to act as one.

Considering a friction based centre seal, friction prevents sliding of the doors in asymmetrical loading conditions:

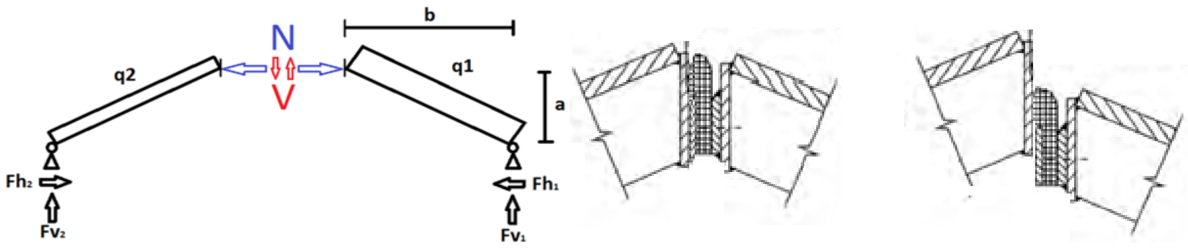


Figure 46: Left: forces in connection between doors; Right: Sliding of the doors

This leads to the following requirement in the closure point of the gate:

$$N\mu > V$$

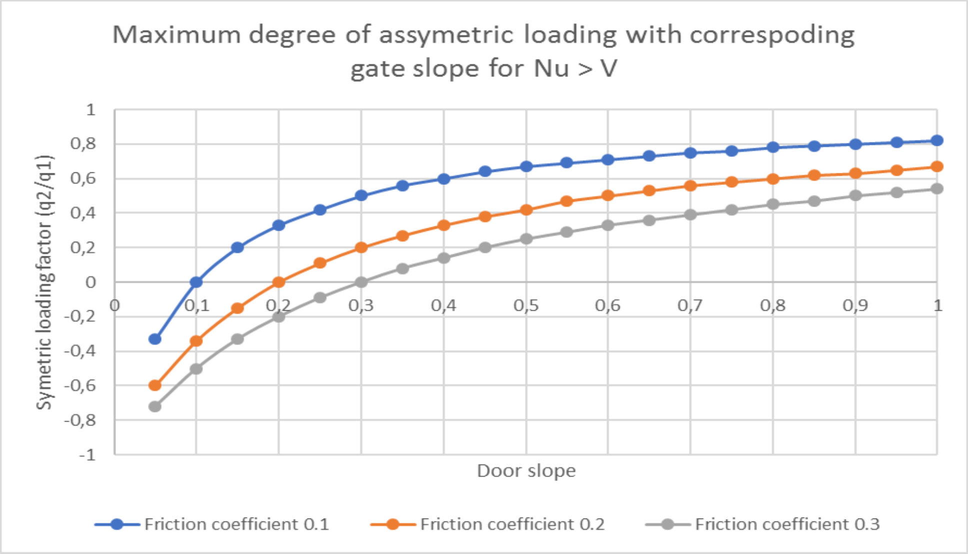
Where N = Normal Force
V = Shear Force
μ = friction coefficient

The normal and shear force in the hinge can be determined by the following equations:

Sum of vertical forces: $V = F_{v1} - q_1 b$

Sum of horizontal forces: $N = F_{h1} - q_1 a$

Now the ratios a/b and q2/q1 can be varied such that $N\mu > V$. The exact value of the friction coefficient μ is fairly uncertain but is estimated to be approximately 0.2 for wood on wet wood (Ramsdale, 2018). Graph 7 shows the minimum symmetric loading factor to the varied door slope for a friction coefficient of 0.1, 0.2 and 0.3 to check the sensitivity around this coefficient.



Graph 6: Stability relation for Nμ>V

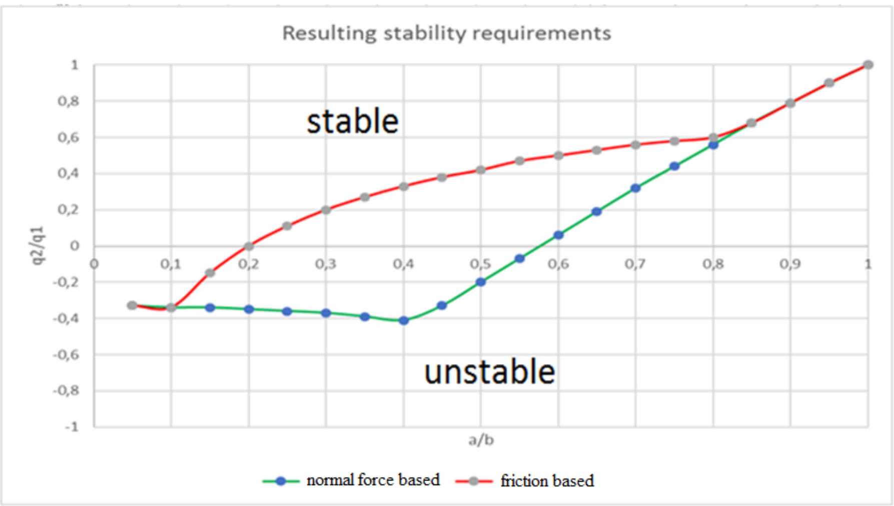
Considering the Normal force based central seal, sliding is impossible making the only stability requirement for there to be a normal reactive force in the contact point between the gates.
This leads to the following requirement in the closure point of the gate:

$$N > 0$$

To meet this requirement it is found that q2/q1 should always be bigger than -1, irrespective of the slope of closure.

5.4.3 Combination of requirements

Graphs 4, 5 and 6 show the individual results of the specific stability requirements. However, for a lock gate to be stable, it has to conform to all the requirements simultaneously. Graphs 7 illustrates the resulting stability relations for lock gates with either a friction based seal or normal force based seal.



Graph 7: Resulting stability requirements

From this graph it can be seen that the type of closure between the doors has a large impact on the stability requirements for the gate when the loads become asymmetrical, the turning point is reached at symmetry ratio of approximately q2/q1=0.6. To visualize what this means an example is worked out below:

If we assume the situation as presented in figure 43, where $\Delta h_1 = \Delta h_2 + 1.5$ a q2/q1 ratio of 0.6 can be found in a situation where the average water level difference between the lock chamber and the outer head is:

$$\Delta h_1 = \Delta h_2 + 1.5$$

$$\frac{\Delta h_2}{\Delta h_1} = 0.6$$

$$\Delta h_1 = 0.6\,\Delta h_1 + 1.5$$

$$\Delta h_1 = \frac{1.5}{0.4} = 3.75m$$

$$\Delta h_2 = 3.75 - 1.5 = 2.25\ m$$

$$\Delta h = 3.75 - 0.5 = 3.25\ m$$

From this calculation can be concluded that the centre seal type governs the stability of the lock gate for retention heights lower than 3.25 m. the centre seal type is unimportant for larger retention heights. It is also important to note that the ratio $\frac{\Delta h_2}{\Delta h_1}$ is not only dependent on the relation $\Delta h_1 = 0.6\,\Delta h_1 + 1.5$, but also on the occurring average retention height, in this case being equal to 3.25 m. If a lock with a retention height of 6.5m would be considered, $\frac{\Delta h_2}{\Delta h_1}$ would turn out to be 0.79. It is important to note that for a constant relation between Δh_1 and Δh_2, like $\Delta h_1 = \Delta h_2 + 1.5$, the symmetric loading factor $\frac{\Delta h_2}{\Delta h_1}$ also strongly depends on the average retention height on the gate. The larger the retention height, the more symmetrical the loading will be.

5.5 Door height

To the door height there are no physical boundary conditions concerning the stability of the doors. However, the lock head is already equipped with pivots. The position of these pivots is calibrated such that they can accommodate the original door sets. The pivots have been designed such that they can bear the loads caused by the original doors. Applying standardization/modularization for the doors the pivots may have to be changed due to a variance in the door heights between the old and new doors. The doors are expected to be heaver when standardized due to over-dimensioning. How the standardization of the doors leads to over-dimensioning will be discussed in the next chapter. The challenges concerning the changes of the pivots will be further discussed in chapter 8.

6 Over-dimensioning

Chapter 4 discussed that standardization should be based on the door/retention height and the lock width/door length. This chapter evaluates how these two determining aspects contribute to potential over-dimensioning and answers the second of RQ 3.

6.1 Deviation from optimum and over-dimensioning

When applying a standard for lock gates, local over-dimensioning becomes inevitable. By local over-dimensioning is meant that the standardized gate design requires more steel than a gate design optimized for local conditions. Assessing the standardization methods chosen in Chapter 4, the over-dimensioning shows what the extra use of required material is when compared to the local optimum.

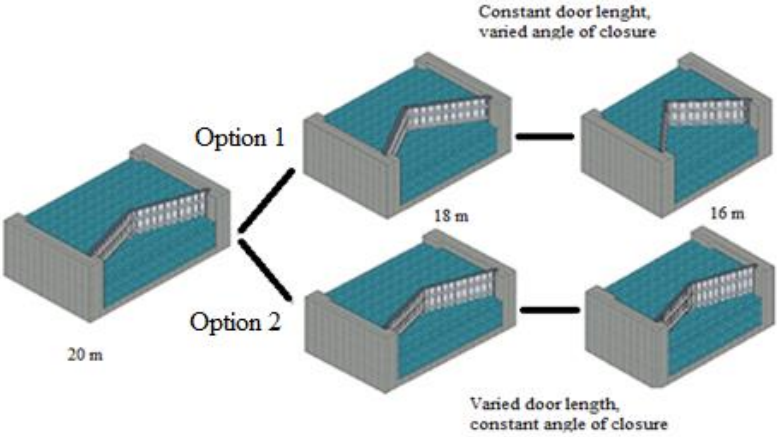


Figure 47: Comparison between standard and optimum gate design over locks with varying widths and

In the image above it is assumed that the lock gates in option 2 are optimized per varying lock width and that the optimum door slope is applied (3:10). Comparing the solutions for option 1 relative to option 2, the over-dimensioning is determined by the following relation:

$$Over\_dimensioning_{\ \%} = 100 * \frac{V_{steel,option1} - V_{steel,option2}}{V_{steel,option2}}$$

This relation gives us the percentage of ***extra*** volume of steel required while placing a large lock gate into a smaller lock. The percentage is relative to the amount of steel needed in the optimum lock gate design for the small lock.

6.2 Over-dimensioning: standardizing door length

To determine the over-dimensioning, the two cases on the right must be compared to each other. Figure 48 illustrates the optimal gate configuration for various lock widths with respect to minimal material usage, the lower figure schematizes the configuration where one door set is applied to the different widths, leading to a larger slope of closure and over-dimensioning. The ratio above each door set indicated the slope of the doors.

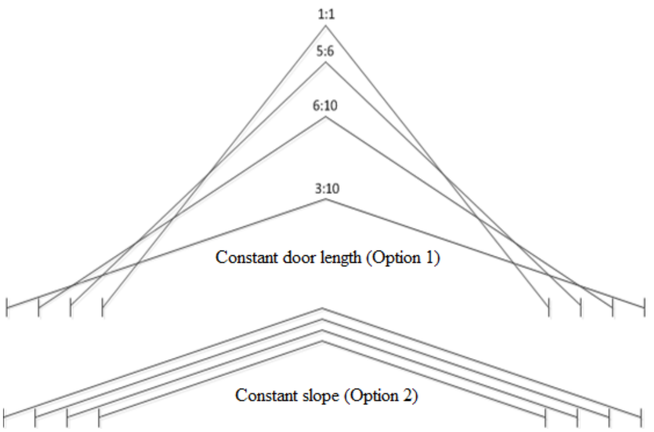


Figure 48: Implementation of same door length for different lock widths

As seen in graph 1, the normal forces in a gate decrease with increasing slopes, therefore it can be said that the governing forces occur at the largest width. The bending moments in the doors are considered to only be dependent on the door length, since the length would remain constant the bending moments would remain constant too. From here the conclusion can be made that the governing configuration is at the largest width with the mildest slope.

To determine the over-dimensioning in the case of the lower illustration of figure 48, the amount of steel required needs to be compared to that of the upper figure. The required amount of steel for the horizontal beams suitable for lock widths ranging from 12m to 20m, with beams under a constant slope of 3:10, have been determined with SCIA engineer using the optimization tool and performing the same iterations as explained in section 3.2.1. An investigation of this influence and the optumum profile and iteration method is discussed in Appendix E. From the performed investigation it became clear that the optimum profiles can be found in standards such as the HEB profiles. For this reason the rest of this report considers profiles of this class only.

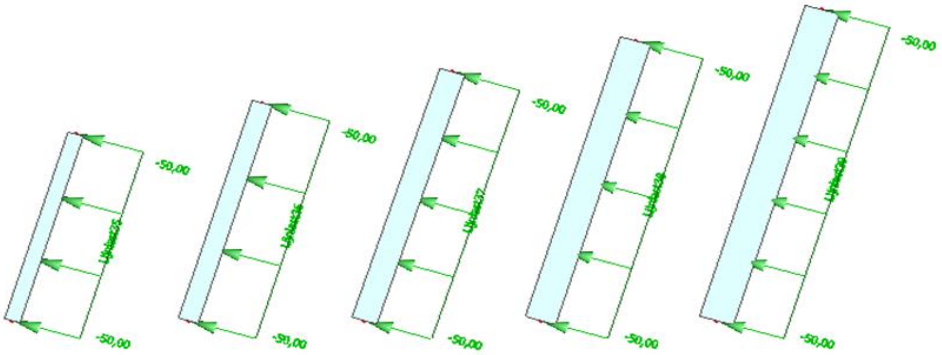
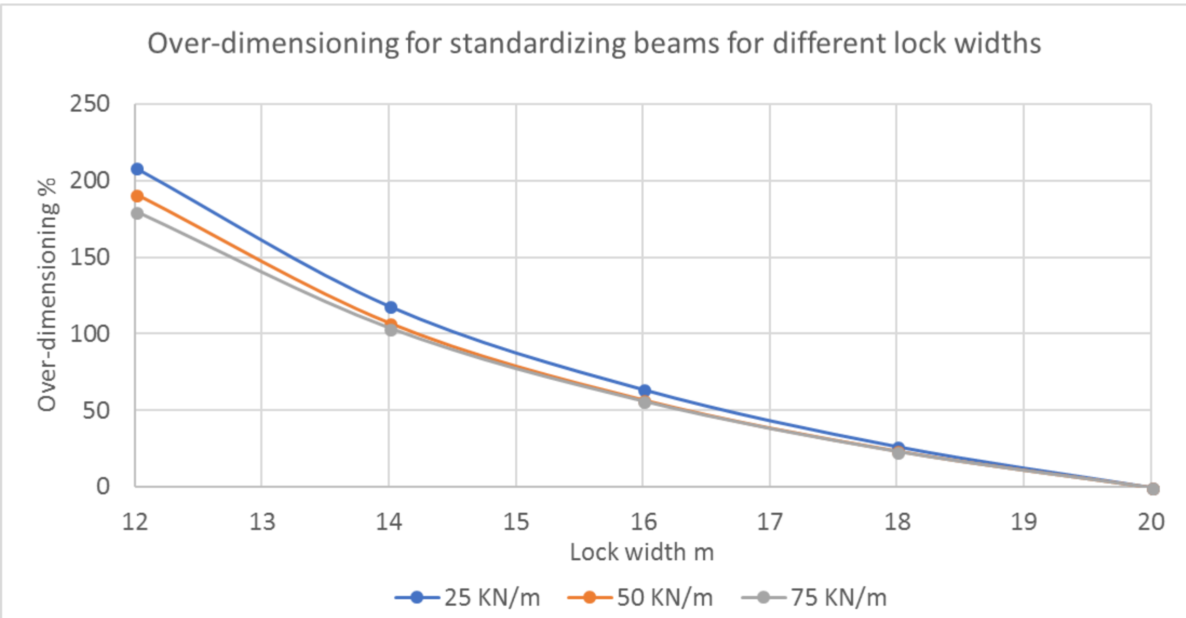


Figure 49: Modelled beams in SCIA Engineer

In this example a distributed load of 25 kN/m, 50 kN/m and 75 kN/m is taken. It is chosen to apply the three distributed loads to investigate what the effect the distributed load has on the over-dimensioning effects caused by standardizing door length. The calculations for the amount of steel needed and the over-dimensioning can be found in the table in Appendix F.

Plotting the over-dimensioning when considering the applience of beams designed for a lock width of 20 m to fit into locks with smaller widths:

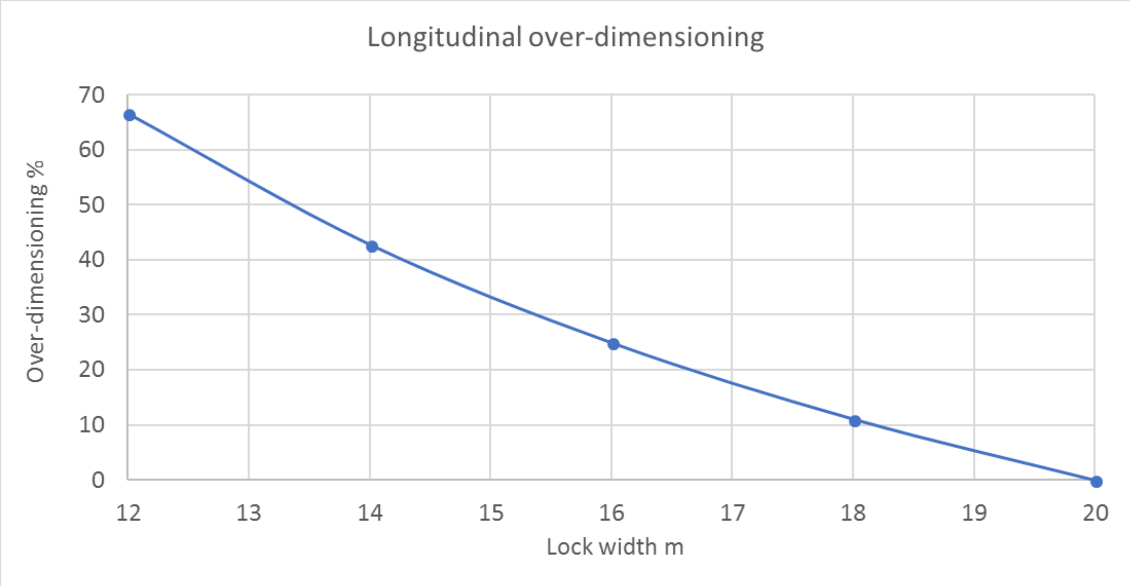


Graph 8: Over-dimensioning caused by applying one beam in various lock widths

Graph 9 indicates that, if a door suitable for a lock width of 20, with a distributed load of 25 kN/m, were to be place in a 14m wide lock, the total over-dimensioning would be 118%, as indicated by the blue line. The lines display the over-dimensioning when a standard beam, designed for a 20 m wide lock, would be placed in locks with narrower widths. The over-dimensioning when applying a door suitable for a lock width of 20m to locks with narrower widths is caused by two factors:

1. Extra door length

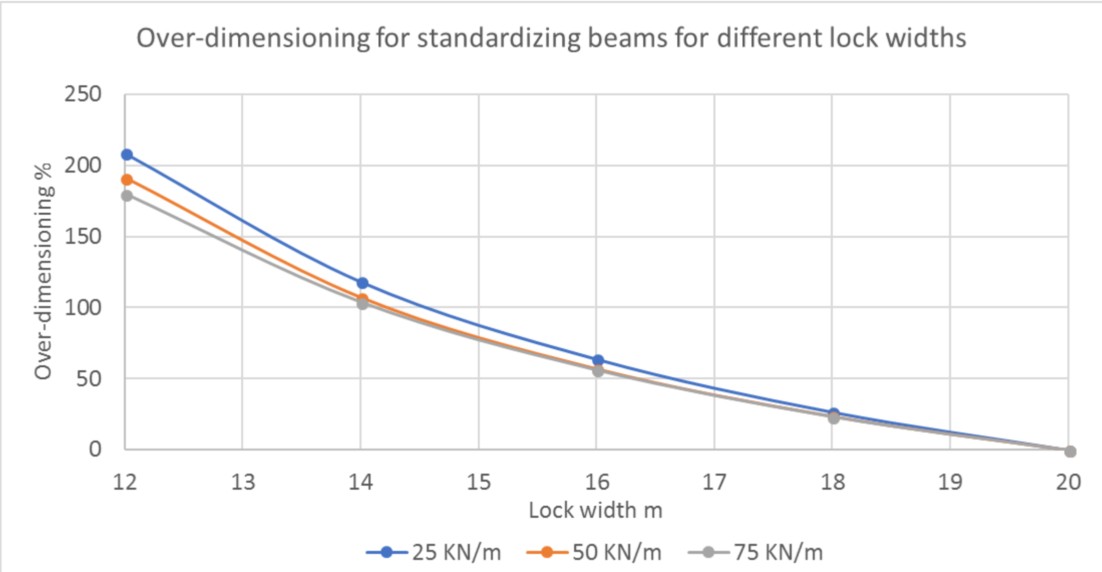
The beams of a 14m wide lock requires 30% less length than they do in a 20m wide lock. It can therefore be said that, when only considering the length of the beam, 43% of steel is already over-dimensioned when placing a door suitable for a 20m lock width to a lock with a width of 14m. The over-dimensioning due to access beam length is not affected by the distributed load.



Graph 9: Over-dimensioning caused by extra door length

2. Cross-sectional area of the beam

A decreasing span leads to a decrease in forcing on the beam, and therefore a beam with a smaller required cross-sectional area. Applying the same cross-sectional area for both a 20m and 14m wide lock results in cross-sectional over-dimensioning. In this case the cross-sectional area of the beam is over-dimensioned by 48.6%.



Graph 10: Over-dimensioning caused by excess profile dimensions

From graphs 9 and 11 it is interesting to notice that the lower the distributed load, the more significant the over-dimensioning becomes.

6.3 Over-dimensioning: standardizing door height

To make an estimation and determine the realtive over-dimensioning caused by implementing standized doors into several locks with different retention heights the following schematiztion is used:

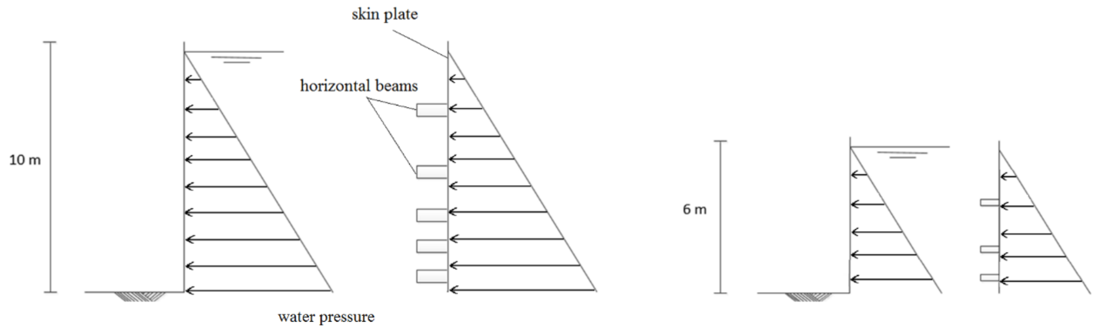


Figure 50: Amount of beams per varying retention height

Figure 50 illustrates the centre to centre (ctc) distance between the main horizontal beams of the doors. This ctc distance is determined such that all horizontal beams are loaded identically, explaining the narrowing ctc distance towards the bottom of the door where the loads are largest. For the sake of consistency, the amount of beams per door are determined by dividing the height of the door by a factor 2.

The load per beam equals to: $\rho g h$

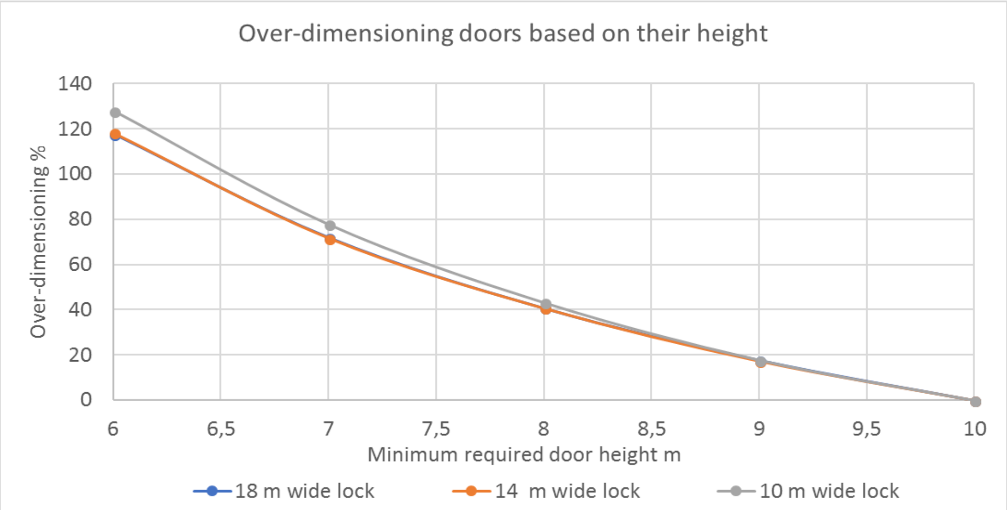
For the large door in Figure 50: $Q = 1000 * 10 * 10 = 100\ kN/m$ per beam

For the small door in Figure 50: $Q = 1000 * 10 * 6 \ = 60\ \ kN/m$ per beam

This section considers the case where one standard door were to be implemented for locks where the optimum door heights required would be ranging between 6 m and 10 m.
Multiplying the cross-sectional area of the beam by the amount of beams present in the door gives the total beam volume in the door.

The second table in Appendix F indicates the volume of steel required in the horizontal beams for the corresponding retention heights. Just like several distributed loads were assessed in the previous section, this section performs the study of over dimensioning caused by standardizing door height taking into consideration three lock widths, namely 10 m, 14 m and 18 m. For all lock widths a slope of closure of 3:10 is applied.

Plotting the over-dimensioning when considering the applience of a door designed to have a height of 10 m to fit into locks which require lower door heights:

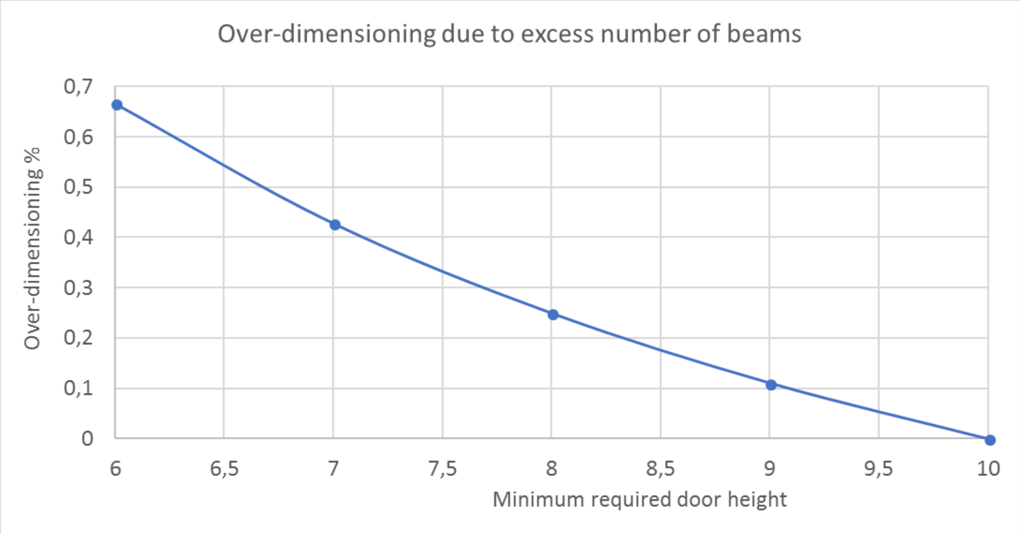


Graph 11: Over-dimensioning caused by applying one door for locks requiring various door heights

Again, the over-dimensioning is determined by two factors:

1. Extra door height

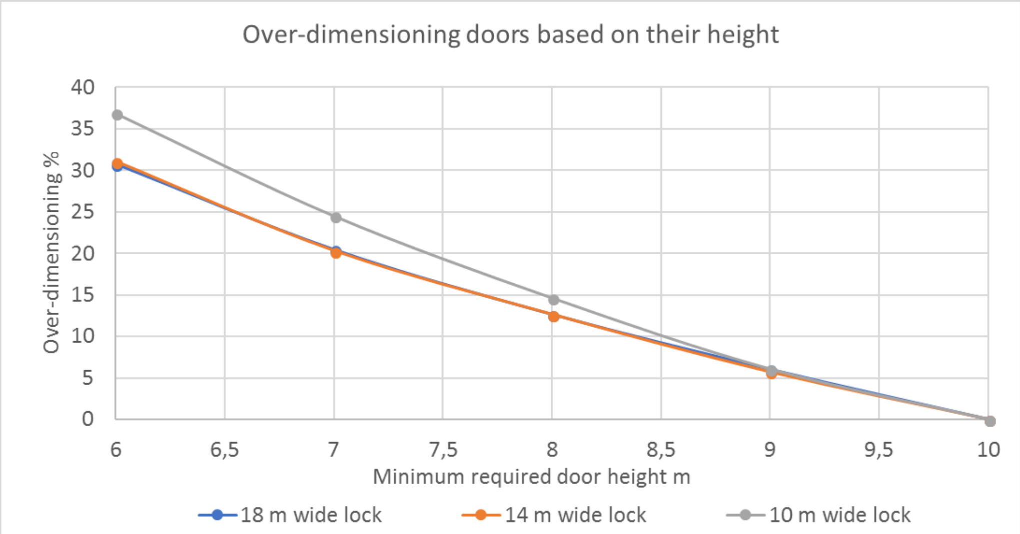
Applying a door designed with a height 10m with a retention height of 6m would already result in 4 excess meters of door height. Considering a situation where all the beams' cross-section would remain constant for varying retention height, the following relation can be found. In this case the over-dimensioning is only caused by the excess number of beams, the varying width of the lock would not have an effect of this over-dimensioning factor.



Graph 12: Over-dimensioning caused by excess number of beams

2. Cross-sectional area of the beam

Since the retention height is closely linked to the distributed load on the beams it is obvious that the beams in a door, having to retain 9m of water level difference, are much larger than those having to retain 5m. The graph below illustrates the over-dimensioning caused only by the increase in required cross-sectional area.



Graph 13: Over-dimensioning caused by excess profile dimensions

It is interesting to notice that the main contributor of the total over-dimensioning is caused by the excess number of beams.

6.4 Over-dimensioning: modularizing door height

Fortunately it is possible to reduce the total over-dimensioning caused by applying a standard door over locks with different retention heights. This can be done by modularizing the door as explained in Section 4.5.

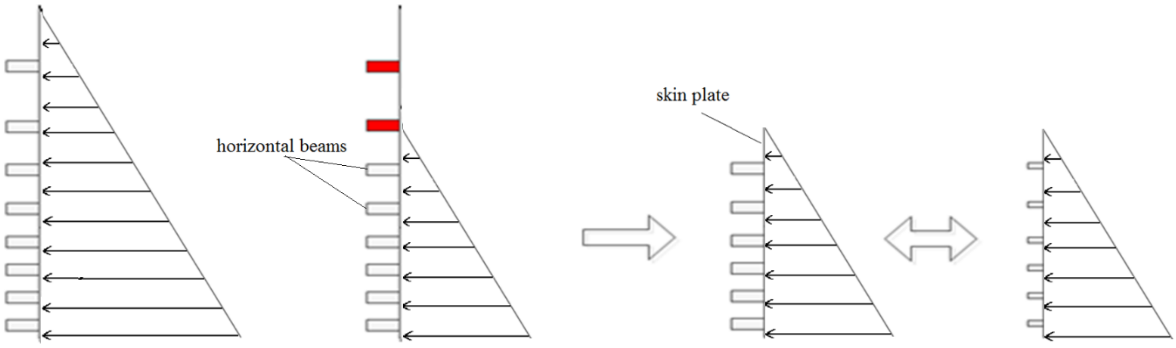


Figure 51: The downscaling of a large door by removing the top modules/beams

Figure 51 illustrates the downscaling process of the top modules to create a smaller lock gate. The beams in the most left situation are designed for the illustrated water pressures. Without modularization this door would be compared to the right most door in order to determine the over-dimensioning. When applying modularization the two top beams of the large door could be removed in order to create a door as illustrated in the middle figures. In this case the over-dimensioning is determined by comparing the two rightmost illustrations.

As explained in the previous section, the total over-dimensioning for gates with different retention heights as shown in graph 12 accounts for both cross-sectional over-dimensioning as door height over-dimensioning. The later can be prevented by applying smart modularization, this could potentially reduce the over-dimensioning relation shown in Graph 12 to the one shown in graph 14. This approach assumes the door to be modularized such that it is capable of containing the same amount of beams as the optimized door.

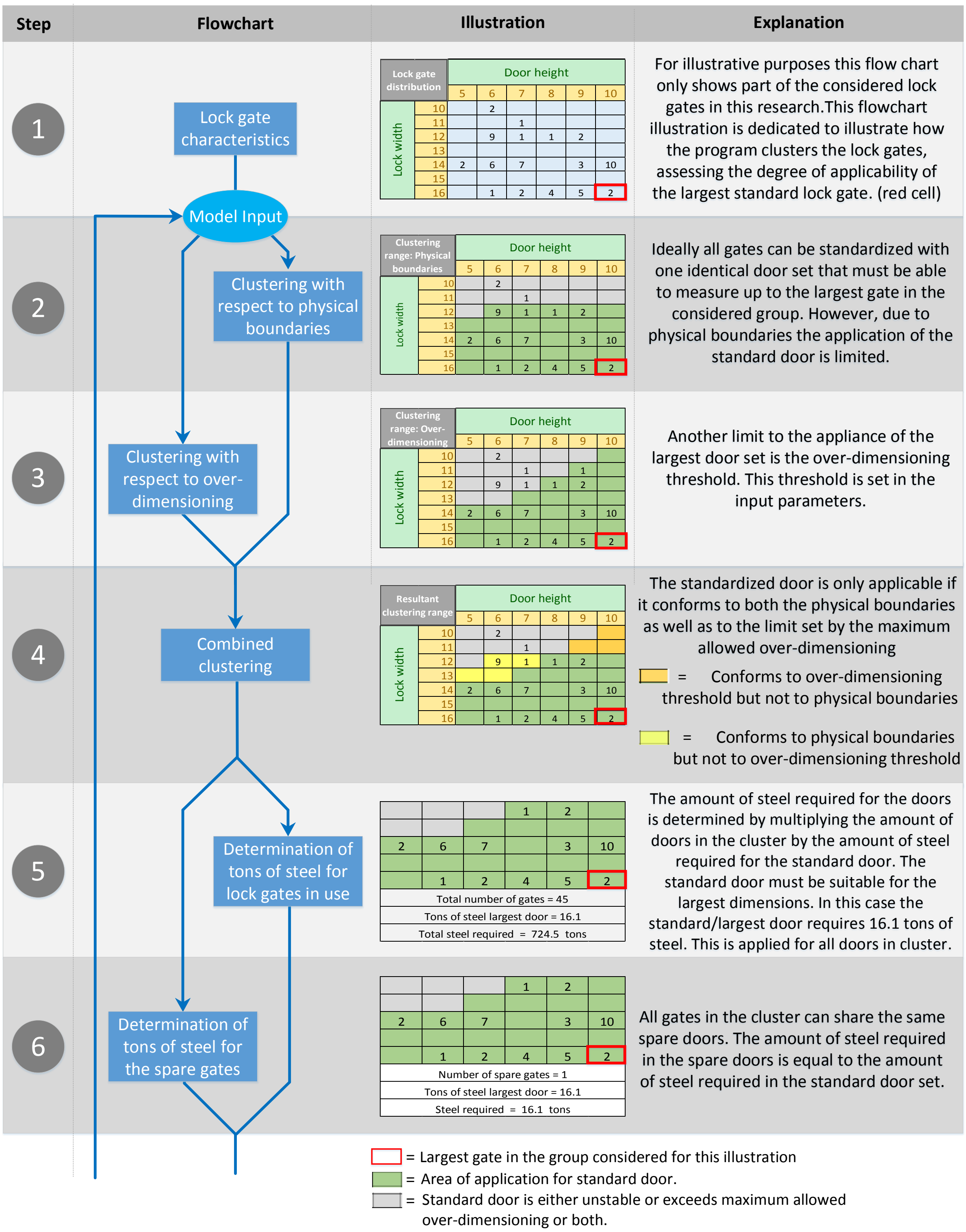
6.5 Conclusion

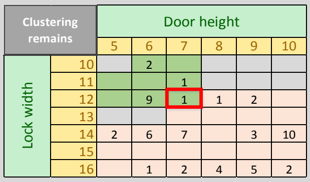
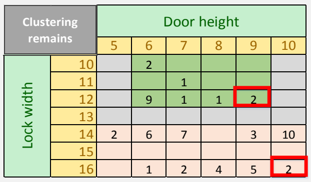
This chapter addressed the over-dimensioning as a consequence of standardizing a door for locks with different widths or different retention heights. It is interesting to notice that both have two factors that contribute to this over-dimensioning, namely the beam length or amount of beams and the cross sectional area of the beams. From the Section 6.3 and Section 6.4 it can be concluded that modularization has a great potential of reducing the over-dimensioning by reducing any excess beams contributing to unnecessary height.

The over-dimensioning was only determined with respect to one of the determining aspects at the time. This helped to visualize how each of the determining aspects play a role in the over-dimensioning when applying standardization over these aspects. Treating only one aspect at the time makes up a two dimensional relation between either lock width or retention height and the volume of steel needed. To classify the MWW lock gates, clusters will have to contain variations in both aspects. A door designed for a 18m wide lock with a retention height of 6m could for instance make up the governing design for all lock gates with a widths between 14m and 18m and a retention heights between 2m and 6m. This will be further elaborated in the next chapters.

7 Setting up the clustering program

The previous two chapters investigated the physical boundaries and over-dimensioning effects the chosen standardization methods have, considering one aspect at a time. To determine the optimum clustering of the gates a clustering program has been made. This chapter explains how this clustering program functions and is set up. The results obtained by using the program will be discussed in the next chapter. The following pages illustrate a flowchart indicating how the clustering program works and which steps are involved. This chapter and the chapter to follow answer RQ 4.



Step	Flowchart	Illustration	Explanation
7	Total steel required for specified cluster	724.5 + 16.1 = 740.6 tons	The summation of the steel required for the gates in use and the spare gate gives the total amount of steel required in the cluster.
8	Clustering of remaining lock gates		For the remaining gates, which have not been clustered so far, the steps 2,3 and 4 can be repeated.
9	Total steel required for cluster	4.7 x 13 + 4.7 = 65.8 tons	Repetition of steps 5, 6 and 7 to determine the amount of steel required for the specified cluster. For this cluster the largest door requires 4.7 tons of steel.
10	Total combined use of material	740.6 + 65.8 = 806.4 tons	The total amount of steel required for the cluster configuration is determined by summing up the amount of steel required in all clusters. This is the summation of the values found after step 7 and 9.
11	Optimization of cluster configuration	 692.3 + 96.2 = 788.5 tons	So far it is shown that the lock gates can be split up in two clusters. The border of the clusters however can still be optimized in order to save on material usage. Iterating the clustering of the lock gates it is possible to determine the optimum cluster configuration. In the case as presented in this step the standard door for the bottom cluster remains 16.1 tons, the door for the upper cluster becomes 5.7 tons. This configuration uses 17.9 tons less than the one previously shown.

= Largest gate in the group considered for this illustration
= Area of application for standard door.
= Standard door is either unstable or exceeds maximum allowed over-dimensioning or both.

7.1 Model input

Until now, this report discussed severable variables having a potential effect on the clustering possibilities and efficiency of the lock gates. To investigate the effect of these variables it has been chosen to incorporate them in the clustering program as specified model input parameters.

7.1.1 Gate modularity

The design of modular gates is a rather complex process and many complications may arise in the design process. Modularization will only be beneficial if the cons of complexity are outweighed by the pros of its effects on clustering, over-dimensioning and possibly others. To assess the positive effects of modularity, this program enables a modularity function and non-modularity function. The program can cluster the gates from either starting points.

7.1.2 Net difference in water head over doors

Chapter 5 discussed the stability of mitre gates by studying the relation between their slope of closure and a certain asymmetry value (q_2/q_1). The asymmetry value was mainly based on two factors:

-Net wave height difference

-Bow thrust elevation

So far this report considers the situation where a wave height causes a net change in outer water level of 1 m over the doors and the bow thrust elevation of 0.5 m in the inner water level (see Figure 43). These values are guessed for an extreme case, but the exact values for these conditions are not considered within the scope of this research. For this reason it is chosen to implement an option for the program where different values can be assigned for these factors.

7.1.3 Centre seal type

Section 5.4.3 indicated the influence of the centre seal type on the stability of the doors. It can be noted that the friction based seal is less stable whereas the normal force based central seal implies a more complex structure. To evaluate the overall influence of the type of centre seal on the clustering of the lock gates, it is chosen to define this as an input parameter for the clustering program.

7.1.4 Maximum allowed degree of over-dimensioning

One of the most important model input parameters is the maximum allowed degree of over-dimensioning. This input basically indicates the limit of clustering. The program aims to cluster the gates to a minimum amount of clusters. As we saw in the previous chapter on over-dimensioning clustering leads to over-dimensioning. If the over-dimension caused by the clustering of a specific gate into a category results in an over-dimensioning smaller than the maximum allowed degree of over-dimensioning the gate is included in the cluster. However, if the over-dimensioning exceeds the input value the gate cannot be included.

7.2 Incorporation of physical boundaries

Chapter 5 investigated the degree at which the slope of the doors can be varied has a limit depending on the degree of asymmetrical loading. This section illustrates how the physical boundaries are taken up in the clustering program by means of an example. The entire effects of the physical boundaries are shown in the last part of this section.

7.2.1 Example calculations

To visualize the effects the boundaries have on the standardization possibilities, two examples are worked out below. The examples both consider 7 locks with different widths ranging from 12 m to 18 m in steps of 1 m. Example A considers the retention height over all the 7 locks are equal at 2 m, Example B considers the retention height to be equal to 6 m. In both cases the relation holds that $\Delta h_1 = \Delta h_2 + 1.5$.

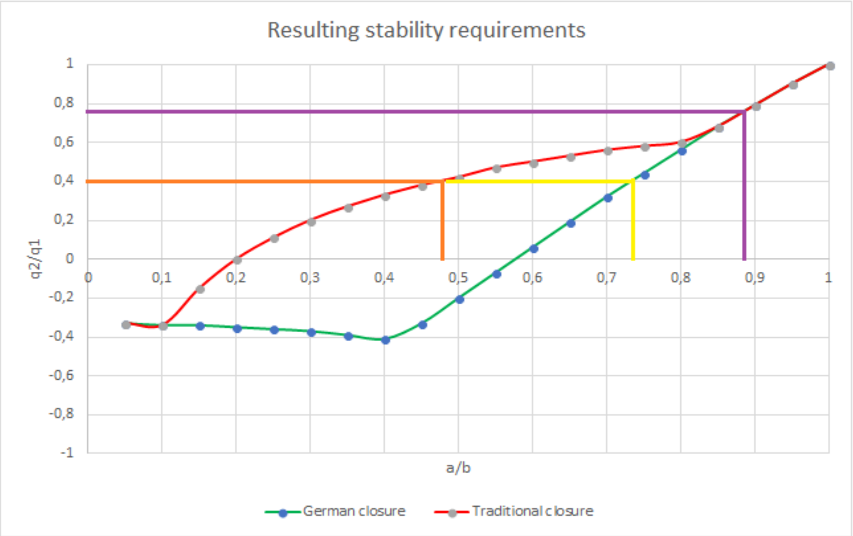
Degree of asymmetrical loading and the maximum slope of closure

Knowing the retention heights and the relation between Δh_1 and Δh_2, the degree of asymmetrical loading can be determined:

For Example A: $$\frac{q_2}{q_1} = \frac{2-0.5-0.5}{2+0.5} = 0.40$$

For Example B: $$\frac{q_2}{q_1} = \frac{6-0.5-0.5}{6+0.5} = 0.77$$

With the help of Graph 16 it is now possible to determine the maximum allowed slope for the doors in the locks of both examples to be stable.



Graph 14: Determining the maximum slope of closure

The orange lines illustrate the relation between the maximum allowed slope to the corresponding q2/q1 factor for Example A. These lines consider the friction seal between the doors, resulting in a maximum allowed slope of 0.48.

The yellow lines indicate this relation in case of the normal force based central seal, resulting in a maximum allowed slope of 0.73.

The purple lines show the relation for the case of Example B. Due to the high retention level and therefore the relatively highly degree of symmetry, the stability of the doors is not governed by the stability requirements regarding the closure between the gates but by the horizontal support reactions in the lock head. Due to this reason it does not matter which closure type is chosen. The maximum allowed slope in this case equals 0.89.

Determination of applicability values

As explained in Section 4.3.1, the standardization method is to apply the doors of a wide lock to a lock with a smaller width. The doors of the wide lock will be placed at the optimum slope 3:10.

The appliance of a single door in all locks would result in an increasing slope for decreasing lock widths. This is shown in Table 3. The left column shows the optimum door length corresponding to the constant slope. The column on the right maintains a fixed door length while the slope of closure of the doors is changed accordingly.

Appliance of doors		7 different doors		1 door	
		door length	slope	door length	slope
Lock width	12	6,26	0,3	9,40	1,21
	13	6,79	0,3	9,40	1,04
	14	7,31	0,3	9,40	0,90
	15	7,83	0,3	9,40	0,75
	16	8,35	0,3	9,40	0,62
	17	8,87	0,3	9,40	0,47
	18	9,40	0,3	9,40	0,30

Table 3: varying door length with constant slope / constant door length with varying slope

The maximum slopes for the stability of the gates impose the limit to which the door for the 18 m wide lock can be applied to the smaller locks. Table 4 shows the degree to which the largest lock gate can be applied for the two examples. The colors of the columns indicate the various situations from the examples with the maximum allowed slope given on the second row. The cells that are given a red color are the cells that exceed this maximum allowed slope and would result in instability.

Case		Example A (q2/q1=0.4) Traditional	Example A (q2/q1=0.4) German	Example B (q2/q1=0.77)
Max slope		0.48	0.73	0.89
Lock width	12	1,21	1,21	1,21
	13	1,04	1,04	1,04
	14	0,90	0,90	0,90
	15	0,75	0,75	0,75
	16	0,62	0,62	0,62
	17	0,47	0,47	0,47
	18	0.30	0.30	0.30

Table 4: Applicable slope of gates designed for 18m wide locks, placed in various lock widths

It can be observed that the optimum door for a 18m wide lock cannot be used in any other lock in the case of a friction based seal for Example A. It can however be used in three locks in case of a normal force based central seal. In case of Example B it can be applied in 5 other locks. Leaving the 18 m wide lock out of consideration and starting at the 17 m lock gives the results as shown in the table on the right. The 17 m wide lock doors can also be placed in one, three and five locks with different widths respectively.

Case		Example A (q2/q1=0.4) Traditional	Example A (q2/q1=0.4) German	Example B (q2/q1=0.77)
Max slope		0.48	0.73	0.89
Lock width	12	1,09	1,09	1,09
	13	0,93	0,93	0,93
	14	0,78	0,78	0,78
	15	0,63	0,63	0,63
	16	0,48	0,48	0,48
	17	0,30	0,30	0,30
	18	N.A.	N.A.	N.A.

Table 5: Applicable slope of gates designed for 18m wide locks, placed in various lock widths

Consequently it is possible to give each cell a value of applicability. The value of applicability demonstrates the degree of appliance of a gate, designed for its corresponding cell conditions. Meaning that in case of Example B, a lock gate designed for a 18 m wide lock can be placed in locks with widths between 18 m and 15 m.

Case		Example A (q2/q1=0.4) Traditional	Example A (q2/q1=0.4) German	Example B (q2/q1=0.77)
Lock width	17	1	3	4
	18	2	3	4

Table 6: Applicability values as derived from Table 4 and Table 5

If the process like shown on the previous page is repeated for the other lock widths as shown in Table 3, the table can be filled with the remaining results for the values of applicability.

Case		Example A (q2/q1=0.4) Traditional	German	Example B (q2/q1=0.77)
Lock width	12	1	2	3
	13	1	3	3
	14	1	3	4
	15	1	3	4
	16	1	3	4
	17	1	3	4
	18	2	3	4

Table 7: Applicability values obtained by continuing process

If it we desired to equip a maximum of amount of locks with gates designed and optimized for a 18 m wide lock, Table 7 tells us something about the boundaries of the degree of applicability of this gate. Using these boundaries, the orange cells in Table 8 indicate all locks that can be equipped with the same lock gates.

Case		Example A (q2/q1=0.4) Traditional	German	Example B (q2/q1=0.77)
Lock width	12	1	2	3
	13	1	3	3
	14	1	3	4
	15	1	3	4
	16	1	3	4
	17	1	3	4
	18	2	3	4

Table 8: Applicability of a gate optimized (slope of 3:10) for a lock width of 18 m

Table 9 indicates the applicability of a lock gate optimized for a 16m wide lock.

Case		Example A (q2/q1=0.4) Traditional	German	Example B (q2/q1=0.77)
Lock width	12	1	2	3
	13	1	3	3
	14	1	3	4
	15	1	3	4
	16	1	3	4
	17	1	3	4
	18	2	3	4

Table 9: Applicability of a gate optimized (slope of 3:10) for a lock width of 16 m

7.2.2 *Programming*

The method for the determination of the applicability values is programed into excel, assigning the closure mechanism and wave and bow thrust conditions as model input parameters. By implementing this method on the range of lock characteristics found amongst the MWW locks, several results can be obtained. Table 7 indicates the applicability values considering a lock gate with a friction based seal and a net height difference of 1.5 m over the gates ($\Delta h_1 = \Delta h_2 + 1.5$). Table 8 assumes the same height difference but considers a normal force based central seal. Table 9 and Table 10 show the application values in case of a friction based and normal force based central seal and a height difference of $\Delta h_1 = \Delta h_2 + 0.5$. The four tables indicate the relation between the standardization opportunities and the type of closure and the assumed water level difference over the doors. The normal force based central seal clearly offers more possibilities for the second and third columns. The possibilities largely increase when the water level difference over the doors is decreased from 1.5 m to 0.5 m.

Applicability Values		Retention height								
		1	2	3	4	5	6	7	8	9
Lock width (m)	5	0	1	1	2	2	2	2	2	2
	6	0	1	1	2	2	2	2	2	2
	7	0	1	2	2	2	2	2	2	2
	8	0	1	2	2	2	2	2	2	2
	9	0	1	2	2	2	2	3	3	3
	10	0	1	2	3	3	3	3	3	3
	11	0	1	2	3	3	3	3	3	3
	12	0	1	2	3	3	3	3	3	3
	13	0	1	3	3	3	3	3	3	4
	14	0	1	3	3	3	4	4	4	4
	15	0	1	3	4	4	4	4	4	4
	16	0	1	3	4	4	4	4	4	4
	17	0	1	3	4	4	4	4	4	4
	18	0	2	3	4	4	4	5	5	5

Table 7: Friction based seal and $\Delta h_1 = \Delta h_2 + 1.5$

Applicability Values		Retention height								
		1	2	3	4	5	6	7	8	9
Lock width (m)	5	1	1	1	2	2	2	2	2	2
	6	1	1	2	2	2	2	2	2	2
	7	1	2	2	2	2	2	2	2	2
	8	1	2	2	2	2	2	2	2	2
	9	1	2	2	2	2	2	3	3	3
	10	1	2	2	3	3	3	3	3	3
	11	2	2	3	3	3	3	3	3	3
	12	2	2	3	3	3	3	3	3	3
	13	2	3	3	3	3	3	3	3	4
	14	2	3	3	3	3	4	4	4	4
	15	2	3	3	4	4	4	4	4	4
	16	2	3	4	4	4	4	4	4	4
	17	2	3	4	4	4	4	4	4	4
	18	2	3	4	4	4	4	5	5	5

Table 8: Normal force based central seal and $\Delta h_1 = \Delta h_2 + 1.5$

Applicability Values		Retention height								
		1	2	3	4	5	6	7	8	9
Lock width (m)	5	1	2	2	2	2	2	2	2	2
	6	1	2	2	2	2	2	2	2	2
	7	2	2	2	2	2	2	2	2	2
	8	2	2	2	2	2	2	2	2	2
	9	2	2	2	3	3	3	3	3	3
	10	2	3	3	3	3	3	3	3	3
	11	2	3	3	3	3	3	3	3	3
	12	2	3	3	3	3	3	3	3	3
	13	3	3	3	3	4	4	4	4	4
	14	3	3	4	4	4	4	4	4	4
	15	3	4	4	4	4	4	4	4	4
	16	3	4	4	4	4	4	4	4	4
	17	3	4	4	4	4	5	5	5	5
	18	3	4	4	5	5	5	5	5	5

Table 9: Friction based central seal and $\Delta h_1 = \Delta h_2 + 0.75$

Applicability Values		Retention height								
		1	2	3	4	5	6	7	8	9
Lock width (m)	5	1	2	2	2	2	2	2	2	2
	6	1	2	2	2	2	2	2	2	2
	7	1	2	2	2	2	2	2	2	2
	8	1	2	2	2	2	2	2	2	2
	9	1	2	3	3	3	3	3	3	3
	10	1	3	3	3	3	3	3	3	3
	11	1	3	3	3	3	3	3	3	3
	12	1	3	3	3	3	3	3	3	3
	13	2	3	3	3	4	4	4	4	4
	14	2	3	4	4	4	4	4	4	4
	15	2	4	4	4	4	4	4	4	4
	16	2	4	4	4	4	4	4	4	4
	17	2	4	4	4	5	5	5	5	5
	18	2	4	5	5	5	5	5	5	5

Table 10: Normal force based central seal and $\Delta h_1 = \Delta h_2 + 0.75$

7.3 Incorporation of over-dimensioning

Chapter 6 investigated the degree at which the standardization methods result in over-dimensioning. This section illustrates how the program determines the over-dimensioning when standardizing a lock gate within a cluster containing various locks with different widths and retention heights.

7.3.1 Approximation amount of steel required and over-dimensioning

Over-dimensioning is based on the comparison of amount of steel used, therefore estimations of the amount of steel required in the lock gates must be made. The optimum amount of steel required is determined by using the same method as in Section 6.3. However, the cross-sectional area of the required beams are determined using linear interpolation for unity checks and profile dimensions, this is explained in Appendix G, showing the entire process.
Table 11 illustrates the amount of steel needed in the beams for the lock gates with a width ranging from 5 m to 8 m and a door height from 4 m to 8 m.

TONS OF STEEL IN BEAMS		Door height (m)				
		4	5	6	7	8
Lock width (m)	5		0,4			
	6					1,3
	7	0,6	0,8			
	8		1,1	1,5		2,3

Table 11: Approximation of steel in beams

7.3.2 Over-dimensioning

The over-dimensioning is relatively easy to determine: if the 8m wide and 8m high lock gate (8 : 8) were to be placed in the 7m wide and 5m high lock gate (7 : 5) the over-dimensioning would be:

$$\frac{Steel\ (8:\ 8) - Steel(7:5)}{Steel(7:5)} * 100 = 184\%$$

Adding modularity to the doors would subtract the extra height of the 8 : 8 door by taking away the excess beams. The weight of the modular door for the 8 : 8 situation remains 2.3tons, whereas the weight of the door when placed in the 7 : 5 lock would be reduced to:

$$\frac{Steel\ (8:8) * amount\ of\ beams\ (7:5)}{amount\ of\ beams\ (8:8)} = \frac{2.3 * 2.5}{4} = 1.45\ tons$$

This is the same as just determining the over-dimensioning based on the over-dimensioning caused by the additional stiffness and length of the profiles and not the additional number of profiles. This was more thoroughly explained in section 6.4.
The reduction of the excess beams leads to the following over-dimensioning:

$$\frac{Steel\ (8:\ 8) * \frac{2.5}{4} - Steel(7:5)}{Steel(7:5)} * 100 = 78\%$$

Tables 12 and 13 indicate the over-dimensioning if all gates within Table 11 were to be clustered with one standardized/modular gate design optimized for the largest required dimensions.

Over-dimensioning %		Door height (m)				
		4	5	6	7	8
Lock width (m)	5		482			
	6					85
	7	305	184			
	8		108	58		0

Table 12: Over-dimensioning is case of standard door heights

Over-dimensioning %		Door height (m)				
		4	5	6	7	8
Lock width (m)	5		264			
	6					85
	7	103	78			
	8		30	18		0

Table 13: Over-dimensioning is case of modular door heights

The input parameter for the over-dimensioning dictates the limit for the occurring over-dimensioning. The clustering program calculates the over-dimensioning per gate automatically, as long as the over-dimensioning of a gate doesn't exceed the input parameter the gate can be clustered with another gate. However, if the over-dimensioning does exceed the limit, a new cluster is formed. The following chapter goes into more detail about this clustering process.

7.4 Clustering process

Clustering the lock gates mainly depends on two things, namely the allowed over-dimensioning and the physical boundaries. Now that these are incorporated in the clustering program, this section illustrates how the program comes up with clusters and the effect of the model input parameters. In order to visualize the clustering process, this section only considers the clustering of the locks withing Table 11.

7.4.1 Physical boundary based clustering

If we initially consider the situation where there is no asymmetrical loading ($\Delta h_2 = \Delta h_1$) on the gates we find the following applicability values as presented in Table 14. This table tells indicates that even when no asymmetrical loading would occur, the gates considered would not be able to be clustered into one category due to the occurrence of instability.

Applicability Values		Retention height (m)				
		1	2	3	4	5
Lock width (m)	5	2	2	2	2	2
	6	2	2	2	2	2
	7	2	2	2	2	2
	8	3	3	3	3	3

Table 14: Applicability values for $\Delta h_2 = \Delta h_1$

From the values found in Table 14 it seems that from the instability point of view, the maximum degree of standardization would be to cluster the lock gates into two categories. The clustering of the lock gates is presented in Table 15. The clusters are to be identified by the colors.

Amount of lock gates		Retention height (m)				
		1	2	3	4	5
Lock width (m)	5		3			
	6					3
	7	5	3			
	8		4	6		4

Table 15: Clustering of lock gates for$\Delta h_2 = \Delta h_1$

Considering the normal force based central seal, the asymmetrical loading does not affect the clustering possibilities until the value for net head difference between the doors reaches the critical value of $\Delta h_2 - \Delta h_1 = 1.2\ m$. For the friction based seal this value is 0.45 m. As the red cell in Table 15 becomes 1 when increasing the net head difference, the bottom cluster in Table 14 must be split up.

Applicability Values		Retention height (m)				
		1	2	3	4	5
Lock width (m)	5	1	1	2	2	2
	6	1	2	2	2	2
	7	1	2	2	2	2
	8	1	2	2	2	2

Table 126: Applicability values for $\Delta h_2 - \Delta h_1 =$ $1.2m$ and normal force based seal

Table 16 indicates that when a gate is designed for a 9m wide lock it can be applied in a 7 m wide lock only when there is a minimum retention height of 2 m. At a retention height of 1 m it is only stable in a 8 m wide lock, hence the red “1”. This change in applicability causes a change in the clustering possibility, splitting up the lower cluster into two clusters as shown in Table 17

Amount of lock gates		Retention height (m)				
		1	2	3	4	5
Lock width (m)	5		3			
	6					3
	7	5	3			
	8		4	6		4

Table17: Clustering of lock gates for $h_2 - \Delta h_1 = 1.2m$ and normal force based seal

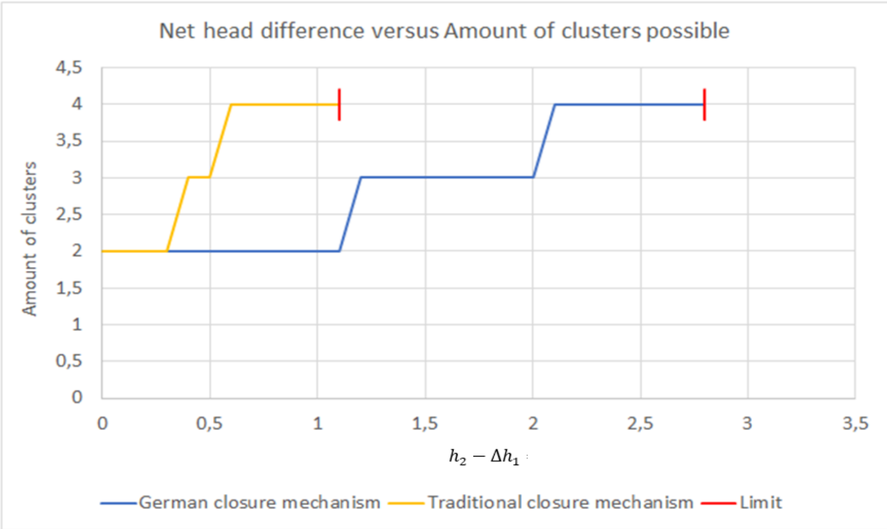
Increasing the value for the net head difference up to 2.1 m causes the upper cluster to become unstable as well resulting in a total of four clusters. For the friction based seal this would be necessary at a net head difference of 0.6 m. Increasing the net head difference from this point onwards does not lead to any further change in the clustering possibilities. Table 18 illustrates the minimum degree of clustering as a result of asymmetric loading.

Amount of lock gates		Retention height (m)				
		1	2	3	4	5
Lock width (m)	5		3			
	6					3
	7	5	3			
	8		4	6		4

Table18: Clustering of lock gates for $h_2 - \Delta h_1 = 2.1m$ and normal force based seal

If increased to 2.85 m none of the gates with a retention of 1m would be stable. This type of instability is not further taken into account in this report nor considered as a physical boundary. The same degree of instability would occur for a friction based seal at a net difference of 1.2 m (see Graph 7).

Graph 16 sums up the effect of the physical boundaries on the clustering possibilities for the lock gates considered in this illustrating section:



Graph 15: Effect of physical boundaries on clustering

7.4.2 Over-dimensioning based clustering

Considering a normal force based centre seal and $h_2 - \Delta h_1 < 1.2\ m$, where the asymmetrical loading does not affect the clustering it's possible to determine the clustering based on over-dimensioning alone. *This section illustrates the clustering over-dimensioning based clustering by addressing modular gates only*

- When initially setting the maximum allowed over-dimensioning to 0% each cell forms its own cluster, this is the minimum form of clustering considered in this research[2]. The tables below illustrate the clusters formed and the over-dimensioning the clustering results to.

Amount of lock gates		Retention height (m)				
		1	2	3	4	5
Lock width (m)	5		3			
	6					3
	7	5	3			
	8		4	6		4

Table 13: Clustering for 0% over-dimensioning

over dimensioning %		Retention height (m)				
		1	2	3	4	5
Lock width (m)	5		0			
	6					0
	7	0	0			
	8		0	0		0

Table 14: Over-dimensioning for 0% over-dimensioning

The steel required in all lock gates is determined by multiplying the amount of gates by their required amount of steel (Table 11). For 0% over-dimensioning this results in 33.2 tons. Under the assumption that gates within category can share the same spare components, the amount of steel required for the spare components can be determined by adding up the tons of steel per unique door. In this case this adds up to a 8.0 tons. The total combined amount of steel required for this configuration therefore becomes 41.2 tons.

Steel in lock gates (tons)	Amount of clusters #	Spare components (tons)	Total (tons)
33.2	7	8.0	41.2

Table 15: Amount of steel required for 0% over-dimensioning

- Increasing the allowed over-dimensioning to 10% the first cluster is formed:

[2] This research assumes that the gates within a cell have identical dimensions. This is however not the case as the true dimensions have been rounded off to their closest integer.

Amount of lock gates		Retention height (m)				
		1	2	3	4	5
Lock width (m)	5		3			
	6					3
	7	5	3			
	8		4	6		4

Table 16: Clustering for 10% over-dimensioning

over dimensioning %		Retention height (m)				
		1	2	3	4	5
Lock width (m)	5		0			
	6					0
	7	0	0			
	8		10	0		0

Table 17: Over-dimensioning for 10% over-dimensioning

In this case the total amount of steel in the locks increases to 33.7 tons due to the over-dimensioning of the four 8 : 2 lock gates. However, since the lock gates for cell 8 : 2 and 8 : 3 share the same door they can also share the same spare components. This reduces the amount of spare gates from 7 to 6, the total amount of steel required in the spare gates is hereby reduced to 6.9 tons. For the total amount of steel used a reduction of 0.6 tons is obtained (total of 40.6 tons)

Steel in lock gates (tons)	Amount of clusters #	Spare components (tons)	Total (tons)
33.7	6	6.9	40.6

Table 18: Amount of steel required for 10% over-dimensioning

- The next cluster is formed when allowing a maximum over-dimensioning of 14%:

Amount of lock gates		Retention height (m)				
		1	2	3	4	5
Lock width (m)	5		3			
	6					3
	7	5	3			
	8		4	6		4

Table 19: Clustering for 14% over-dimensioning

over dimensioning %		Retention height (m)				
		1	2	3	4	5
Lock width (m)	5		0			
	6					0
	7	14	0			
	8		10	0		0

Table 20: Over-dimensioning for 14% over-dimensioning

Steel in lock gates (tons)	Amount of clusters #	Spare components (tons)	Total (tons)
34.1	5	6.3	40.4

Table 21: Amount of steel required for 14% over-dimensioning

- Allowing a maximum over-dimensioning of 30%:

Amount of lock gates		Retention height (m)				
		1	2	3	4	5
Lock width (m)	5		3			
	6					3
	7	5	3			
	8		4	6		4

Table 22: Clustering for 30% over-dimensioning

over dimensioning %		Retention height (m)				
		1	2	3	4	5
Lock width (m)	5		0			
	6					0
	7	14	0			
	8		30	18		0

Table 23: Over-dimensioning for 30% over-dimensioning

Steel in lock gates (tons)	Amount of clusters #	Spare components (tons)	Total (tons)
36.6	4	4.8	41.5

Table 24: Amount of steel required for 30% over-dimensioning

- Allowing a maximum over-dimensioning of 85%:

Amount of lock gates		Retention height (m)				
		1	2	3	4	5
Lock width (m)	5		3			
	6					3
	7	5	3			
	8		4	6		4

Table 25: Clustering for 85% over-dimensioning

over dimensioning %		Retention height (m)				
		1	2	3	4	5
Lock width (m)	5		0			
	6					85
	7	71	50			
	8		10	0		0

Table 26: Over-dimensioning for 85% over-dimensioning

Steel in lock gates (tons)	Amount of clusters #	Spare components (tons)	Total (tons)
40.2	3	4.2	44.5

Table 27: Amount of steel required for 85% over-dimensioning

- Allowing a maximum over-dimensioning of 97%:

Amount of lock gates		Retention height (m)				
		1	2	3	4	5
Lock width (m)	5		3			
	6					3
	7	5	3			
	8		4	6		4

Table 28: Clustering for 97% over-dimensioning

over dimensioning %		Retention height (m)				
		1	2	3	4	5
Lock width (m)	5		97			
	6					0
	7	14	0			
	8		30	18		0

Table 29: Over-dimensioning for 97% over-dimensioning

Steel in lock gates (tons)	Amount of clusters #	Spare components (tons)	Total (tons)
37.8	3	4.4	42.2

Table 30: Amount of steel required for 97% over-dimensioning

- Allowing a maximum over-dimensioning of 103%:

Amount of lock gates		Retention height (m)				
		1	2	3	4	5
Lock width (m)	5		3			
	6					3
	7	5	3			
	8		4	6		4

Table 31: Clustering for 103% over-dimensioning

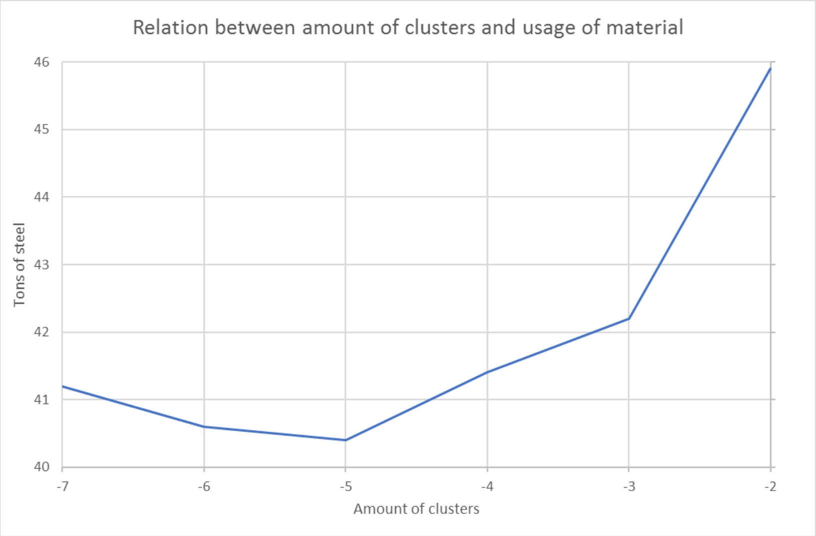
over dimensioning %		Retention height (m)				
		1	2	3	4	5
Lock width (m)	5		97			
	6					0
	7	103	78			
	8		30	18		0

Table 32: Over-dimensioning for 103% over-dimensioning

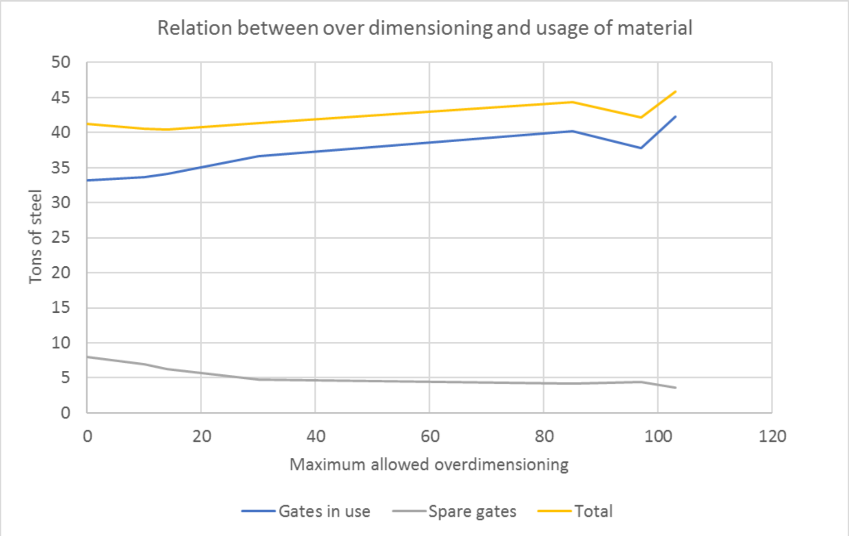
Steel in lock gates (tons)	Amount of clusters #	Spare components (tons)	Total (tons)
42.3	2	3.6	45.9

Table 33: Amount of steel required for 103% over-dimensioning

By summarizing the results for the amount of steel required for the various clustering configurations given in Tables 19 to 38, the following two graphs are obtained:



Graph 16: Clustering and usage of material[3]



Graph 17: Over-dimensioning and usage of material

From the Graphs 17 and 18 it is interesting to notice how the amount of material used decreases as the over-dimensioning increases from 85% to 97% where both situation count the same amount of clusters. This is because apparently the higher over-dimensioning offers a more efficient clustering concerning the material required in the spare components.

7.5 Conclusion

This chapter described the functioning of the clustering program. It demonstrated the effects of the model input parameters and what results can be obtained by means of applying the program. The demonstration was based on a small section of the MWW lock gates. The data from the clustering program can be used to determine the relation to the amount of material required in the lock gates and the degree to which these are clustered and standardized. The following chapter discusses the results obtained by applying the clustering program to the entire MWW lock gate arsenal as given in Table 2.

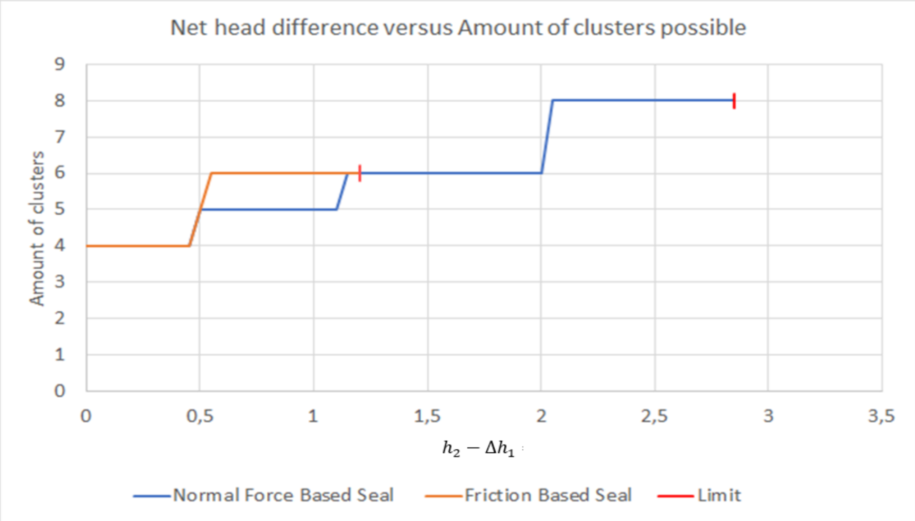
[3] The minimum amount of clusters is defined by the amount of unique doors (this is given by the amount of cells containing a number)

8 Clustering results

The previous chapter brought clarity on to how the clustering program works and which results can be obtained. So far all the clustering has been done only considering a fraction of the gates. The section shows the results obtained if all the relevant lock gates are taken in consideration. This chapter answers RQ 4.

8.1 Physical boundaries

Graph 19 illustrates how the net head difference over the gates relate to the clustering possibilities, clearly indicating the effect of the different centre seal types.

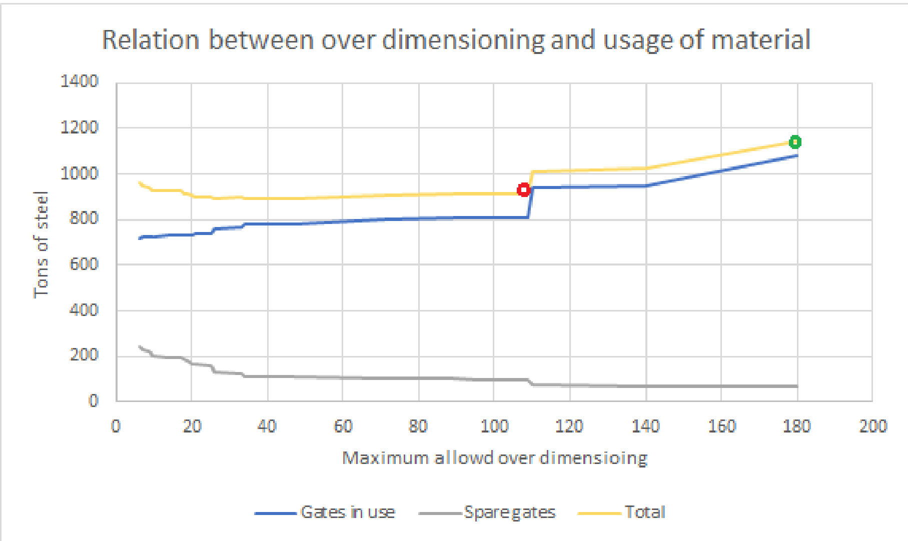


Graph 18: Effect of physical boundaries on clustering

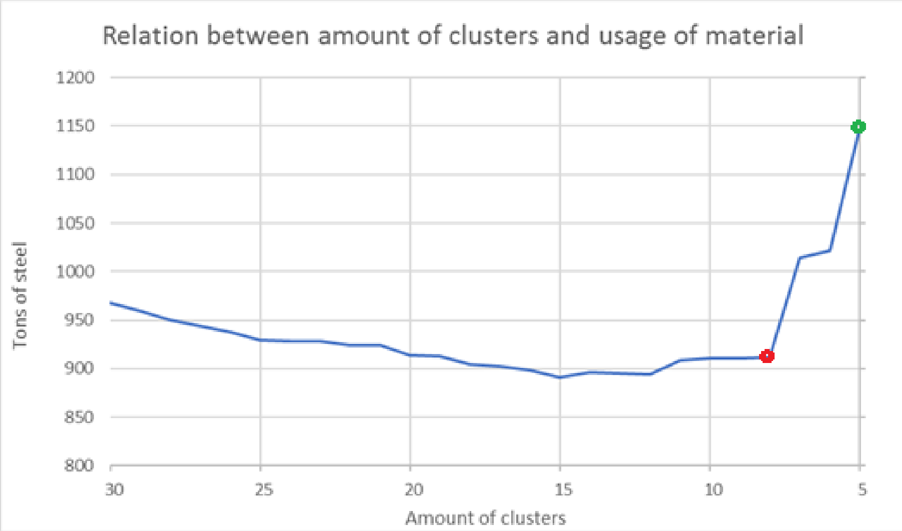
The lines indicate the minimum amount of clusters possible with a certain net head difference occurring between the doors. The red lines indicate the maximum allowed net head difference for each corresponding centre seal type. In practice the net head difference over the doors are never exactly equal to each other. This report further assumes $h_2 - \Delta h_1$ to range between 0.5 m and 1 m.

8.2 Over-dimensioning and use of material

Graphs 19 and 20 illustrate how the clustering of the lock gates relates to the amount of required steel and maximum over-dimensioning, **only considering modular gates**.



Graph 19: Over-dimensioning and usage of material



Graph 20: Clustering and usage of material

The red dots on the graphs indicate a cluster configuration which offers a great degree of standardization: a total of 8 clusters and a decrease for the total amount of steel required of 6% with respect to the configuration with 0% over-dimensioning. The green dot corresponds to the configuration with the maximized degree of standardization (for $0.5\,m < h_2 - \Delta h_1 < 1\,m$). Where amount of clusters is reduced to 5. In this case the total amount of material required is increased by 18.5% with respect to the configuration with 0% over-dimensioning. The two clustering configurations are displayed in the tables below:

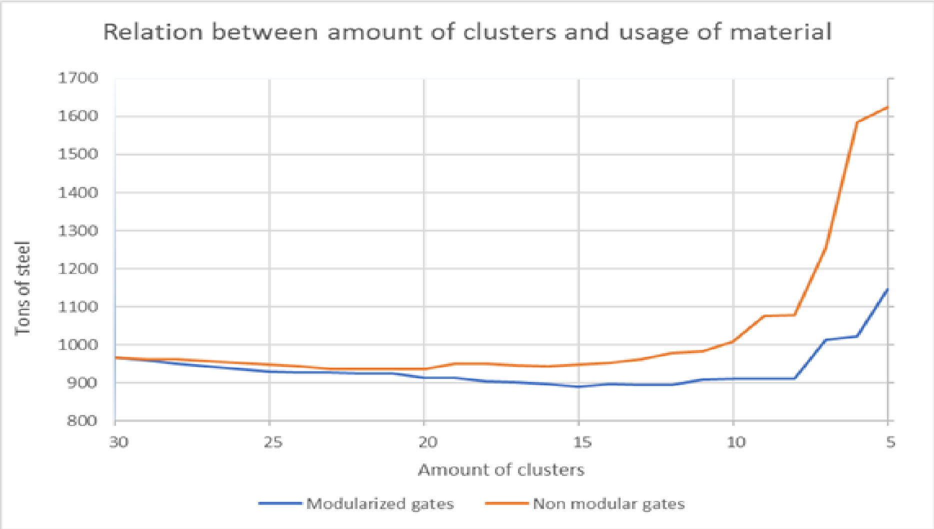
Clustering by color	Door height										Total amount of gates per cluster
Lock width (m)	4	5	6	7	8	9	10	11	12	13	6 gates
5		3									
6					3						18 gates
7	5	3									
8		4	6		4			2			6 gates
9											
10			2								17 gates
11				1		1					
12			9	1	1	2					28 gates
13											
14		2	6	7		3	10				14 gates
15											
16			1	2	4	5	2				5 gates
17											
18			1	2	2			3		1	4 gates

Table 34: Red dot configuration with 8 clusters

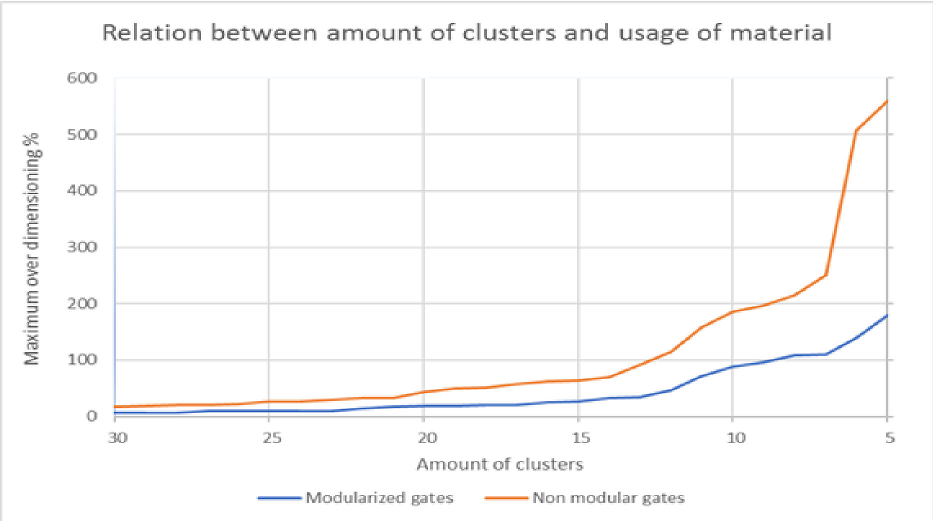
Clustering by color	Door height										Total amount of gates per cluster
Lock width (m)	4	5	6	7	8	9	10	11	12	13	6 gates
5		3									
6					3						18 gates
7	5	3									
8		4	6		4			2			17 gates
9											
10			2								28 gates
11				1		1					
12			9	1	1	2					14 gates
13											
14		2	6	7		3	10				
15											
16			1	2	4	5	2				
17											
18			1	2	2			3		1	

Table 35: Green dot configuration with 5 clusters

The entire process of clustering can also be done in case the doors would not be modular. The graphs below illustrate the effects this would have on the use of material and the maximum over-dimensioning.



Graph 21: Comparison between the tons of steel required for modular and non-modular gates



Graph 22: Comparison between the over-dimensioning for modular and non-modular gates

8.3 Conclusion

This chapter gives the answer to the fourth research question presented in the problem definition of this report:

How does the standardization method relate to the clustering of the lock gates with regard to over-dimensioning and the physical boundaries?

It can be concluded that the modularization has a big effect on the amount of required material and the maximum over-dimensioning. This effect significantly increases if the amount of clusters decrease. At eight clusters, the method with a standardized door height requires 19% more steel than the method with modularized door heights and 42% in case of five clusters. Concerning the physical boundaries, the normal force based centre seal enhances the stability of the lock gates, having a significant impact on the clustering possibilities. To determine the optimum configuration, a trade-off must be made between variety reduction and amount of steel required. In this case the two most interesting configurations are the ones shown in Tables 40 and 41. In this case the trade-off must be made between having eight clusters or five clusters, requiring either 6% less steel or 18% more steel respectively when compared to the case where no standardization is applied.

9 Design of a modular gate

So far, this research has been conducted on a theoretical scale, assuming the doors of a mitre gate are purely made up of horizontal beams and that modularization would result in a direct addition or subtraction of beams. One of the findings so far, is that this type of modularization brings many benefits towards the use of material and over-dimensioning. In reality the design of a door is much more complicated than just horizontal beams, and modularization cannot be accounted for by a simple addition or subtraction of horizontal beams. In this chapter the conceptual design is made for a modular gate within ***one*** specified gate cluster. The design process focusses on the leveling systems, torsional stability, size of the modules, connection between the modules and the connection between the doors and the lock head. To find an appropriate solution for these gate characteristics a number of requirements are set up, based on which the gate design is made. The purpose of this chapter is to gain better understanding of the overall design principles of standardized lock gates, this is done by only addressing one design suitable for only one specified cluster. This chapter answers RQ 5.

9.1 Selection of the cluster and the actual lock data

To illustrate what a standardized gate, designed according to the standardization theory as discussed in this research, focus is put on the largest cluster possible. This cluster includes locks ranging from 16.00m to 18.00m wide and doors heights from 6.35m to 12.70m. During the entire research the heights and widths of the doors have been rounded off to whole numbers, based on which they were placed in their corresponding cells. For the design of a door it is important to assess the actual dimensions. Tables 42 and 43 illustrate the cluster considered along with the real dimensions of the locks and the characteristics relevant for the conceptual standardized door design. This chapter only includes the design of a door suitable for a lock gate within this cluster only.

Amount of lock gates	Door height									
Lock width (m)	4	5	6	7	8	9	10	11	12	13
5		3								
6					3					
7	5	3								
8		4	6		4			2		
9										
10			2							
11				1		1				
12			9	1	1	2				
13										
14		2	6	7		3	10			
15										
16			1	2	4	5	2			
17										
18			1	2	2			3		1

Table 36: Chosen cluster (red)

Lock name	Lock length	Lock width	Ship Class	Door height	locking diffenence
Sluis Roermond	267	16	CEMT Va	6,35	2,35
Sluis Linne	268	16	CEMT Va	6,75	2,75
Schutsluis Belfeld oost (oude sluis)	260	16	CEMT Va	7,55	3,05
Schutsluis Sambeek oost	260	16	CEMT Va	8,25	4,25
Sluis Linne	268	16	CEMT Va	8,50	4,00
Sluis Roermond	267	16	CEMT Va	8,65	2,75
Sluis Heumen	250	16	CEMT Vb	9,15	4,86
Sluis Heumen	250	16	CEMT Vb	10,05	4,86
Middensluis	95	18	CEMT IV	6,35	3,88
Middensluis	95	18	CEMT IV	7,06	3,88
Prinses Marijkesluis westelijke sluis	260	18	CEMT Vb	8,35	2,60
Prinses Marijkesluis westelijke sluis	260	18	CEMT Vb	11,35	2,60
Zuidersluis	104	18	CEMT Va	12,70	5,65

Table 37: Real lock characteristics of locks within chosen cluster

9.2 Requirements for a modular design

The starting points that govern the design of the modular door are given in the following list. The challenge of designing the door will be to take each of them into account, even if some might be contradictory.

1. Minimum effect on existing civil structure
   - Effect on sill is inevitable as angles are varied
   - Effect on pivots is caused by two potential reasons:
     - Increased door weight compared to previous door weight (=increase in pivot loads)
     - Change in door height might lead to relocation of upper pivot.
2. Minimum number of modules
   - Section 4.2 indicated that one of the main starting points considered in this research is to aim for variety reduction, thus as little unique components as possible in order to keep maintenance and management optimal and easy.
3. Ease of assembly & disassembly
   - The spare modules must be easy to assemble in a minimum amount of time in order to prevent the unavailability in case of unexpected damage to a lock gate. This also refers

to the starting point of minimum amount of modules, the fewer modules, the easier the assembly.

4 Emptying/filling through valves in gates
   - Most the locks had their filling and emptying system in the lock gates. The other alternative are culverts through the concrete civil works (sill and/or lock heads). To implementing emptying and filling systems into an existing concrete structure seems a very complicated and costly procedure, hence it is chosen to place the valves in the modularized doors.

5 Water tight connections between modules
   - It comes without saying that the doors must be water tight, meaning no seepage is allowed between the modules.

6 Minimum extra height above existing lock heads
   - From an aesthetic point of view it is undesirable to create gates much higher than the original height and the lock head. Since the doors will be made out of modules, the combination of modules might not result in the exact same height of the original door. This starting point conflicts with the previous one. The more modules there are the easier it will be to match the various different original door heights.

7 Strive for equal loads on horizontal girders (in governing situation)
   - The centre to centre distance between the beams needs to be determined such that the loads on the beams are identical to one another.

9.3 Gate elements

A mitre gate consists of many different elements, this section shortly describes the main ones that are included in the modular gate design:

- Front posts: responsible for the load transfer between the doors. As the doors retain water these are pushed together by the thrust (spat krachten). An essential part is that the posts form a watertight seal.
- Back posts: connect the doors to the pivots in the lock heads. In the case of pivots with clearance, upon closure, the back posts are pushed against the lock head walls. Usually a strip of wood or rubber is placed at the point of contact such that this mechanism serves as a seal between the doors and the lock head.
- Horizontal girders: transfer the loads acting on the gate to the front and back posts.
- Cladding: enables the desired water level difference between both sides of the gate.
- Vertical beams: transfer the loads from the cladding onto the horizontal girders.
- A structure enhancing the torsional strength of the doors.
- Emptying/filling valves: enable the filling and emptying of the lock.

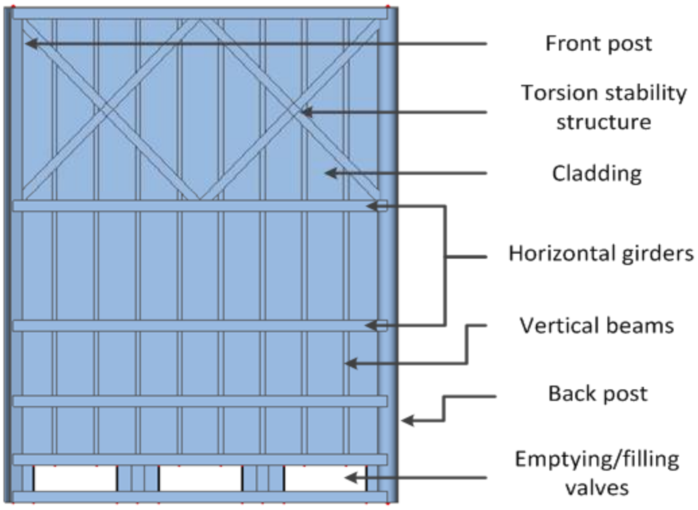


Figure 52: Elements of a door

9.4 The design of fixed modules

A combination of certain modules will make up a door for a lock with certain required door height. Having a range of modules it is possible to set up door with various heights to match the door height of the original door in the considered locks. Regardless of the required door height, each door must contain emptying/filling valves and a torsional stability structure. These elements of a lock gate can be incorporated in “fixed” modules, present in each door. The other modules mainly containing horizontal girders, vertical beams and cladding will be used as flexible modules that can be added or removed from the doors to match different lock heights. Throughout this sections the design of the fixed modules (containing the leveling system and the torsional stability element) are determined.

9.4.1 Leveling module

The leveling module contains the valves through which water can flow either into or out of the lock chamber. This section calculates the maximum opening of the valves for the specified cluster, the degree to which these are opened can be adjusted by the valve operating system.
Concerning the height of the module containing the valves, the height of the module must be predetermined as the conveyance area of the valves have a large influence on the locking time. The larger the conveyance area the shorter the locking time. There is, however, a limitation to the conveyance area of the valves. This limitation mainly has to do with the fact that the filling and/or emptying of a lock causes disturbances in the water inside the lock chamber due to translator waves and strong currents. These may impose loads on the ship that is berthed to the lock chamber walls. This force is known as the Hawser force (F). Figure 52 illustrates how the filling of the lock results in a slope in the water level, exerting a horizontal load on the ship. The Hawser force is the reaction force of the ship to the bollard where it is attached.

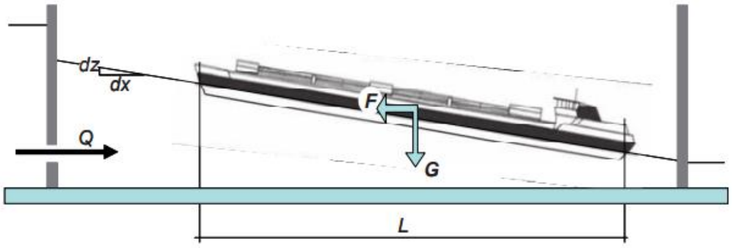


Figure 52: Hawser forces caused by filling the lock through the gates (Molenaar, 2011)

A large Hawser force (large horizontal loads from the shit to the chamber walls) may result in severe damaging of the lock walls or the ship (Wilschut, 2017). For this reason the opening of the valves should be designed such that opening area (area of conveyance) is maximum to the extent that filling and emptying does not result in Hawser forces exceeding 0.08% of the ships dead weight tonnage (DWT) (Molenaar, 2011).

The following formulas show the equations used to determine the maximum conveyance area of the gate valves in order for this Hawser force to remain under its critical value:

The Hawser force is given by the following relation:

$$F = \frac{dz}{dx} G = iG$$

Where G is the weight of the vessel (DWT) and i is the average slope of the water surface due to a translation wave:

$$i = \frac{dQ}{dt} * \frac{1}{g(A_v - n)}$$

Where:

A_v	=	conveyance area of the lock (water depth * lock width m^2)
n	=	wet area of vessel (draught * vessel width m^2)
g	=	gravitational constant (9.81 m/s^2)
$\frac{dQ}{dt}$	=	first derivative of the discharge through the valves

The discharge through the valves is dependent on various factors such as the water level difference and the conveyance area. Since the valves are not opened instantaneously, the opening time t_h also plays an important role in the discharge through the valves at a given time. During the opening of the valves ($t < t_h$) the discharge is given by:

$$Q = \frac{m_s f\sqrt{2g\Delta H}}{t_h}t - \frac{m_s^2 f^2 g}{2At_h^2}t^3$$

Once the valves are completely opened this function becomes:

$$Q = \frac{m_s^2 f^2 g}{A}t + m_s f\sqrt{2g\Delta H}$$

Where:

m_s	=	discharge coefficient for submerged flow ($estimated\ at\ 0.85$)
f	=	total valve area ($v_w * v_h\ \ m^2$)
v_w	=	valve width (0.67 * door length = 12.71m)
v_h	=	valve height (m)
A	=	lock surface area (lock width * lock length m^2)
t	=	time
ΔH	=	water level difference

To determine the maximum Hawser force $\frac{dQ}{dt}_{max}$ needs to be determined. From the two functions for Q, the maximum derivative can be given by either:

$$\frac{dQ}{dt} = \frac{m_s^2(12.71v_h)^2 g}{A} \quad \text{or} \quad \frac{dQ}{dt} = \frac{m_s(12.71v_h)\sqrt{2g\Delta H}}{t_h}$$

Combining the functions above leads to the expression:

$$i = \frac{m_s^2(12.71v_h)^2 g}{A} * \frac{1}{g(A_v - n)} \quad or \quad i = \frac{m_s(12.71v_h)\sqrt{2g\Delta H}}{t_h} * \frac{1}{g(A_v - n)}$$

With t_h and f as independent variables. These have to be determined such that i stays below 0.0008 and that the leveling time is reduced to it's possible minimum. The total leveling time is given by the following relation:

$$T_{total} = \frac{2A\sqrt{\Delta H}}{m_s(12.71v_h)\sqrt{2g}} + \frac{1}{2}t_h$$

Applying the relations given above the optimal valve height and opening times can be determined, these are shown in Table 44.

Lock name	Total time (s)	Total valve area (m^2)	Valve height (m)	width per valve (m)	Opening time (s)
Sluis Roermond	411	12,6	1,18	1,79	273
Sluis Linne	444	12,8	1,19	1,79	297
Schutsluis Belfeld oost (oude sluis)	461	12,5	1,17	1,79	306
Schutsluis Sambeek oost	545	12,5	1,17	1,79	363
Sluis Linne	535	12,8	1,19	1,79	357
Sluis Roermond	444	12,6	1,18	1,79	294
Sluis Heumen	570	12,3	1,15	1,79	381
Sluis Heumen	570	12,3	1,15	1,79	381
Middensluis	298	9,0	0,84	1,79	198
Middensluis	298	9,0	0,84	1,79	198
Prinses Marijkesluis westelijke sluis	397	15,1	1,41	1,79	264
Prinses Marijkesluis westelijke sluis	397	15,1	1,41	1,79	264
Zuidersluis	371	9,5	0,89	1,79	246

Table 38: Maximum dimensions for valves for the considered locks

From the results as presented above it is chosen to give all the valves a height of 1.41m. This means that the drive mechanisms will have to be calibrated per lock gate to only open partially for locks where the maximum valve height should be smaller.

In order to dissipate energy the valves often get wider through the gate where horizontal dissipation bars are placed. These two attributes are to dissipate the water energy entering the lock chamber and minimalize the water disturbances. Due to this added reasons it is chosen to design the module containing the filling and emptying systems with a height of 2.1m in order to leave enough space for these extra facilities around the valves.

9.4.2 Torsional stability module

The height of the torsional stability module is set at approximately 1/3rd of the door length. In some locks it is seen that diagonals cover the entire height of the doors, due to modularization this is perceived as unpractical. It should be noted that not only the diagonals of the module play an important role in guaranteeing the increased torsional stiffness, but also the outer horizonal girders of the module. Assuming the connections to be hinged the following schematization can be applied:

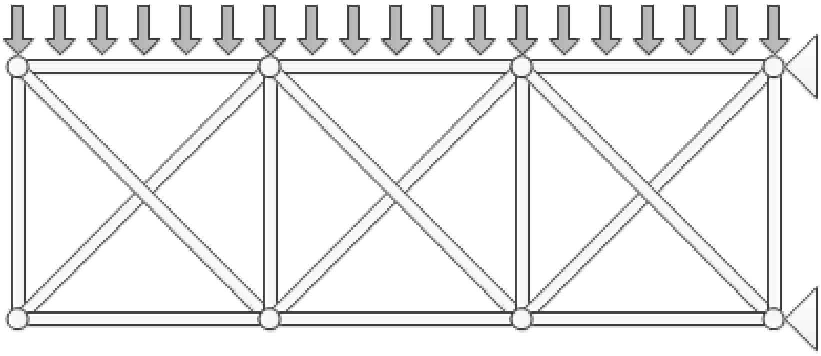


Figure 53: Loading of the torsional stability module (height = 1/3rd of door length)

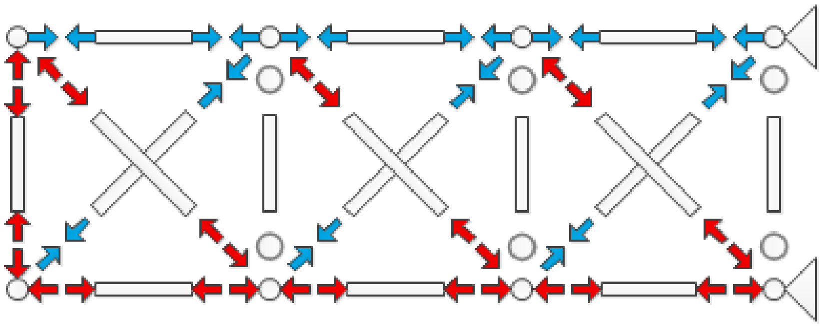


Figure 54: Load transfer in beams (blue = tension, red = compression, 0 = stress free)

It is important to notice that the upper beam is under tension and the bottom beam under compression.

9.5 Set up of the modular door

For the modularization of the door it is important to consider how the modules would connect to each other. In order to connect the modules there are two main options:

1. Connecting the modules through the vertical beams
2. Connecting the modules through the horizontal girders

Due to the fact that the horizontal girders are the main load carriers of the door it seems unfavorable to have them contain the connection and seal system as well. For this reason it is chosen to connect the modules through the vertical beams.

Ideally each door module contains one horizontal girder. However, from the last two sections, it became clear that the leveling and torsional stability modules have to contain two horizontal girders, combining the total horizontal girders in the modules to four girders in total. Because of the negative effects on the modularization of the door, it is chosen to combine the leveling and torsional stability module into one module. In this way, the compressive loads on the bottom module of the torsional stability modules are exerted on the strong upper girder of the leveling module. From this point the governing door will be comprised of the modules as presented on the right. This figure illustrates the bottom module containing both the torsional stability and the leveling systems of the door as one module. On top of that modules with varying heights can be added in order to make the door large enough for the required door height. These modules consist of cladding, vertical beams and horizontal girders where the vertical girders are situated at the top of the module.

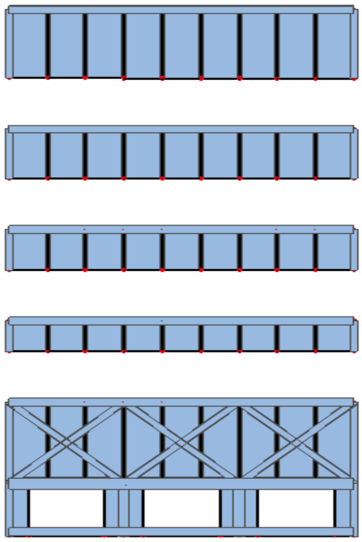


Figure 55: Set up of the modular door

9.6 Dimensions of the removable modules

This section lays focus on the determination of the optimal height of each module such that the requirements 2, 3, 4 and 6 are met as closely as possible. So far the height bottom module is set at 5.3 m (2.1m for leveling system and 3.2 m for the torsional stability element). The largest required door must have a height of 12.7 m, meaning another 7.4 m of door height has to be covered by the remaining modules. The horizontal girders and vertical beams of the door can be schematized as shown in figure 56.

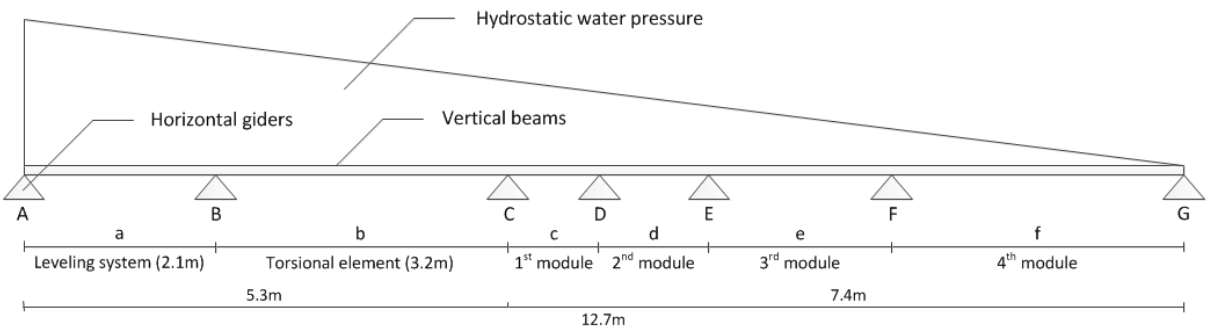


Figure 56: Schematiztion for the vertical beams supported by the horizontal girders

In the scheme above the horizontal girders are modeled as hinge supports along a beam which represents the vertical beams. The horizontal girders A, B and C are all part of the bottom module containing the torsional stability element and the leveling valves. The girders represented by supports D, E, F and G are part of the remaining 1st, 2nd, 3rd and 4th module. The figure illustrates the case at which the maximum door size must be met (12.7 m) and the door thus comprises all the modules. Removing certain modules can make up different door heights for locks with smaller retention heights.

Due to design simplicity, it is chosen to aim for equal loads in the horizontal girders so that these can have the same profile. The loads in the horizontal girders are mainly dependent on their respective centre to centre distance. Therefore, the size of the modules (hence centre to centre distances between the horizontal girders) have to determined such that most of the horizontal girders are loaded identically for the governing loading situation.

Concerning the girders A, B and C, the centre to centre distance has already been established due to previous requirements. This means this cannot be altered for optimization and equal load distribution. This means that these three girders will have their own specific loads and dimensions. This leaves optimization for the load on girders D, E and F by altering the centre to centre distances c, d, e and f.

The beam can be split up into six segments equal to the ctc distances. Splitting up the beam results in an additional bending moment at the location of the cut, the splitting of the beam and the bending moments are shown in Figure 57.

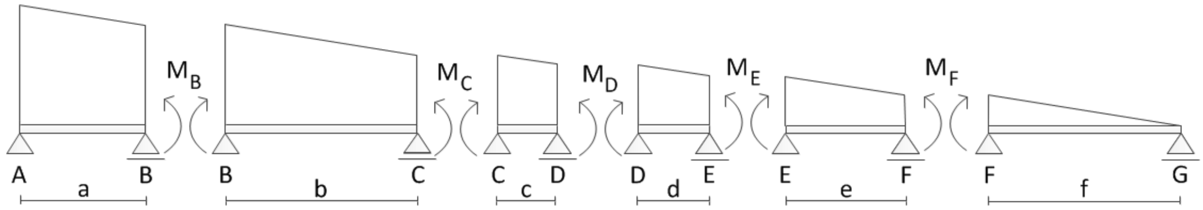


Figure 57: Splitting up the statically indeterminate beam into sections

The loading will cause deformation in the beams. The figure below illustrates possible angle rotations at both ends of the sections.

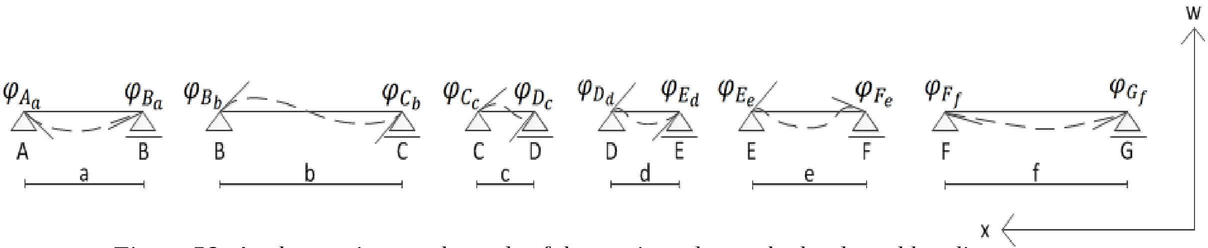


Figure 58: Angle rotations at the ends of the sections due to the loads and bending moments

To show how such an angle rotation can be determined the angle rotation φ_{Cb} is worked out as an example.

Using the 4th order differential equation for the displacement of a beam it is possible to analytically solve the displacement and change of shape, and thus φ_{E_e}

Differential equations:

$$EIw''''(x) = q = 10(f + x)^4$$

$$EIw'''(x) = \frac{10x^2}{2} + 10fx + C_1$$

$$EIw''(x) = \frac{10x^3}{6} + \frac{10fx^2}{2} + C_1x + C_2$$

$$EIw'(x) = \frac{10x^4}{24} + \frac{10fx^3}{6} + \frac{C_1x^2}{2} + C_2x + C_3$$

$$EIw(x) = \frac{10x^5}{120} + \frac{10fx^4}{24} + \frac{C_1x^3}{6} + \frac{C_2x^2}{2} + C_3x + C_4$$

Boundary conditions:

$$EIw''''(0) = 0 \qquad EIw''''(e) = 0$$

$$EIw''(0) = -M_F \qquad EIw''(e) = -M_E$$

[4] The term $10(f + x)$ stands for the hydrostatic load on the vertical beam where the gravitational constant has been approximated by 10 instead of 9.81 (q is given in KN/m^2)

Filling boundary conditions into the differential equations:

$$EIw''''(0) = C_4 = 0 \qquad EIw''(0) = C_2 = -M_F$$

$$EIw''(e) = \frac{10e^3}{6} + \frac{10fe^2}{2} + C_1 e - M_F = -M_E$$

$$EIw(e) = \frac{10e^5}{120} + \frac{10fe^4}{24} + \frac{C_1 e^3}{6} - \frac{M_F e^2}{2} + C_3 e = 0$$

Two unknowns, two equations:

$$\begin{bmatrix} \frac{e^3}{6} & e \\ e & 0 \end{bmatrix} * \begin{bmatrix} C_1 \\ C_3 \end{bmatrix} = \begin{bmatrix} -\frac{10e^5}{120} - \frac{10fe^4}{24} + \frac{M_F e^2}{2} \\ -\frac{10e^3}{6} - \frac{10fe^2}{2} + M_F - M_E \end{bmatrix}$$

Solving for C_1 and C_2

$$C_1 = -\frac{10e^2}{6} - \frac{10fe}{2} + \frac{M_F}{e} - \frac{M_E}{e}$$

$$C_3 = \frac{7}{36}e^4 + \frac{5}{12}fe^3 + \frac{1}{3}M_F e + \frac{1}{6}M_E e$$

$$EIw'(e) = -\frac{2e^4}{9} - \frac{5fe^3}{12} - \frac{M_F e}{6} - \frac{M_E e}{3}$$

$$\varphi_{Cb} = -EIw'(e)$$

$$\varphi_{E_e} = \frac{10fe^3}{24EI} + \frac{2e^4}{9EI} + \frac{M_F e}{6EI} + \frac{M_E e}{3EI}$$

Where the bending moments M_E and M_F are unknown. To determine these bending moments certain boundary conditions can be set, namely:

$$\varphi_{Ba} = \varphi_{Bb} \qquad \varphi_{Cb} = \varphi_{Cc} \qquad \varphi_{Dc} = \varphi_{Dd} \qquad \varphi_{Ed} = \varphi_{Ee} \qquad \varphi_{Fe} = \varphi_{Ff}$$

The determination of the equations for the rest of the rotations is done in Appendix H. Where the trick is to solve the values for c, d, e and f such that $F_D = F_E = F_F$. It is chosen to compute all the equations into a Matlab program. The program iteratively finds the values for c, d, e and f for which the requirement of equal loading is met, the code can be found in the second part of Appendix H.
The exact solution for c, d, e and f such that $F_D = F_E = F_F$ results in modules which, when combined for the locks with a certain required door height, largely exceed the height of the old original doors. To better match the height of the original doors, c, d, e and f are altered slightly. The centre to centre distances and resulting support reaction in the main horizontal girders are illustrated in the figures below, where the forces are checked with the engineering software "Matrix Frame".

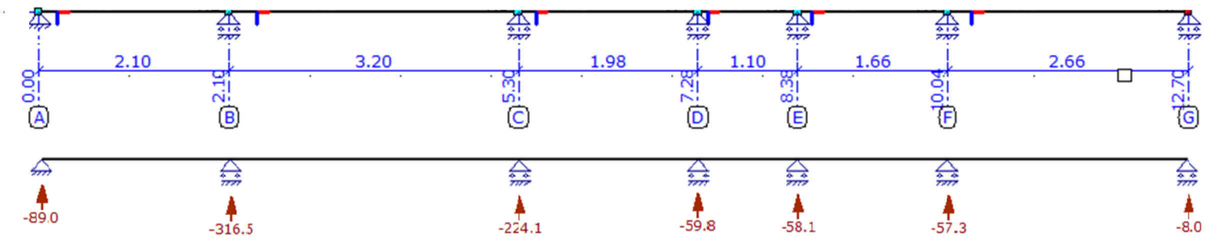


Figure 59; Top: ctc distance between horizontal girders; Bottom: resultant distributed loads in horizontal girders.

Altering the height this way reduces the total door exceedance of 3.5m to 2.1m. This comes at the cost of having an exactly equal load on the horizontal girders D, E and F. However, due to the relatively small variations in the centre to centre distances between the beams the loads are still very similar to each other. Table 45 illustrates the combinations that can be made with the modules to create door heights matching that of the actual doors.

Module combinations	a b d	a b e	a b c	a b f	a b d	a b c d	a b e f	a b c d f	a b c e f	a b c d e f
Door height (m)	6,5	6,9	7,3	8,0	8,5	8,9	9,2	10,1	11,6	12,8
Actual door heights (m)	6,4	6,8	7,1	7,6	8,3 8,4	8,5 8,7	9,2	10,1	11,4	12,7
Exceedence (m)	0,2	0,2	0,2	0,5	0,2 0,1	0,4 0,2	0,0	0,0	0,2	0,1

Table 39: Combinations of modules to fit to the existing locks

A similar research has been performed trying to cut down on the amount of modules and increasing the centre to centre distances. This however leads to very unfavorable combinations to match the existing lock heads as the exceedance becomes too large. Another option is to increase the amount of modules in order to better match the required door heights, this would however conflict with the starting points 2 and 4 mentioning that it should be aimed for minimum amount of modules. The current layout seems as the optimal solution between the tradeoff between amount of modules and exceedance above the lock heads.

Figure 60 shows the conceptual design of the largest door considered in this research, as was treated in Section 9.6. This figure illustrates the position of the leveling systems and the torsional stability elements as well as the vertical beams and the modules. The next two sections will give more information about the connection between the modules and the connection to the lock head and back post. Figures 61 and 62 a smaller door comprising the first second and fifth module of the large door (counting upwards). Figure 61 also illustrates the front of the valves with the sliding panels and their drive mechanisms.

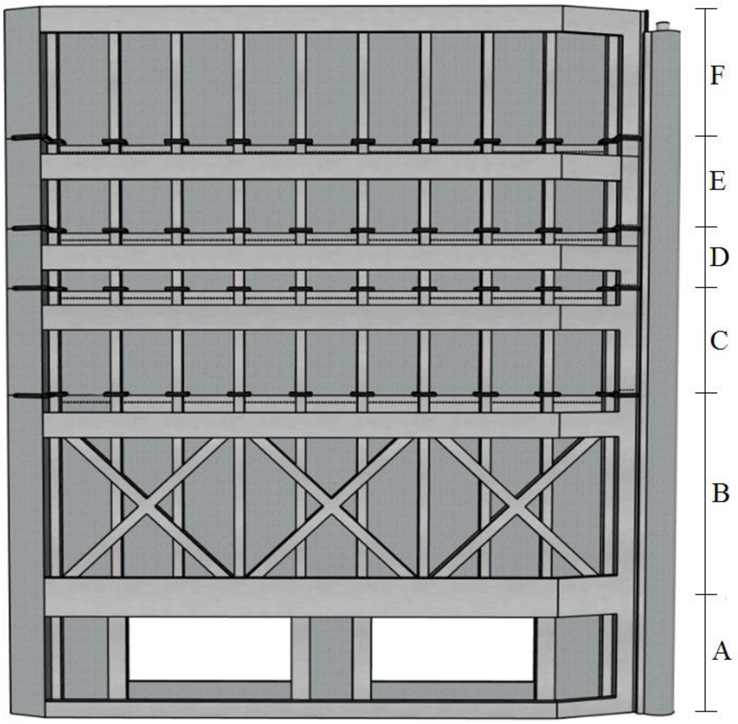


Figure 60: Conceptual design of the largest door (with the modules indicated by the letters, where A + B form the fixed bottom module)

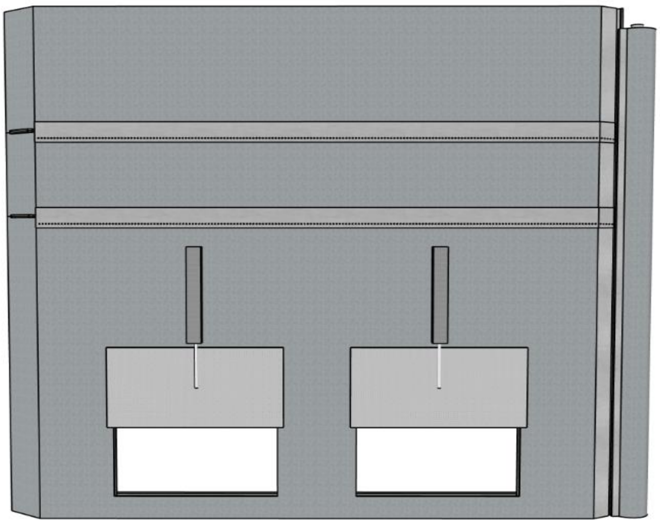


Figure 61: Front of the modular door with reduced height (modules D and E have been removed)

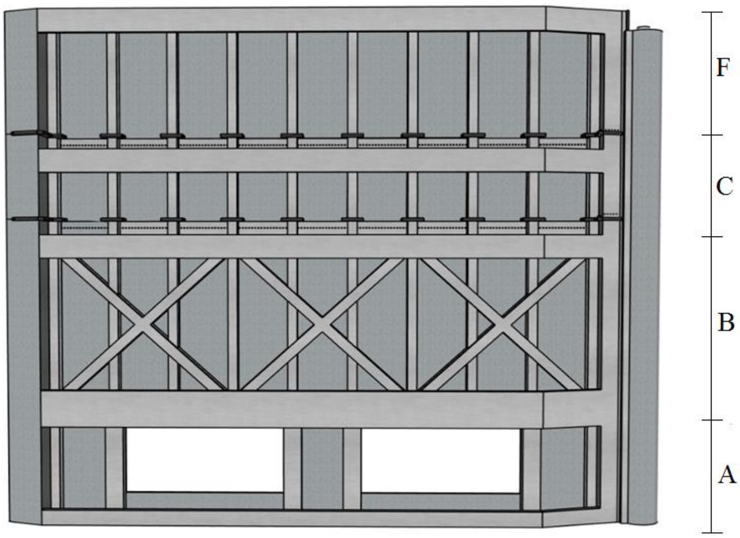


Figure 62: Back of the modular door with reduced height (modules D and E have been removed)

9.7 Connection between the modules

Determining the connection between the modules it should be noted that starting points 4 and 7 have to be taken into account (ease of assembly & disassembly and a water tight connection). Making the best choice for the connection type is again a tradeoff: welding the modules together would result in the most reliable watertight connection between them, whereas bolting would result in ease of assembly and disassembly, since the mean idea behind this modularization is that the doors can be taken apart when maintenance is required and reassembled when preserved. As modules will have to undergo many assembly's and disassembly's, it is therefore chosen to apply the bolted connection.
To structurally connect the modules, it is chosen to connect the vertical beams of the modules by means of a cantilever capable to transferring bending moments as well as shear and normal stresses. The water tight seal consists of an overlap over the front plates of the modules. To completely ensure water tightness it would be possible to apply a rubber band in between.

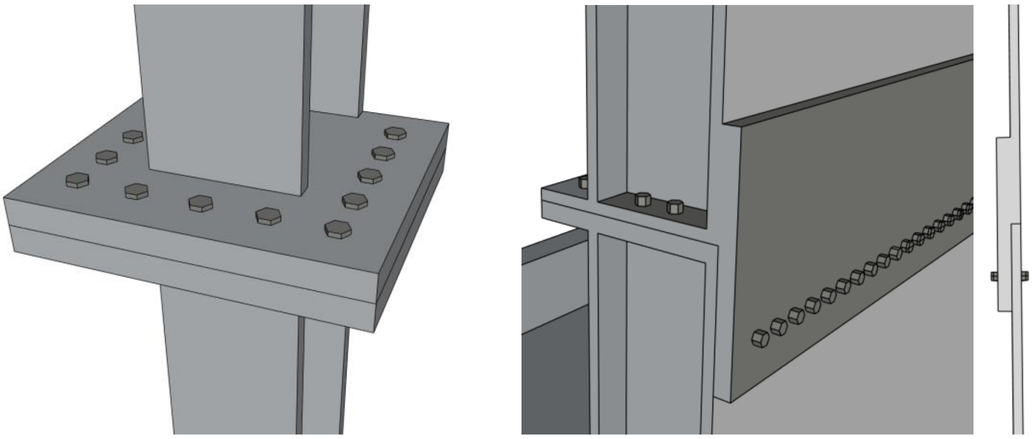


Figure 63: Left: Structural connection between modules, Middle and Right: Water tight connection between modules as plates are overlapping and bolted

With the application of bolted connections it should be noted that, unlike the modules themselves, the bolts do not come in a coating. Also coating the doors after assembly would result in too large waiting times in case of an emergency replacement. The most evident option is to apply stainless steel bolts. It should however be noticed that these should not come in direct contact with the steel applied in the modules and this might accelerate corrosion, this type of corrosion is called galvanic corrosion (Burkert A, 2009).

9.8 Connection to the lock head

Considering the connection of the door to the lock head, starting point 2 has to be taken into account. In order to minimize the required changes to the civil structure it is chosen to create unique back posts, matching the height of the original door. Since the pivots are connected to these back posts they will not need to be repositioned. The modules will be connected to the back posts by means of a sliding mechanism.

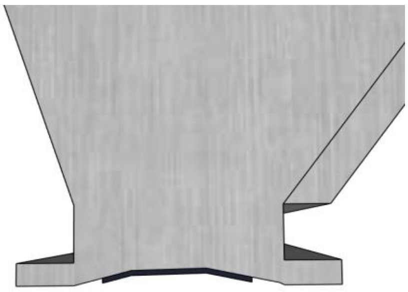


Figure 64: Top view of the extremity of the doors, to be slid into the back post

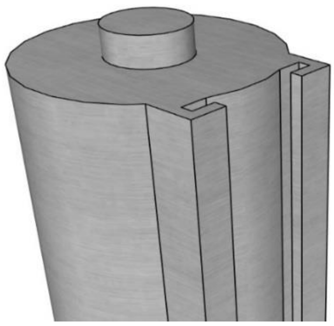


Figure 64: Back post

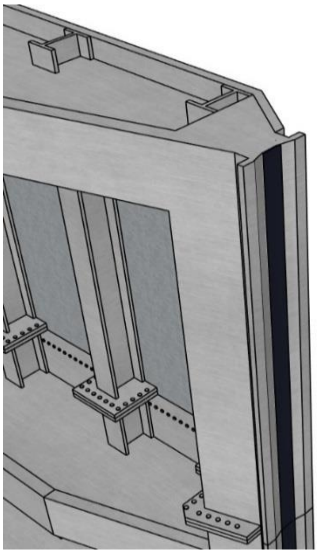


Figure 65: extremity of the door to be slid into the back post

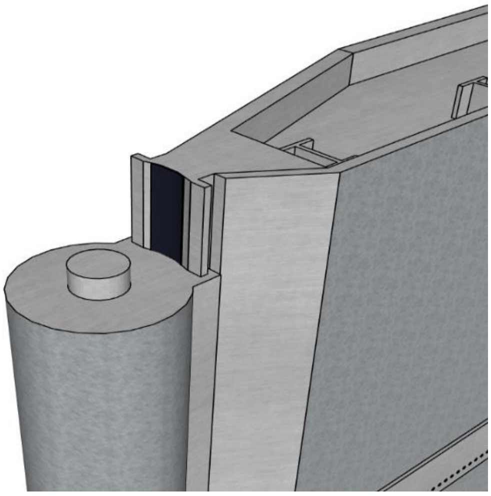


Figure 66: Door slid into the back post

Figures 63 to 66 illustrate the sliding mechanism in more detail. This type of connection to the lock head the top module might now exceed the height of the back post with a difference up to 0.4 m. With such a connection it becomes even more beneficial to place the torsional stability elements in the bottom module instead on the top module. The reason behind this is that the torsional stability element exerts great shear loads on the back post at the positions of its upper and lower horizontal beam. If the upper beam were not directly attached to the back post this would result in large local forces and therefore design complications would arise.

A disadvantage of this type of connection between the back post and the modules is that it can be considered as the weak link of the gate and bending moments should be avoided to prevent damages. It is usual for mitre gates to be supported eccentrically when closed in order to reduce the maximum occurring bending moments in the doors. However, the eccentricity does cause a bending moment to occur at the back post of the door, this process is further explained in the last section of Appendix C . Due to the chosen connection method this type of eccentricity will be complicated and should possibility be prevented, causing larger bending moments on the horizontal beams. This connection would however be suitable for the transfer of normal forces as these merely push the modules against the post. The black strip at the T end represents a rubber strip to help absorb these loads and seal off the connection between the modules and the back post.

9.9 Further considerations

This section discusses further considerations to be taken into account when continuing the design of the modular lock gates.

9.9.1 Pivots

As this report clearly stated, applying standardization results in over-dimensioning, meaning that many doors will become heavier then the original doors. The increase in weight of the doors will most likely result in forces onto the pivots. If the larger forces become problematic the pivots might have to be replaced by stronger ones. Another option is to partially unload the pivots, this can be achieved with several measures explained below and illustrated in Figure 68.

- Equipping the bottom modules with air chambers. The net weigth of the doors would be reduced due to bouyant lift forces as a result of the trapped air bellow the water line. This measure would help reduce both vertical as horiztonal loads on the pivots.

- Applying a roller or slide pad aong the track of the front posts would have a similar result. Since the sills of the locks need to be changed anyway due to the deviation of the slope of closure of the gates, these works could be combined.

- Partially suspending the gates with outside hinges and cables. The position where the cables meet de door determines the extent to which it helps to reduce the horizontal loads on the pivots.

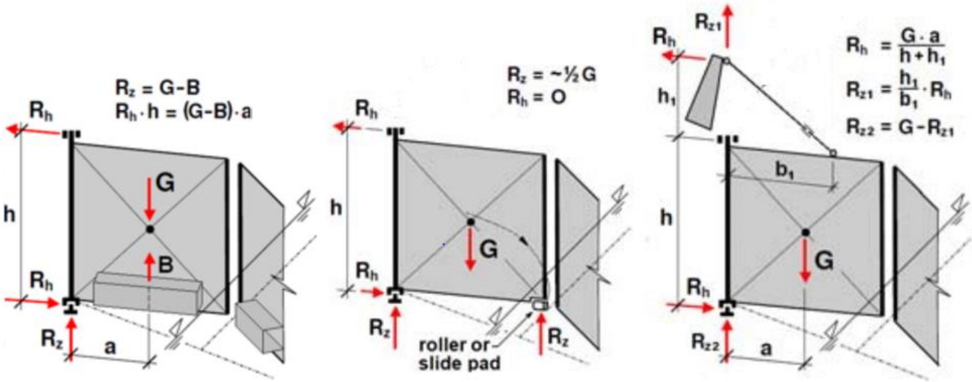


Figure 68: Measures to reduce the loads on the pivots (Johnson, 2017)

9.9.2 Ship impact & overall reliability

It is expected that the over-dimensioning of certain lock gates will result in lock gates that are much stronger and more robust then they would have been if standardization wouldn't have taken place. This excess strength of the gates can have a favorable outcome concerning the reliability of the gates. Chances are also that the over dimensioned gates might be able to better withstand ship impacts due their increase strength. For the gates where over-dimensioning barely plays a role and ship impact has a significant risk it can be chosen to equip the lock heads with preventive structures or to design a impact absorption module that could be placed on top of the doors.

9.9.3 Adaptation to sill and gate recess

It is inevitable that some change to the civil structure must occur. Since the standardization method involves long doors at a larger angle of closure the sill and gate recess require adaptation. The sill need to be elongated. This can take place by adding a concrete slab. The gate recess also requires elongation, this means part of the existing structure needs to be removed in order to create extra space for the longer doors.

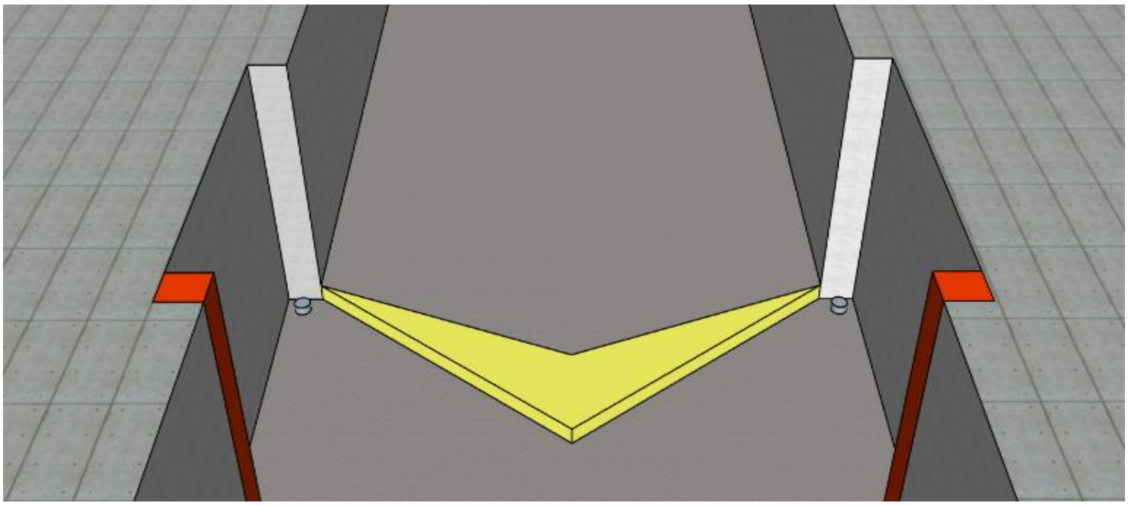


Figure 69: Required adaptation of the lock head when implementing doors with larger lengths than the original doors

Figure 69 illustrates the adaptation to the civil structure. The yellow shape is the volume of concrete to be added for the adaptation of the sill. The red volume needs to be removed to create more space for the doors when opening the gate.

9.9.4 Drive mechanism

Appendix B covers the characteristics of various drive mechanisms used. The current distribution for the applied drive mechanisms is about 50% electro hydraulic and 50% electro mechanical which specific electro mechanical systems is unknown. Over the assessment of the various drive mechanisms it can be concluded that in the cylinders (electro mechanical as well as electro hydraulic) have a minimum of required space in the lock head. From here the assumption is made that a cylinder will be able to fit inside a head which was originally designed for another, larger drive mechanism, the Panama Wheel for instance. Since the preservation of the existing civil structure is one of the main starting points for this research it is recommended to apply cylinders for the operations of the doors.

Choosing whether to apply an electro mechanical or hydraulic cylinder mainly depends on the LCC's, reliability and availability. In general terms, electro hydraulic drive mechanisms require more frequent small maintenance whereas electro hydraulic less frequent, but large maintenance when required. It was found that the main issue with electro mechanical systems is the frequent unavailability of certain components, resulting in longer unavailability (De Graaf, 2018). From a standardization point of view the maintenance required for the hydraulic systems cannot be optimized. For the mechanical systems however, standardization would make it more appealing to start managing spare components. Keeping this in mind the recommended type of drive mechanism would be the electro mechanical cylinder.

9.10 Conclusion

When modularizing lock gates it is best to combine the torsional stability and leveling elements into one fixed module. By smartly determining the size of the modules the excess height of the door in comparison to the original door can be minimized. Implementing a slinging facility between the modules and the back post, the upper pivot won't require displacement and can remain at its original location. The general built-up of the door, the method of modularizing and the connections between the modules and lock head are considered as the general design principles, these are referred to in the next chapter.

10 Comparative study

Chapter 8 indicated two cluster configurations having a great potential in decreasing the variability found in the gates of the MWW locks. This variety reduction severely reduces the amount of spare gates required. Chapter 9 investigated the design of a modular door within a specified cluster. Although the design only applies to the specified cluster, the design principles are assumed to hold for all clusters.
With the knowledge obtained from both chapters, a comparison can be made between the case where the standardization would be implemented and the case where it wouldn't.
This chapter initially estimates the total direct construction costs for various cluster configurations. Finally a discussion is set up addressing the influence standardization/clustering has on the main MWW goals, namely simplifying maintenance and improving the overall availability and reliability of the locks. This Chapter forms the answer to RQ 6.

10.1 Cost factors

At the Dutch Ministry of Infrastructure and Water Management, ***direct construction costs*** of lock gates are mainly estimated by relating certain cost factors to the estimated mass and surface area of the doors (Werf, 2018). This section discusses the process of the determination for the direct construction costs of the lock gates.

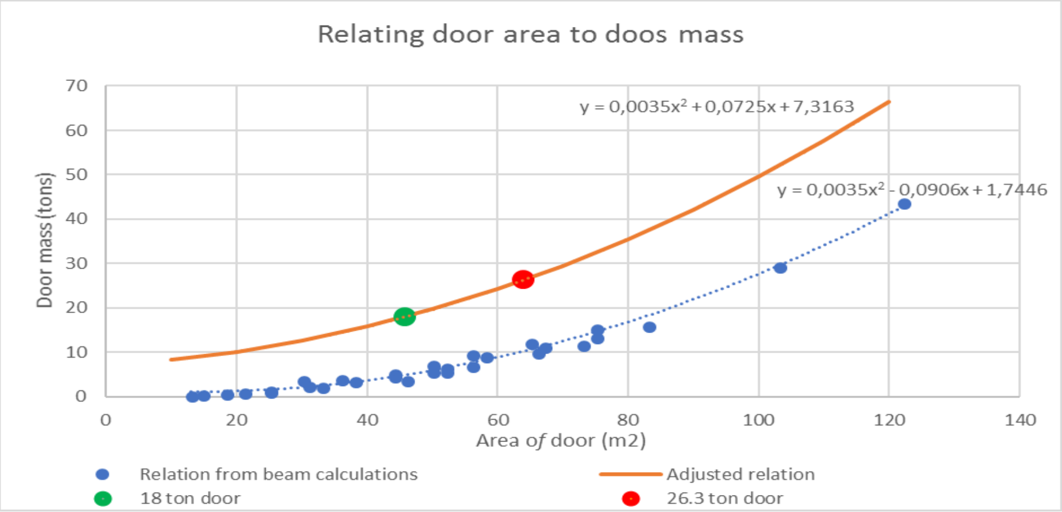
10.1.1 Relating door area to door mass

So far, the steel estimations of the lock gates have been determined by only addressing the amount of steel required in its main horizontal beams. The blue line in Graph 23 indicates the relation between the area of a door to its mass according to the beam estimates (so far this research has been based on these values).
The green and red dots in the graph illustrate the door area and mass of the doors for two actual lock gates, namely the ones placed in the navigation locks at Born and Maasbracht (Loncaric, 2009):

Door area at Born: $46\ m^2$
Door mass at Born: $18\ tons$

Door area at Maasbracht: $64\ m^2$
Door mass at Maasbracht: $26.3\ tons$

The data about these realized doors enable an alteration in the relation shown by the blue line. Under the assumption that the mass of the horizontal beams in a door are the only door elements that relate to the weight of the door in a quadratic manner, it is chosen to preserve the first constant of the formula and vary the second and third so that the relation matches the values for the realized doors.



Graph 23: Relation between door area to door mass

The orange line in Graph 23 indicates the relation found after adjusting the formula found for the line of best fit from the beam calculations to a relation matching the data for the doors at Born and Maasbracht.

10.1.2 Cost factors

To translate the weight and area of the door into costs, the Ministry (Werf, 2018) uses specific pricing for the following factors:

Purchase cost steel:	$€/ton$
Manufacturing costs:	$€/ton$
Transport	$€/ton$
Mounting the doors:	$€/ton$
Engineering:	$€/ton$
Coating:	$€/m^2$

Unfortunately this information is confidential and cannot be presented in this report, however the total cost of all factors would come down to approximately 6400 $€/ton$.

10.1.3 Cost estimate for MWW lock gates

Knowing the required door dimensions and the way these relate to the costs, calculations for the entire lock gate arsenal can be made. These costs are shown in the table below:

Cost per door set		Door height									
Lock width (m)	Optimum door length (m)	4	5	6	7	8	9	10	11	12	13
5	2,6		€ 114.955								
6	3,1					€ 148.033					
7	3,7	€ 118.537	€ 127.750								
8	4,2		€ 135.063	€ 148.033		€ 178.661			€ 236.323		
9	4,7										
10	5,2			€ 170.418							
11	5,7				€ 208.149		€ 267.451				
12	6,3			€ 196.319	€ 225.736	€ 258.668	€ 295.116				
13	6,8										
14	7,3		€ 191.758	€ 225.736	€ 264.499		€ 356.381	€ 409.499			
15	7,8										
16	8,4			€ 258.668	€ 308.047	€ 363.676	€ 425.555	€ 493.684			
17	8,9										
18	9,4			€ 295.116	€ 356.381	€ 425.555			€ 680.540		€ 890.082

Table 40: Cost estimates per door set

Gate distribution		Door height									
Lock width (m)	Optimum door length (m)	4	5	6	7	8	9	10	11	12	13
5	2,6		3								
6	3,1					3					
7	3,7	5	3								
8	4,2		4	6		4			2		
9	4,7										
10	5,2			2							
11	5,7				1		1				
12	6,3			9	1	1	2				
13	6,8										
14	7,3		2	6	7		3	10			
15	7,8										
16	8,4			1	2	4	5	2			
17	8,9										
18	9,4			1	2	2			3		1

41: Lock gate distribution

10.2 Direct construction cost estimation for minimum degree of standardization

So far this report considered the situation without standardization to be where the doors within the same cell are identical and share the same spare components. In reality however, this is not the case as the dimensions of the doors have been rounded to the closest whole number for the sake of simplicity considering the clustering. This can be well observed by addressing Tables 42 and 43: Table 42 indicates 10 unique doors with different sizes; Table 43 gives their actual, non-rounded dimensions, indicating there are 13 unique doors with different sizes. In this section cost estimations are made for both cases: minimum degree of standardization and no standardization.

10.2.1 Direct construction costs in case of minimum degree of standardization

The total costs of all the MWW lock gates when (in case) these are standardized according to the minimum degree of standardization, include both the costs of the gates in use and the spare gates.

Direct construction costs of doors in use:
The costs of the doors in use are equal to the costs as shown in Table 45. Multiplying these costs by the number of gates as shown in Table 46 gives the total costs of the lock gates in use. This adds up to a total of:

€ 27.000.000,-

Direct construction costs of spare doors:
In the case of a minimum form of applied standardization, gates within the same cell of Table 45 can share the same spare components, this reduces the total spare gate costs to:

€ 8.800.000,-

Total direct construction costs:
The total direct construction costs can be determined by adding the costs for all the doors in use and the spare doors:

€ 35.800.000,-

10.2.2 Direct construction costs in case of no degree of standardization

The total costs of all the MWW lock gates in case these are not standardized at all include both the costs of the gates in use as well as the spare gates.

Direct construction costs of doors in use:
The costs of the doors in use are equal to the costs as shown in Table 45. Multiplying these costs by the number of gates as shown in Table 46 gives the total costs of the lock gates in use. This adds up to a total of:

€ 27.000.000,-

Direct construction costs of spare doors:
As explained in the introduction of this section, the amount of actual unique doors is larger than illustrated in Table 46. On average it is found that 1.8 lock gates can share the same spare gates. Using this number it is found that the direct construction costs of the spare gates add up to:

€ 15.000.000,-

Total direct construction costs:
The total direct construction costs can be determined by adding the costs for all the doors in use and the spare doors:

€ 42.000.000,-

10.3 Cost estimation for cluster configurations

The cost estimation for cluster configurations as shown in Tables 39 and 40 is more complicated than the estimation in the previous section. This is because the modularity should be taken into account along with potential cost reduction factors caused by standardization.

10.3.1 Reduction factor due to modularization

Chapter 9 gave a good insight into how a modular door should be designed for a specific lock gate cluster: a heavy fixed module in the bottom, containing the torsional stability structure as well as the leveling system. The upper part of the door is relatively light and can be added or removed to adapt the door to various required door heights.
Considering the largest door (left of Figure 70), it can be noticed that about 2/3rd of the total loads are on the fixed bottom module. Only 1/3rd remains in all the removable modules. For now it is assumed that the amount of steel in the door is distributed in the same way, meaning that the bottom module contains 2/3rd of all the steel in the door. The weight of the door when removing certain modules can therefore be given by the following function:

$$F_{reduced} = F_{largest} - 273.8 * \left(\frac{h_{reduced}}{7.4}\right)$$

Where:

$F_{reduced}$	=	Net horizontal force on reduced door
$F_{largest}$	=	Total horizontal force on largest door
$h_{reduced}$	=	Height reduction

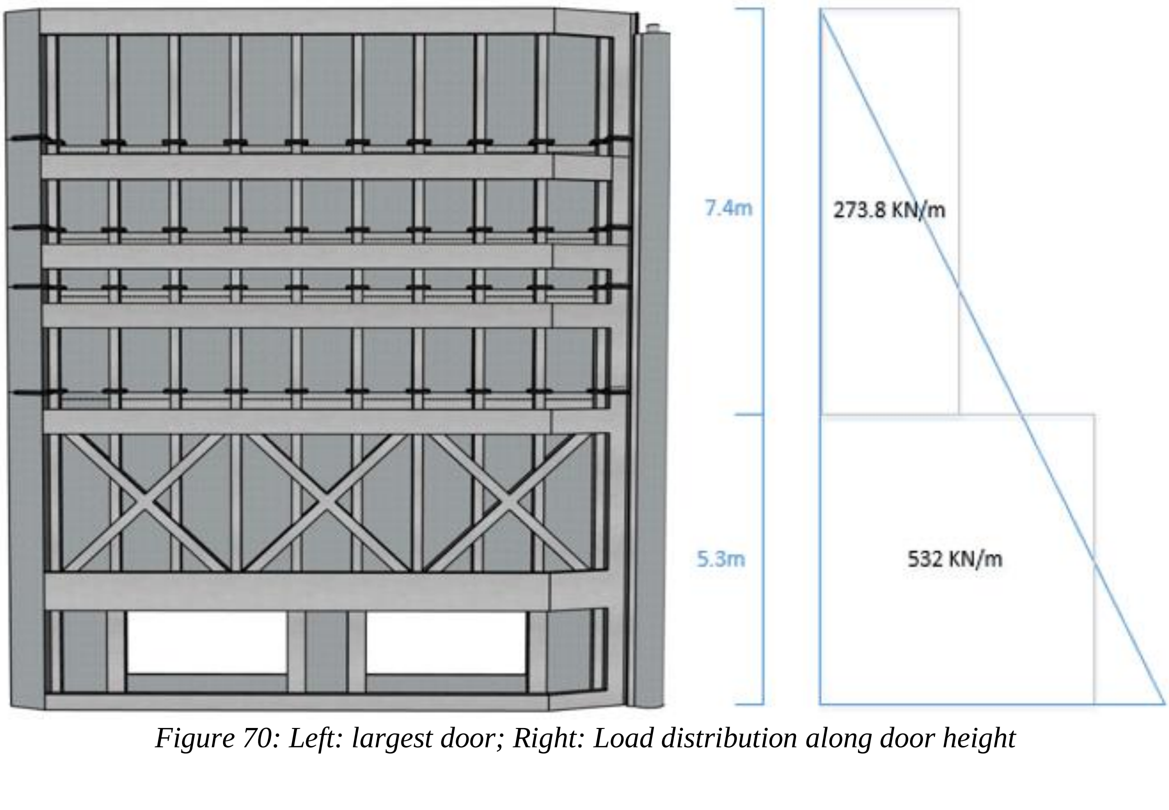


Figure 70: Left: largest door; Right: Load distribution along door height

Dividing the weight of the reduced door by the weight of the largest door gives the reduction factor:

$$r = \frac{F_{reduced}}{F_{largest}}$$

Example:

In order to fit the door shown in Figure 70 into a lock with a lower required door height, some of the top modules need to be removed. Assuming the door height must be reduced by 3 m, the reduction factor would be:

$$F_{reduced} = F_{largest} - 273.8 * \left(\frac{h_{reduced}}{7.4}\right)$$

$$F_{reduced} = 805.8 - 273.8 * \left(\frac{3}{7.3}\right)$$

$$F_{reduced} = 692.7\ kN/m$$

$$r = \frac{F_{reduced}}{F_{largest}} = \frac{692.7}{805.8} = 0.86$$

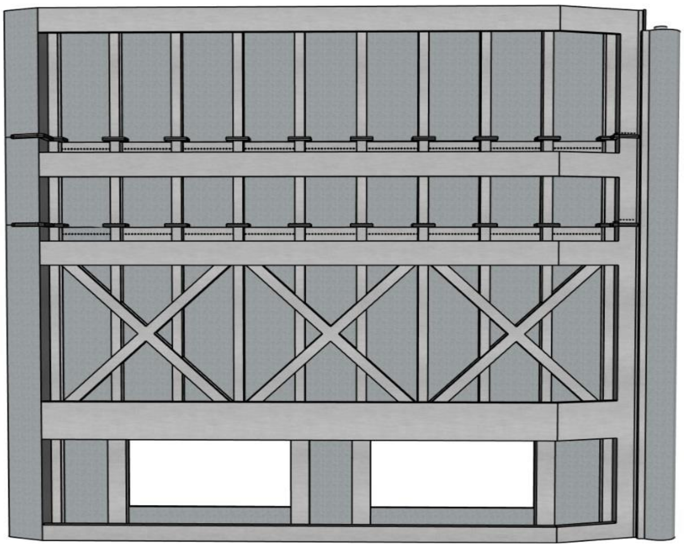


Figure 71: 3 m reduced door height

Continuing this process reveals the following reduction factors for the lock gates within the corresponding clusters. These are shown in the table below:

Reduction factors		Door height									
		4	5	6	7	8	9	10	11	12	13
Lock width (m)	5		0,78								
	6					0					
	7	0,64	0,64								
	8		0,64	0,7		0,82			0		
	9										
	10			0,74							
	11				0,83		0				
	12			0,74	0,83	0,91	0				
	13										
	14		0,64	0,71	0,78		0,93	0			
	15										
	16			0,68	0,73	0,77	0,82	0,86			
	17										
	18			0,68	0,73	0,77			0,91		0

Table 42: Reduction factors

10.3.2 Engineering cost reduction due to standardization

Section 10.1.2 indicates the various cost factors upon which the total costs of the doors depend. One of the cost factors are the engineering costs, assuming the door is uniquely designed. Standardization of the lock gates would mean that many doors would have the same design and engineering would only have to be applied once per cluster, instead of once per gate. So if the MWW locks are clustered into five categories, only 5 doors will have to be engineered, reducing the average engineering costs form € 1100/ton to € 183/ton. And if the locks are clustered into eight categories, the average engineering costs would be € 294/ton[5].

[5] The € 1100/ton engineering costs are assumed to hold for the case where no standardization is applied (30 clusters). In the case of five unique doors, the engineering costs are reduced by 5/30, for eight unique doors this factor becomes 8/30.

10.3.3 *Cost estimate for 5 clusters*

Applying the cost reduction methods as described in the previous sections, the cost per door set can be determined, these are indicated in the table below:

Cost per door set		Door height									
Lock width (m)	Optimum door length (m)	4	5	6	7	8	9	10	11	12	13
5	2,6		€ 99.205								
6	3,1					€ 127.185					
7	3,7	€ 130.012	€ 130.012								
8	4,2		€ 130.012	€ 142.201		€ 166.578			€ 203.144		
9	4,7										
10	5,2			€ 187.713							
11	5,7				€ 210.543		€ 253.666				
12	6,3			€ 187.713	€ 210.543	€ 230.836	€ 253.666				
13	6,8										
14	7,3		€ 225.212	€ 249.845	€ 274.478		€ 327.262	€ 351.894			
15	7,8										
16	8,4			€ 519.683	€ 557.895	€ 588.464	€ 626.676	€ 657.246			
17	8,9										
18	9,4			€ 519.683	€ 557.895	€ 588.464			€ 695.458		€ 764.240

Table 43: Cost per door set for the case where all gates are clustered into five categories

Multiplying these values by the amount of required lock gates determines the total cost of this type of cluster configuration.

Direct construction costs of doors in use:
The costs of the doors in use are equal to the costs as shown in Table 48. Multiplying these costs by the number of gates as shown in Table 46 gives the total costs of the lock gates in use. This adds up to a total of:

€ 30.000.000,-

Direct construction costs of spare doors:
Only a total of five spare gates (door sets) are required, these cost the same as the largest gates per cluster. Summing up the costs of the largest gates per cluster (as shown in Table 48) results in:

€ 1.700.000,-

Total direct construction costs[6]*:*
The total direct construction costs can be determined by adding the costs for all the doors in use and the spare doors:

€ 31.700.000,-

[6] The costs of the required adaptation have been neglected due to their minor significance on the total costs

10.3.4 Cost estimate for 8 clusters

Applying the cost reduction methods as described in the previous sections, the cost per door set can be determined, these are indicated in the table below:

Cost per door set		Door height									
Lock width (m)	Optimum door length (m)	4	5	6	7	8	9	10	11	12	13
5	2,6		€ 101.149								
6	3,1					€ 129.678					
7	3,7	€ 105.039	€ 119.304								
8	4,2		€ 119.304	€ 129.678		€ 169.831			€ 207.111		
9	4,7										
10	5,2			€ 191.380							
11	5,7				€ 214.656		€ 258.622				
12	6,3			€ 191.380	€ 214.656	€ 235.346	€ 258.622				
13	6,8										
14	7,3		€ 229.620	€ 254.735	€ 279.850		€ 333.667	€ 358.782			
15	7,8										
16	8,4			€ 307.054	€ 337.327	€ 367.600	€ 402.198	€ 432.471			
17	8,9										
18	9,4			€ 305.727	€ 339.282	€ 372.837			**€ 709.150**		**€ 779.286**

Table 44: Cost per door set for the case where all gates are clustered into eight categories

Multiplying these values by the amount of required lock gates determines the total cost of this type of cluster configuration.

Direct construction costs of doors in use:

The costs of the doors in use are equal to the costs as shown in Table 48. Multiplying these costs by the number of gates as shown in Table 46 gives the total costs of the lock gates in use. This adds up to a total of:

€ 26.000.000,-

Direct construction costs of spare doors:

Only a total of eight spare gates (door sets) are required, these cost the same as the largest gates per cluster. Summing up the costs of the largest gates per cluster (as shown in Table 48) results in:

€ 2.700.000,-

Total direct construction costs:

The total direct construction costs can be determined by adding the costs for all the doors in use and the spare doors:

€ 28.700.000,-

10.4 Maintainability and management

The goals of MWW mainly consider the maintenance and management of navigation locks. This section therefore focusses on the potential life cycle of the MWW doors and describes the process of storing, transporting, assembling and exchanging the standardized modular lock gates.

10.4.1 Maintenance and storage facility

Usually spare doors are stored next to the corresponding navigation lock. Some storage facilities also combine with maintenance and repair facilities for damaged doors. These combined facilities are costly.

Therefore this study recommends to build one large storage facility where lock doors can also be maintained and repaired. Due to the wide geographical spread of locks in the Netherlands, the province of Utrecht appears to be the best location for such a central facility.

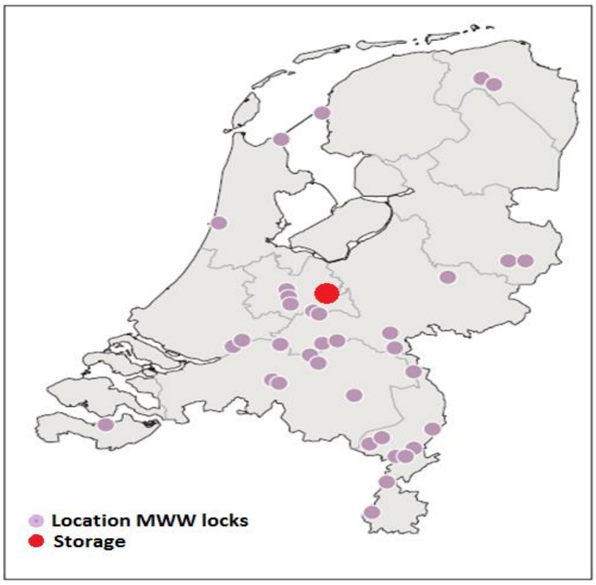


Figure 72: Locations of MWW locks and the proposed central storage facility

10.4.2 Transport

Large maintenance should be conducted every 12 to 15 years (Vrijburcht, 2000). This means that when doors of a lock require maintenance, they will have to be removed and replaced by new modules that will be transported from the storage facility.

In this study the largest modules are found to be 18.4m long, 5.6m high and it is assumed that they will be 1m to 1.4m thick. According to the transportation firm Zwatra, transportation of modules of this size is relatively easy and is unlikely to present a challenge (Zwatra, 2018). The modules would be transported as exceptional freight, which means transportation would mostly occur during the night. Modularization makes on-road transport more efficient, and in case of emergency the modules could be on site within one day. The total transportation costs from the storage facility to the furthest locks would amount to around € 1600,- (Bolk, 2018).

10.4.3 Exchanging gates

When gates of a lock require maintenance, the modules making up the gate can be selected from the storage facility and be loaded onto trucks to be transported to the concerned lock. Depending on the type of maintenance and the design of the back post, one can choose to either leave the back post in the lock head or to replace it as well. The option of leaving the back post simplifies the exchange significantly as the upper pivot won't need to be removed. The modules can be lifted out of the lock head and be slid out of the back post. This lifting operation will require a heavy lifting crane. In the meantime the new modules can be assembled on the side of the lock. The latter may require a large horizontal scaffolding structure to keep the modules in place while these are bolted together. After having removed the old gate from the lock head, the back post can, if necessary, be taken out and replaced. Finally, the assembled modules can be slid into position.

10.5 Availablity

During the design of a lock complex, it is usual for a tradeoff to take place, assessing the economic damage due to unavailability of the lock versus the cost of spare gates.
When lock gates have to be taken out for large maintenance, which has to take place every 12-15 years, and when there are no spare gates in stock, a lock is expected to be unavailable for about 30 days. In case of severe damage due to ship collision, the period of unavailability may be much longer, as the gates that have to be fully replaced would have to be built first (Vrijburcht, 2000).
When maintenance is needed while spare gates are available, the period of non-availability of the lock would only depend on the time required to exchange the gates. To determine whether to equip a lock with a spare gate n economic trade-off is usually made:

$$Economic\ damage\ due\ to\ non\_availability > Cost\ of\ spare\ gate$$

$$\downarrow$$

Equip the lock with spare gates

$$Economic\ damage\ due\ to\ non\_availability < Cost\ of\ spare\ gate$$

$$\downarrow$$

Accept the economic damage

As the relations above suggest, the logical choice to make is to choose the alternative that costs least. This alternative is called the ***availability costs***.

In case clustering is applied and several locks can share the same spare gate, the economic damage becomes the sum of economic damages for the locks within the cluster. This increases the potential benefits of having a spare gate.

In this report, economic damage due to non-availability has not been considered. For the sake of simplicity it was assumed that every lock gate must have a set of spare doors to replace them.

In the tables below three cases are worked out. The first case indicates the situation where no clustering is applied and every lock head has a spare gate in stock. In the second case all lock heads are equipped with a ***standardized*** gate meaning that all lock heads can share one spare gate. Finally, the third case presents a situation where no standardization is applied and where a trade-off is made on whether to equip the heads with a spare gate or not. For each head the cheapest outcome is chosen, either to accept economic damage due to non-availability or to build a spare gate.

Case 1: No clustering is applied but each lock head will still have a spare gate.

Considered lock head	Applied gate	Cost of gate	Total cost gates in use	Economic damage due to non-availability	Cost of spare gate	Decision	Availability costs	Availability	Total cost
Lock A	Gate A	€ 45.000		€ 13.000	€ 45.000	spare gate		99%	
Lock B	Gate B	€ 40.000	€ 120.000	€ 60.000	€ 40.000	spare gate	€ 120.000	99%	€ 240.000
Lock C	Gate C	€ 35.000		€ 43.000	€ 35.000	spare gate		99%	

Case 2: All lock heads are clustered and a standard gate is applied (the largest one costing € 45.000)

Considered lock head	Applied gate	Cost of gate	Total cost gates in use	Economic damage due to non-availability	Cost of spare gate	Decision	Availability costs	Availability	Total cost
Lock A	Gate A	€ 45.000		sum of all economic	Share one			99%	
Lock B	Gate A	€ 45.000	€ 135.000	dammages	spare gate	spare gate	€ 45.000	99%	€ 180.000
Lock C	Gate A	€ 45.000		€ 116.000	€ 45.000			99%	

Case 3: No clustering applied, each lock head is equipped with a unique gate.

Considered lock head	Applied gate	Cost of gate	Total cost gates in use	Economic damage due to non-availability	Cost of spare gate	Decision	Availability costs	Availability	Total cost
Lock A	Gate A	€ 45.000		€ 13.000	€ 45.000	no spare gate		95%	
Lock B	Gate B	€ 40.000	€ 120.000	€ 60.000	€ 40.000	spare gate	€ 88.000	99%	€ 208.000
Lock C	Gate C	€ 35.000		€ 43.000	€ 35.000	spare gate		99%	

Deciding whether to implement standardization or not van be done by a financial comparison, ether between Case 1 and Case 2 or between Case 2 and Case 3.

It can be seen that standardization seems a lot more favorable when the first comparison is made (Case 1 and Case 2). This comparison would result in the conclusion that the availability in both cases is equal but that standardizing would save up to € 60.000.

With the second more complicated, but more realistic comparison (Case 2 and Case 3) this financial benefit would be reduced to € 28.000. The average availability of Case 3 is however 1.3% lower than that of Case 2.

Since this report didn't take economic damage due to non-availability into account, the approach used is similar to comparing Case 1 to Case 2. This means that no standardization is calculated to be more expansive than need be. However, ***for this research the availability of the locks due to lock gate maintenance is independent of whether standardization is applied or not.***

10.6 Reliability

This study focusses largely on the effects of standardization on over-dimensioning where over-dimensioning is seen as the excess of material required. If standardization is applied and over-dimensioning occurs, a lot of the lock gates will be much stronger than they would need to be. It is expected that this will contribute to the overall structural reliability of the lock gates.

10.7 Conclusion

During the cost analysis, the approximation of steel within the considered lock gates has been modified on the basis of two actual, realized lock gate designs. Plotting the area of the mitre gate door against its mass illustrated a clear relation between the two. Thus it can be concluded that there is no need in figuring out a three dimensional relationship between the door height, width and mass as was previously done in this report. A two dimensional relationship suffices.
According to the direct cost calculations, standardizing and clustering lock gates has a large potential in reducing the total construction costs of the doors that require renewal during the MWW renovation project. This cost reduction is the result of the fewer spare gates required. One of the main starting points of this research was that each lock gate must have a spare gate in stock. This starting point results in a constant availability, no matter what degree of standardization is applied (see Section 10.5). Addressing the reliability is seems clear that standardization makes the average lock gate more structurally reliable as most gates will be over-dimensioned.

	No standardization	**Standardize into 30 clusters**	**Standardize into 8 clusters**	**Standardize into 5 clusters**
Direct construction costs	€ 42.000.000,-	€ 35.800.000,-	€ 28.700.000,-	€ 31.700.000,-
Maintainability	0	+	++	++
Availability	0	0	0	0
Reliability	0	0	+	+

Table 45: Summary of the comparison between various degrees of standardization

11 Conclusions

The conclusion of this study is presented according to the structure of this report, answering each of the sub-research questions separately and finally answering to the main research question.

RQ1: On what aspects should the standardization be based on?

Throughout this research it was found that the main design determining aspects of a mitre gate are the required gate height and the lock width. It was qualitatively and quantitatively argued that these have the most significant effect on the required dimensions and loading of the doors.

RQ2: What standardization method could be applied amongst the MWW lock gates?

The challenge of applying standardization over locks with various dimensions was tackled by determining a standardization method that would allow doors to be compatible in a range of locks with different characteristics. In this research two standardization options were assessed, namely the creation of a "one size fits all" lock gate and a modular lock gate which could be modified within a category.

RQ3: What are the structural effects and physical boundaries of the standardization method ?
&
RQ4: How does the standardization method relate to the clustering of the lock gates with regard to over-dimensioning and the physical boundaries?

It was found that the modularization of the lock gates has good potential to confine the extra amount of material required if the lock gates were to be standardized. Due to the more efficient use of material when modularizing the gates, gate modularization is highly recommended.
The physical boundaries of the chosen standardization methods revealed the limits of applying standardization with respect to the instability of the doors. It was found that instability plays a large role in the limitations to standardization. Concerning the instability of doors, an assessment has been made for the influence the type of centre seal has on the stability of the doors. The assessment revealed that the normal force based centre seal adds to the stability of the doors, leading to enhanced clustering possibilities.

RQ5: What would the design of a standardized mitre gate door look like?

The determination of the conceptual modular door design within one of the specifies gate clusters illustrates that through smart modularization, the modular doors will be able to fit well into the various locks. The degree at which the gates will exceed the lock heads will be minor and the adaptations to the civil structure will be limited. Through the potential life cycle assessment of the modular doors it was found that the implementation of this type of standard facilitates ease of maintenance and management and therefore is in accordance with the wishes of MWW.

RQ6: How does the chosen standardization strategy compare to the situation where no standardization is applied?

From the performed cost analysis it seemed that the clustering configurations with eight or five clusters caused a large decease in the direct construction costs when compared to the case where no standardization is applied. Standardization also has potential benefits concerning the ease of handling and managing spare components and gate replacement. The overall reliability of the lock gates is increased due to over-dimensioning whereas the availability stays constant no matter the degree of standardization applied.

How to standardize the MWW lock gates with steel mitre gates to reduce variability?

By applying a modular standard for the lock gates, capable of closing under a varying slope, it is possible to standardize lock gates in locks with varying widths. Making the doors modular in height enables them to be placed in locks with different required door heights, the latter has a significant influence on the degree of over-dimensioning. Using the approach of modular gates capable of fitting in locks with varying widths, the 98 considered MWW lock gates can be clustered into a minimum of five gate clusters. A cost analysis has however shown that clustering the gates into eight clusters is economically more beneficial and reduces the total construction cost by € 7.100.00 and therefore seems optimal.

12 Evaluation and recommendations

This research has shown that standardization of the MWW lock gates is possible by designing a lock gate capable of closing under a varying slope and being modular in height. This type of standardization may reduce lock gates eight unique gate designs. From the comparative analysis it became clear that standardization may benefit the total construction costs, availability and reliability of the lock gates. It is therefore recommended to follow up on the recommendations given in the paragraphs below. Here the evaluation of the scope, approximations and starting points and the corresponding recommendations are presented.

Scope

The scope of this research limited the investigation to the standardization of mitre gates, only addressing steel as the structural material. Taking this research a step further, one can ask if this report may also give insights for the standardization of other gate types, in different materials with a different support system.

Concerning the gate types, mitre gates have the great advantage that a door with a fixed length can be placed in a range of lock widths by adjusting the slope of closure. This enables the standardization of doors in locks with different widths. For a vertical lift gate or a rolling gate, the option of creating one standard gate length for locks with different widths would be much more difficult. In case of the vertical lift gates the lifting towers would have to be relocated and in case of the rolling gate the entire gate recess will have to be enlarged (rolling gates have a much larger gate recess area than mitre gates).

The maximum degree of clustering is mainly dominated by physical boundaries concerning the stability of the doors during closure. This stability was purely determined on the relation between the slope of closure and possible occurrences leading to the asymmetrical loading on the doors. Material is not expected to have an influence on the investigated stability and therefore not on the clustering possibilities either. Therefore, it is assumed that the maximized clustering configurations would be similar for any material. So far only steel was assessed, it would be interesting to perform an investigation for the over-dimensioning for various different gate materials, possibly leading to clusters having their own specific gate material. However, it should be kept in mind that modularization might not be possible in other materials than steel.

Approximations

Most of this research is based on the approximation of steel mass within lock gates. This approximation was based on calculating the amount of steel required in the main horizontal girders of the doors. Higher doors would result in an increase for the amount of required beam, increasing the loads resulting in larger cross-sections. Longer doors would results in longer beams, also with an increase in their cross-sections. In reality, a mitre consist of many more elements then just horizontal beams. The change in material required of each of these elements behave differently towards an overall increase in door size or load. It is expected that an increase in door dimensions has the largest influence on the change in material required in the horizontal beams, meaning that the over-dimensioning determined in this research is on the conservative side. In order to enhance the exactness of this research it is recommended to come up with a more detailed model for the determination of the required material and hence over-dimensioning. The two dimensional relationship between door area and door mass (found in Section 10.3) is expected to be more realistic than the steel approximations used in the clustering model. For the model to come up with more accurate results it is recommended to use the new relation as the input parameters and determine a new relation between clustering and over-dimensioning.

To determine the physical boundaries of applying a gate with a fixed door length, a model was set up. In this model it was assumed that an oblique wave and a departing ship will cause an asymmetrical loading on the doors of a mitre gate, potentially leading to instability of the doors. This load was approximated as a net difference for the retention heights of the doors (one door would have a larger retention height than the other). According to this approximation the appliance of varying the slope of closure of mitre gates is limited. This report assumed a net difference in the retention heights ranging between 0.5 m and 1 m. It is recommended to test if this range is a realistic approximation for the asymmetrical loading on the gates.

Main starting points
The entire standardization of lock gates is based on the lock width and required door height as these are estimated as the main load contributors and have the largest degree of influence on the material required. From a financial point of view it might be beneficial to include other aspects for the determination of the clusters as the costs of a gate do not only depend on the material used. One can for instance think of the required corrosion protection for either sea locks or river locks. In the case of this research, all lock gates within a cluster containing a sea lock, will have to be coated as if they were to be placed in salt water. Since salt water is more aggressive then fresh water, the coating requirements are more severe. The additional coating might lead to such an increase in costs for the locks that would only require the fresh water coating that sea locks and river locks may have to separate into different clusters. Even though amount of material gives some indication of the costs, it is recommended to investigate the other cost factors of a lock gate and to determine the significance of the other determining aspects based on their contribution to the total cost of the gates.

Concerning the management of spare components it the assumption is made that a group of gates within one cluster can share one set of spare components. This means that, considering the largest possible cluster, 28 lock gates will have to share one spare gate set, seeming unrealistic. If the gates were to undergo large maintenance once every 12 years (Vrijburcht, 2000) (meaning they would have to be replaced with a spare gate and repaired in a storage facility), the average time of repair would have to be under five months. If a gate would have to be replaced during the repair time of the spare gate problems would arise. For this reason it is recommended to perform a risk analysis, per cluster, in order to figure out the amount of required spare gates.

This report excluded the economic trade-off between building spare gates and accepting economic damage due to non-availability. Section 10.5 indicated that this trade-off may significantly influence the decision on whether to standardize or not. It is recommended to include economic damage due to non-availability for a better financial comparison.

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Appendix A: MWW lock data

The tables below give the lock data used in this research (T. Wilschut, 2017)

lock #	naam	region	navigation route	x-coordinate	y-coordinate	hightwater	exceedence	retention	HW retention	locking length	lock width	chambers
1	Sluis III	ZN	7. Maasroute	130533	399297	No	n.v.t.	One sided	Single retention	65	5	2
2	Driewegsluis	NN	5. Amsterdam - Noord-Nederland	235748,5	582746,4	Ja	1/300	One sided	Single retention	47	6	1
3	Ottersluis	WNZ	3. Westerschelde - Rijn	111903	422858	No	n.v.t.	One sided	Single retention	39	7	1
4	Helsluis	WNZ	1. Rotterdam - Duitsland	113280	424836	No	n.v.t.	One sided	Single retention	39	7	1
5	Noordersluis Kleine westelijke sluis	MN	2. Amsterdam - Rijn	135811	451536	No	n.v.t.	Two sided	Single retention	55	7	1
6	Sluis 0	ZN	7. Maasroute	150060	411080	No	n.v.t.	One sided	Single retention	124,2	7	1
7	Sluis Panheel (oude kolk,noord)	ZN	7. Maasroute	188176	354024	No	n.v.t.	One sided	Single retention	145	7,5	2
8	Dorkwerdersluis	NN	5. Amsterdam - Noord-Nederland	229893	586088	Ja	1/100	One sided	Single retention	70	7,5	1
9	Sluis bij Den Hommel	MN	2. Amsterdam - Rijn	134085	454904	Ja	n.v.t.	One sided	Single retention	29	8	1
10	Sluis V	ZN	7. Maasroute	167410	391460	No	n.v.t.	One sided	Single retention	82,39	8	1
11	Sluis 15	ZN	7. Maasroute	180360	364912	No	n.v.t.	One sided	Single retention	65	8	1
12	Sluis II	ZN	7. Maasroute	127600	400930	No	n.v.t.	One sided	Single retention	65	8	1
13	Sluis IV	ZN	7. Maasroute	142497	389940	No	n.v.t.	One sided	Single retention	65	8	1
14	Grote Kolksluis	ON	5. Amsterdam - Noord-Nederland	201360	517120	Onbekend	Onbekend	Two sided	Double retention	Unknown	8	1
15	Sluis Hulsen	ZN	7. Maasroute	181089	365485	Nee	n.v.t.	One sided	Single retention	70,68	9,5	1
16	Kleine Sluis	WNN	8. Kustcorridor	100923	497655	Ja	1/10000	One sided	Single retention	111	11	1
17	Noordersluis Grote oostelijke sluis	MN	2. Amsterdam - Rijn	135842	451567	Nee	n.v.t.	One sided	Single retention	120	12	1
18	Zuidersluis	MN	2. Amsterdam - Rijn	135515	450868	Ja	onbekend	Two sided	Single retention	120	12	2
19	Wilhelminasluis, Andel	ZN	1. Rotterdam - Duitsland	131630	422900	Nee	n.v.t.	Two sided	Single retention	110	12	1
20	Koninginnensluis	MN	2. Amsterdam - Rijn	134797	446485	Ja	n.v.t.	One sided	Double retention	220	12	2
21	Noordersluis	WNN	2. Amsterdam - Rijn	125969	488304	Ja	1/1250	Two sided	Double retention	72	14	1
22	Zuidersluis	WNN	2. Amsterdam - Rijn	125942	488266	Ja	1/1250	Two sided	Double retention	72	14	1
23	Stevinsluizen	MN	5. Amsterdam - Noord-Nederland	132115	549355	Ja	1/10000	Two sided	Double retention	138,75	14	2
24	Lorentzsluizen kamer 1	MN	5. Amsterdam - Noord-Nederland	151634	564705	Ja	1/10000	Two sided	Double retention	137,8	14	1
25	Lorentzsluizen kamer 1	MN	5. Amsterdam - Noord-Nederland	151634	564705	Ja	1/10000	Two sided	Double retention	137,8	14	1
26	Terhorne sluis	NN	5. Amsterdam - Noord-Nederland	180529	561983	Ja	1/100	One sided	Single retention	260	14	2
27	Henriettesluis (Schutsluis Engelen)	ZN	7. Maasroute	146135	415673	Nee	n.v.t.	One sided	Single retention	92	14	1
28	2e Sluis Bewesten Utrecht (Muntsluis)	MN	2. Amsterdam - Rijn	134589	455821	Nee	n.v.t.	One sided	Single retention	120	14	1
29	Sluis Linne	ZN	7. Maasroute	192560	354230	Nee	n.v.t.	One sided	Single retention	267,8	16	1
30	Schutsluis Sambeek oost	ZN	7. Maasroute	196224	405947	Nee	n.v.t.	One sided	Single retention	260	16	1
31	Sluis Roermond	ZN	7. Maasroute	196500	358250	Nee	n.v.t.	One sided	Single retention	266,5	16	1
32	Schutsluis Belfeld oost (oude sluis)	ZN	7. Maasroute	205579	370472	Nee	n.v.t.	One sided	Single retention	260	16	2
33	Sluis Heumen	ZN	7. Maasroute	187030	420210	Ja	1/1250	Two sided	Single retention	250	16	2
34	Middensluis	WNN	2. Amsterdam - Rijn	125955	488284	Ja	1/1250	Two sided	Double retention	95	18	1
35	Zuidersluis	WNN	8. Kustcorridor	101432	497856	Ja	1/10000	One sided	Single retention	104	18	1
36	Prinses Marijkesluis oostelijke sluis	MN	2. Amsterdam - Rijn	152985	440660	Ja	1/1250	One sided	Single retention	260	18	1
37	Prinses Marijkesluis westelijke sluis	MN	2. Amsterdam - Rijn	152969	440630	Ja	1/1250	One sided	Single retention	260	18	1
38	Sluis Eefde	ON	6. Rijn - Oost-Nederland	213017	463916	Ja	Onbekend	One sided	Single retention	140	12	1
39	Sluis Delden	ON	6. Rijn - Oost-Nederland	243142	473971	Nee	n.v.t.	One sided	Single retention	140	12	1
40	Sluis Hengelo	ON	6. Rijn - Oost-Nederland	251809	474061	Nee	n.v.t.	One sided	Single retention	140	12	1
41	Sluis St. Andries	ZN	7. Maasroute	152941	423283	Ja	1/1250	Two sided	Single retention	110	14	1
42	Sluis Lith zuid (oud)	ZN	7. Maasroute	159614	424475	Nee	n.v.t.	Unknown	Single retention	113,5	14	1
43	Sluis 16	ZN	7. Maasroute	174613	361809	Nee	n.v.t.	Unknown	Single retention	76	15,8	1
44	Sluis Weurt oost	ZN	7. Maasroute	185000	429520	Ja	1/1250	Two sided	Single retention	266	16	2
45	Sluis Bosscherveld	ZN	7. Maasroute	176148	319757	Ja	1/250	Unknown	Single retention	132	16	1
46	Sluis Born west	ZN	7. Maasroute	183778	338557	Nee	n.v.t.	Unknown	Single retention	136	16	1
47	Prinses Beatrixsluis westelijke sluis	MN	2. Amsterdam - Rijn	135929	447341	Ja	1/1250	Two sided	Single retention	225	18	1
48	Prinses Irenesluis Oude sluis (sluis 1)	MN	2. Amsterdam - Rijn	150366	442083	Ja	1/1250	Two sided	Single retention	350	18	2
49	Prinses Beatrixsluis oostelijke sluis	MN	2. Amsterdam - Rijn	135954	447333	Ja	1/1250	Two sided	Single retention	225	18	1
50	Middensluis, Terneuzen	ZD	4. Westerschelde	45601	372920	Ja	1/1250	Two sided	Single retention	140	20	1
51	Middensluis	WNN	8. Kustcorridor	101432	497856	Ja	1/10000	Two sided	Single retention	200	25	1
52	Noordersluis	WNN	8. Kustcorridor	102100	498030	Ja	1/10000	Two sided	Single retention	400	47,3	1
	Locks within scope of research											
	Locks outside of scope of research											

lock #	door type	material	# of do	HW outer	LW outer	average out	max locking lvl	min locking lvl	bottom lvl	sill depth	H lock head (NAP)	H door (N	water type	HW inner	LW inner	average in	max locking lvl	min locking lvl
1	Mitre gate	Wood	2	7,85	7,5	7,7	12,85	7,2					Fresh	12,85	12,35	12,55	7,7	12,85
2	Rolling gate	Wood	3	2,3	0,33	0,53	n.v.t.	n.v.t.	-4,5	-2,95	2,25	4,92	Fresh	0,9		-1,28	n.v.t.	n.v.t.
3	Mitre gate	Wood	2	3,3	0,65		2,49			-2,2	2,8	2,57	Fresh				2,49	
4	Mitre gate	Wood	2	3,5	0,64	0,64	2,49			-1,65	3,05	2,67	Fresh				2,49	
5	Mitre gate	Wood	4	0,8	0	0,45				-3,1	2,38		Fresh	-0,2	-0,5	-0,4		
6	Mitre gate	Steel	2										Fresh					
7	Mitre gate	Steel	2	22,76	20,7			20,6		17,9	29,5		Fresh	28,9	28,58	28,65		28,58
8	Rolling gate	Steel	2	0,9	0,33	0,53	n.v.t.	n.v.t.	-5,95	-2,38	2,8	5,4	Fresh	-0,73	-1,05	-0,93	n.v.t.	n.v.t.
9	Mitre gate	Wood	2						-1,8	-3,1	2,38	2,38	Fresh	-0,2	-0,5	-0,4		
10	Mitre gate	Wood	2										Fresh					
11	Mitre gate	Steel	2	28,85	28,35	28,65			26	26		33,98	Fresh	34,1	33,25	33,61		
12	Mitre gate	Wood	2	5,4	4,95	5,15	7,55	4,95					Fresh	7,85	7,5	7,7	7,55	4,95
13	Mitre gate	Wood	2	12,85	12,2	12,55			9.7	10,1	15,41	15,03	Fresh	15,03	14,75	15		
14	Mitre gate	Wood	4	1,8	-1,74								Fresh	1,2	-0,9	-0,16		
15	Mitre gate	Wood	2			28,65							Fresh			31,65		
16	Mitre gate	Steel	2	5,15	-3	0,97/-0,73	2	-1,5	-5,9	-3,75	5,85	4,85	Salt	-0,3	-0,5	-0,4		
17	Mitre gate	Wood	2	0,8	0	0,45			-3	-3,73	2,38		Fresh	-0,2	-0,5	-0,4		
18	Mitre gate	Wood	5	0,8	0	0,45			-3.25	-3,73			Fresh	-0,2	-0,5	-0,4		
19	Waaierdeur	Steel	2	5,23		0,95	4,5			-2,14	5,86	5,23	Fresh	3,5		0,65		
20	Mitre gate	Steel	4	6,5	-1,15	1,09	4,7	-0,4		-2,25		7,12	Fresh	0,8	0,3	0,45		
21	Mitre gate	Steel	3	0,7	-3,17	-0,4 tot -0,2				-4,5	2,5	1,85	Fresh	0,89	-0,71	-0,4		
22	Mitre gate	Steel	3	0,7	-3,17	-0,4 tot -0,2				-4,5	2,5	1,85	Fresh	0,89	-0,71	-0,4		
23	Mitre gate	Steel	6	4,5			1,8			-4,4	5	4,88	Salt	1,2	-1,13	-0,4 tot -0,2		
24	Mitre gate	Steel	5	4,75			1,8			-4,4	5,25	5,13	Salt	1,2	-1,13	-0,4 tot -0,2		
25	Mitre gate	Steel	5	4,75			1,8			-4,4	5,25	5,13	Salt	1,2	-1,13	-0,4 tot -0,2		
26	Mitre gate	Steel	4	-0,52		n.v.t.	0	n.v.t.	-4,5	-4,66	n,v,t,	n.v.t.	Fresh			-0,52	n.v.t.	n.v.t.
27	Mitre gate	Wood	2										Fresh					
28	Mitre gate	Steel	2	0,8	0	0,45				-3,33	2,32		Fresh	-0,2	-0,5	-0,4		
29	Mitre gate	Steel	3		20,7	20,85				16,6	22,6	23,35	Fresh		16,7	16,85		
30	Mitre gate	Steel	3			11,1						11,9	Fresh			7,65		
31	Mitre gate	Steel	3		16,7	16,85				11,9	21,25	20,55	Fresh		14,05	14,1		
32	Mitre gate	Steel	2		11	14,05				7,45		15	Fresh			14,1		
33	Mitre gate	Steel	3	12,46	7,41		12,15	8,3	3,35	3,35	13,4	13,4	Fresh	8,3	7,6			
34	Mitre gate	Steel	3	0,7	-3,17	-0,4 tot -0,2				-4,5	2,5	1,85	Fresh	0,89	-0,71	-0,4		
35	Mitre gate	Steel	2	5,15	-3	0,97/-0,73	2	-1,5	-8,5	-7,85	5,85	4,85	Salt	-0,3	-0,5	-0,4		
36	Mitre gate	Steel	2	8,15	1,2					-2,35		9	Fresh	5,55				
37	Mitre gate	Steel	2	8,15	1,2					-2,35		9	Fresh	5,55				
38	Vertical lift	Steel	2		1,55				-1	0		9,95	Fresh	10,1	9,9	10		
39	Vertical lift	Steel	2	10,42	8,65				6,55	6,56	21,52		Fresh	16,5	14,35			
40	Vertical lift	Steel	2	16,5	14,3					12,2	25,8		Fresh	25,37	23,35	25		
41	Vertical lift	Steel	2	10,05	4,86				-3	-3	10,55	10,5	Fresh	6,96	4,2			
42	Vertical lift	Steel	2							-3			Fresh					
43	Vertical lift	Steel	2	34,1	33,25						36,43		Fresh	36,1	35,4	35,68		
44	Rolling gate	Steel	3	14,66	4,22					3	15,1	13	Fresh	8,6	7,6	7,6 tot 8,5		
45	Vertical lift	Steel	2	44,17	43,9				40,4	36,4	46	47,3	Fresh	40,48	40,3	40,35		
46	Vertical lift	Steel	2		43,9								Fresh		32,5	32,65		
47	Vertical lift	Steel	2	6,4	-1,15					-4,5	6,5		Fresh	-0,2	-0,5	-0,4		
48	Vertical lift	Steel	3	8,4	1,2				-2,3	-5,5	9,1	9,1	Fresh	-0,2	-0,5	-0,4		
49	Vertical lift	Steel	2	6,4	-1,15					-4,5	6,5		Fresh	-0,2	-0,5	-0,4		
50	Rolling gate	Steel	4	5,8					-7,58				Fresh			2,13		
51	Mitre gate	Steel	6	5,15	-3				-10,6	-10	5,85	5,85	Salt	-0,3	-0,5	-0,4		
52	Rolling gate	Steel	2	5,15	-3				-15,5	-15	5,85	5,85	Salt	-0,3	-0,5	-0,4		

lock #	bottom lvl	sill depth	lock head (NAH	door (NAP	water type	constructed	end LC	lvling type	# openings	# valves	drive mechanism	drive mechanism	remote ctrl	setting dry	ship class	lockings/year	lvling time
1					Fresh	1916	2025	Culverts	Unknown	Unknown	Elektromechanical	Elektrohydraulisch	Yes	Unknown	CEMT II	Unknown	Unknown
2		-2,95	2,3	4,79	Fresh	1934	2043	Unknown	4	2	By hand	By hand	Yes	Unknown	CEMT II	Unknown	Unknown
3		-2,2	2,8	2,57	Fresh	1863	2035	In doors	2	2	Elektrohydraulic	Elektrohydraulisch	Yes	Yes	CEMT I	5188	Unknown
4		-2,2	3,05	2,67	Fresh	1863	2035	In doors	2	2	Elektromechanical	Handmatig	Yes	Yes	CEMT 0	4605	Unknown
5		-3,1	2,38		Fresh	1937	2046	In doors	4	2	Elektrohydraulic	Elektrohydraulisch	Yes	No	CEMT Va	4254	< 3 min
6					Fresh	1931	2040	In doors	Unknown	Unknown	Elektromechanical	Elektrohydraulisch	Yes	Unknown	CEMT II	19	Unknown
7		25,5	29,5		Fresh	1930	2039	Culverts	Unknown	Unknown	Elektromechanical	Elektromechanisch	Yes	Yes	CEMT II	5049	Unknown
8	-5,9	-3	2,8	5,4	Fresh	1929	2038	Culverts	Unknown	Unknown	Elektrohydraulic	Elektromechanisch	Unknown	Yes	CEMT II	3577	Unknown
9	-3,1	-3,1	2,38	2,38	Fresh	1937	2046	In doors	Unknown	2	Elektromechanical	Elektromechanisch	Yes	No	CEMT Va	Unknown	Unknown
10					Fresh	1920	2035	Unknown	Unknown	Unknown	Unknown	Unknown	Yes	Unknown	CEMT II	Unknown	Unknown
11	30,35	30,8		33,98	Fresh	1930	2051	Culverts	32	4	Elektrohydraulic	Elektromechanisch	Yes	Yes	CEMT II	5177	< 15 min
12					Fresh	1916	2025	Culverts	Unknown	Unknown	Elektromechanical	Elektrohydraulisch	Yes	No	CEMT II	Unknown	Unknown
13	11,9	12,26	15,41	15,03	Fresh	1920	2058	Culverts	8	Unknown	Elektrohydraulic	Elektrohydraulisch	Yes	Yes	CEMT II	Unknown	Unknown
14					Fresh	1942	2057	In doors	Unknown	Unknown	Elektromechanical	Elektromechanisch	Unknown	Unknown	CEMT III	Unknown	Unknown
15					Fresh	1932	2032	Culverts	Unknown	Unknown	Elektromechanical	Elektromechanisch	Yes	Unknown	CEMT II	Unknown	Unknown
16	-7,5	-3,75		3,5	Fresh	1876	2051	In doors	4	4	Elektrohydraulic	Elektrohydraulisch	Yes	No	CEMT IV	Unknown	Unknown
17	-3,9	-3,73	2,38	2,35	Fresh	1937	2046	In doors	6	2	Elektrohydraulic	Elektrohydraulisch	Yes	No	CEMT Va	767	< 5 min
18	-3,25	-3,73		2,35	Fresh	1937	2046	In doors	Unknown	2	Elektrohydraulic	Elektrohydraulisch	Yes	No	CEMT Va	7174	Unknown
19		-2,89	5,86	5,23	Fresh	1896	2033	In doors	4	4	Elektromechanical	Elektromechanisch	Yes	No	CEMT Va	4481	Unknown
20		-2,7		3,55	Fresh	1885	Onbekend	In doors	4	4	Elektromechanical	Elektrohydraulisch	Yes	Yes	CEMT Va	3897	Unknown
21		-4,5			Fresh	1870	2059	In doors	4	4	Elektrohydraulic	Elektrohydraulisch	Yes	No	CEMT III	14773	< 7,5 min
22		-4,5			Fresh	1870	2059	In doors	4	4	Elektrohydraulic	Elektrohydraulisch	Yes	No	CEMT III	2030	< 7,5 min
23		-4	3	2,88	Fresh	1930	2051	In doors	Unknown	Unknown	Elektromechanical	Elektrohydraulisch	Yes	Unknown	CEMT Va	7583	Unknown
24		-4	3	2,88	Fresh	1931	2051	Culverts	Unknown	Unknown	Elektromechanical	Elektrohydraulisch	Yes	Unknown	CEMT Va	10689	Unknown
25		-4	3	2,88	Fresh	1931	2051	Culverts	Unknown	Unknown	Elektromechanical	Elektrohydraulisch	Yes	Unknown	CEMT Va	10689	Unknown
26	-4,5	-4,66	2,08	5,75	Fresh	1948	2057	In doors	2	2	Elektromechanical	Elektromechanisch	Yes	No	CEMT IV	Unknown	Unknown
27					Fresh	1898	2035	Culverts	Unknown	Unknown	Elektromechanical	Elektromechanisch	Yes	No	CEMT IV	7859	Unknown
28		-4,18	2,32		Fresh	1906	Onbekend	In doors	Unknown	2	Elektromechanical	Elektromechanisch	Yes	No	CEMT Va	Unknown	Unknown
29		13,45	24	21,95	Fresh	1921	2035	Culverts	36	6	Elektromechanical	Elektromechanisch	Yes	Yes	CEMT Va	6033	< 7 min
30			12,6	11,9	Fresh	1925	2034	In doors	Unknown	Unknown	Elektromechanical	Elektromechanisch	Yes	Unknown	CEMT Va	9016	Unknown
31		10,7	17,75	17,05	Fresh	1926	2035	Culverts	36	6	Elektromechanical	Elektromechanisch	Yes	Yes	CEMT Va	6880	< 7 min
32		8,45	15,6	15	Fresh	1926	2035	In doors	Unknown	Unknown	Elektrohydraulic	Elektromechanisch	Yes	Yes	CEMT Va	6291	Unknown
33	3,35	3,35	12,5	12,5	Fresh	1927	2036	Culverts	26	Unknown	Elektromechanical	Elektrohydraulisch	Yes	No	CEMT Vb	Unknown	< 21 min
34		-4,5			Fresh	1870	2059	In doors	4	4	Elektrohydraulic	Elektrohydraulisch	Yes	No	CEMT IV	15187	< 7,5 min
35	-8,5	-7,85		3,5	Fresh	1876	2051	In doors	6	6	Elektrohydraulic	Elektrohydraulisch	Yes	No	CEMT Va	Unknown	Unknown
36		-2,35			Fresh	1937	2046	In doors	8	4	Elektromechanical	Elektromechanisch	Yes	Unknown	CEMT VIb	0	Unknown
37		-2,35			Fresh	1937	2046	In doors	8	4	Elektromechanical	Elektromechanisch	Yes	Unknown	CEMT Vb	0	Unknown
38		6,5		10,6	Fresh	1933	2051		6	6				Yes	CEMT Va	14618	Unknown
39	12,1	12,25	17	16,5	Fresh	1933	2042		n.v.t.	n.v.t.				No	CEMT Va	10735	Unknown
40	21,1	21,25	25,8		Fresh	1935	2044		6	6				No	CEMT Va	1508	Unknown
41	-3,2	-3	8,25	8,78	Fresh	1934	2043		n.v.t.	n.v.t.				Unknown	CEMT Va	14050	< 8 min
42		-1			Fresh	1936	2045		Onbekend	Onbekend				No	CEMT Va	10229	Unknown
43		32,43	36,43		Fresh	1930	2039		n.v.t.	n.v.t.				No	CEMT II	4081	Unknown
44		3	11,04	11,04	Fresh	1927	2050		2	6				Yes	CEMT Vb	11873	Unknown
45	36,4	40,4	46,03	45,5	Fresh	1930	2039		n.v.t.	n.v.t.				Yes	CEMT Va	4900	Unknown
46					Fresh	1933	2042		Onbekend	Onbekend				Yes	CEMT Va	4237	Unknown
47		-4,5			Fresh	1933	2055		6	6				Yes	CEMT Vb	19824	< 7 min
48	-4,7	-5,5	9,1	9,1	Fresh	1937	2046		6	6				Unknown	CEMT Vb	13094	Unknown
49		-4,5			Fresh	1938	2055		6	6				Yes	CEMT Vb	20210	< 7 min
50					Salt	1910	2034		Onbekend	Onbekend				Unknown	CEMT VIb	7538	Unknown
51	-10,6	-10		2,5	Fresh	1891	2047		10	10				No	CEMT VIa	Unknown	< 12 min
52	-15,5	-15		5	Fresh	1923	2051		4	4				Yes	CEMT VIa	Unknown	Unknown

Appendix B: Lock gates, materials and drive mechanisms

This appendix gives more information about the various lock gate types found in the Netherlands, the material applied and the range of possible drive mechanisms

Gate Types

A mitre gate cosists of two “doors” that close the lock by being “pushed”against eachother. When opened, the gates are positioned allong the length of the lock in their gate recess area. Although the gate allows for a narrow lock without air draught limitation, it does require extra lock length for the storage of the gates when opened. Due to the structural form, the forces acting upon the gates are mainly transferred into normal compressive forces on the elements of the gates. Because of this advantageous load transfer, the gates can be relatively light and become very cost effective. Mitre gates can only retain water in one direction, to retain water in two directions a double set of doors is required. In closed position the door always points towards the side with the higher water level.

Figure 73: Closed mitre gate (Hensen, 2018)

Instead of stoing the gates along the length of the lock when these are opened vertical lift gates store the gate above the lock. A vertical lift gate usually consists of two towers containing large counter weights and a drive mechanism in order to lift the gate to the required height to enable the passage of the vessels passing through the lock. Two main beneficial charactiersitcs about verical lifting gates is that they can retain a water level difference from both sides and that they can close during the flowing water. Since the gate is lifted vertically and stored somewhere above the water level it still forms a barrier for vessels with a large air draught, causing air draught limitations of the waterway the lock is on. Also due to the large height of the towers some resistance can be found by local stakeholders as the structre can be considered as visual pollution.


Figure 74: Example Lift Gate (Van Erp, 2017)

Rolling gates are large vertical water barriers on rails. When the gates are opened they are rolled in the horizontal plane along their length into their chamber. This type of gate storage requires an excessive amount of space as the gate system of the lock required about double the width of that of the lock. However, due to the fact that this gate is supported along its length and the lock head, it is possible to apply this type for locks with very large widths.


Figure 75: Example Rolling Gate (Van Erp, 2017)

Materials

Amongst lock gates, steel is the most common type of material and is found in every gate type. Although steel is very often used, wood is also frequently applied. This material however is only applicable in miter gates. The use of new materials is also on the rise, research into the applicability of Ultimate High Performance Fiber Reinforced Concrete (UHPFRC) is currently being done and recently the first Dutch lock with composite miter gates has been constructed. Due to the fact that this variety of material usage is mainly found in miter gates this section focusses on this specific gate type.

Steel

Concerning mitre gates, steel can be applied for both narrow as large spans. The picture below illustrates a steel miter gate, pointing out some of its main elements, namely the horizontal girders, intermediate diaphragms and diagonals. Steel structures like these often require frequent inspection and maintenance due to possible corrosion. It is found that steel miter gates require maintenance once every 15 years (R.C.A. Beem, 2000). This span can be increased by applying extra material and cathode protections. Ideal for this maintenance is to every now and then exchange the gates with a spare gate. The old gate can then be checked for corrosion and be conserved. Once repairs and restoration works are finished, the old gate will serve as the new spare gate ready to be placed for the next exchange.

Figure 76: Steel Mitre Gate (Daly, 2017)

Wood

The second alternative for mitre gates is the use of wood. Wooden miter gates are usually only seen in relatively narrow spans. Amongst the MWW locks, the largest wooden span is 12 m and the applicability therefore varies between 7 m and 12 m.

Compared to steel, wood requires less inspection and maintenance, ideally once every 25 years. The choice of wood over steel is often made with regard to economic considerations as fever maintenance and cheaper material lead to lower overall life cycle costs.

With the application of wood it should be kept in mind that the use of tropical hardwood should be prevented as much as possible. The picture on the right shows a wooden miter gate where the large horizontal beams are the main load carriers for the horizontal load transfer.

Figure 77: Wooden Mitre Gate

Fibre reinforced polymer (FRP)
Both of the materials mentioned above require frequent costly maintenance, which often significantly contributes to the total life cycle costs. To cope with these high maintenance costs a new material has made its entry on the Dutch market, namely fibre reinforced polymer (FRP). Figure 14 shows the installation of the mitre gates of Sluis III in the city of Tillburg for which the gates are 12.9 m tall and 6.2 m wide. The design of the gates seems to be very simple as the gates are mere flat doors without any beams transfer the loads to the supports. Although FRP is a relatively new material and no data is available on the life cycle of doors made of this type, it is expected to have a life cycle of over 100 years and to require minimum maintenance.

Figure 78: FRP Mitre Gate (Daly, 2017)

Ultimate high performance fibre reinforced concrete
Another material that qualifies for the use of lock gates would be Ultimate High Performance Fibre Reinforced Concrete (UHPFRC). Although this material has not been used in any mitre gate yet, it has been applied in a rolling gate. The application for this material instead of steel or wood were, just like

with FRP, to compete with their life cycle costs with respect to the maintenance costs, as it is said that gates from this type of material need little to no maintenance. Recently A.D.Reitsma conducted his master thesis on the design of a UHPFRC miter gate. He showed that in comparison to steel, a UHPFRC gate would reduce life cycle costs with 55% and would result in 85% decrease in CO_2 emissions.

Figure 79: Concrete Rolling Gate (Haitsma Beton, 2010)

Drive mechanisms

In order to operate, mitre gates need driving mechanisms, these exert a normal force at some location on the door causing a turning moment resulting in the opening or closure. Figure XXX illustrates a mitre gates in closed position with two hydraulic cylinders as its driving mechanism. It is usual for driving mechanisms to have their point of engagement on the door such that the distance from the doors pivot is 1/3 times the total length of the door or at 1/3b.

There are various types of drive mechanisms, namely hydraulic cylinder (as shown in the last two illustrations), Panama wheel, rack bar and the electro mechanical cylinder.

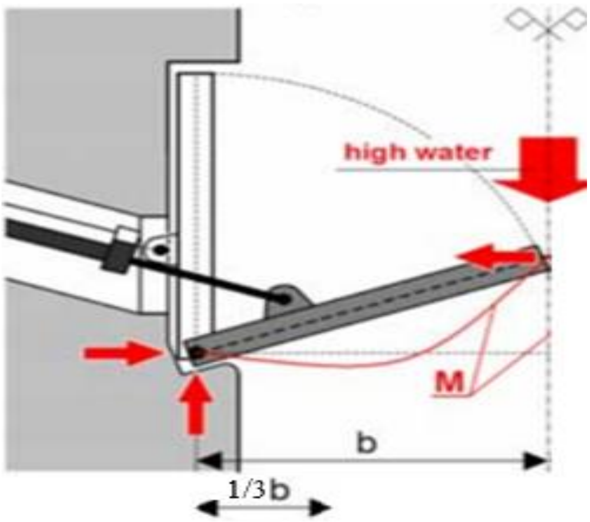


Figure 80: Drive mechanism and mitre gate door (Johnson, 2017)

Electro hydraulic cylinder

An electro-mechanical operating system consists of a horizontally placed hydraulic cylinder which includes a pump, operated by an electro-motor and a piston rod. The piston rod is moved by adjusting oil pressures in the cylinder with the help of the systems pump. As the hydraulic cylinder is compressed and decompressed the required storage in the lock head is relatively small, therefore only small basement chambers are required. Usually, the connection point of the piston on the gate is close to the turning point of the gate which requires larger forces to obtain a similar turning moment as with electro mechanical systems.

Figure 81: Hydraulic Cylinder (Vrijburcht, 2000)

The main advantages and disadvantages of a hydraulic cylinder are:

Advantages	Disadvantages
Requires small chamber space	Installation takes a lot of time due to piping and wiring installations
Cylinder can function under water without any problems	Installation is a lot more complicated than with electro-mechanical systems
Drive unit can be positioned in any available location	Concrete space for cylinder must be conditioned against leakage
Cheap installation compared to electro-mechanical systems	Standing time is shorter when compared with electro-mechanical systems while inspection and preventative maintenance is required more often
The cylinder is easy to exchange	Maintenance requires skilled and trained personnel
Insensitive to measurement deviations in gates, therefore also to the exchange of gates	Low return of the installation, therefore requires a high motor capacity
	More susceptible to malfunction due to the large number of components

Table 46: Advantages and disadvantages Hydraulic Cylinder

The hydraulic cylinder is applicable for every gate size. This system is most suitable for high operating loads during movement of the gate, when there is little space in the lock heads and when the water levels are high so that the system can be submerged under water.

Electro mechanical cylinder

This system very much resembles the hydraulic cylinder except for the fact that the cylinder is not driven by pressurized hydraulic oil but by an inner piston that is rotated in a helix inside the cylinder causing the cylinder to expand. When comparing these two types of cylinders the main advantage this type has over the hydraulic cylinder is that it’s a relatively more simple mechanism involving fewer components and therefore is less maintenance sensitive. A disadvantage however, is that spare components are more rare and harder to obtain when needed in case of unexpected maintenance.

Panama wheel

For a Panama wheel the operating mechanism consists of a large, horizontally positioned gear wheel that is connected to the gate via a push-pull rod and is driven by a pinion. The mechanical system is usually placed in a concrete basement inside the lock head while the push-pull rod sticks out through an opening to connect to the gate. The figures below and on the right illustrate a top and side view of such a system:

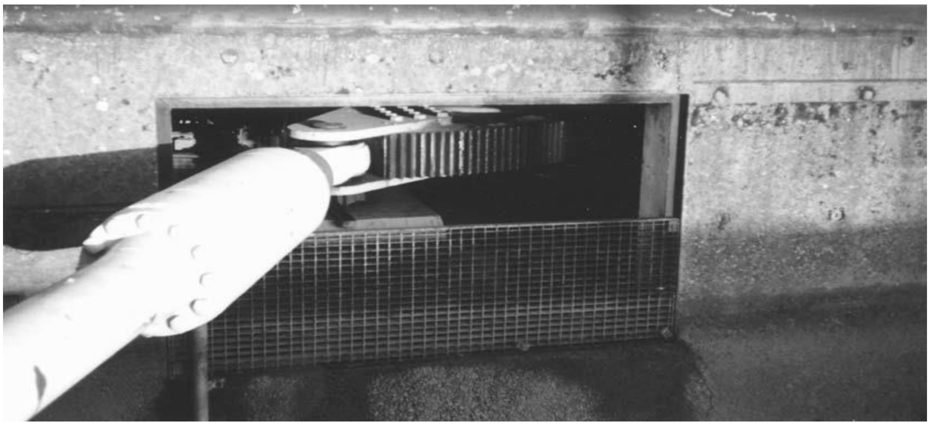


Figure 82: Panama Wheel (Vrijburcht, 2000)

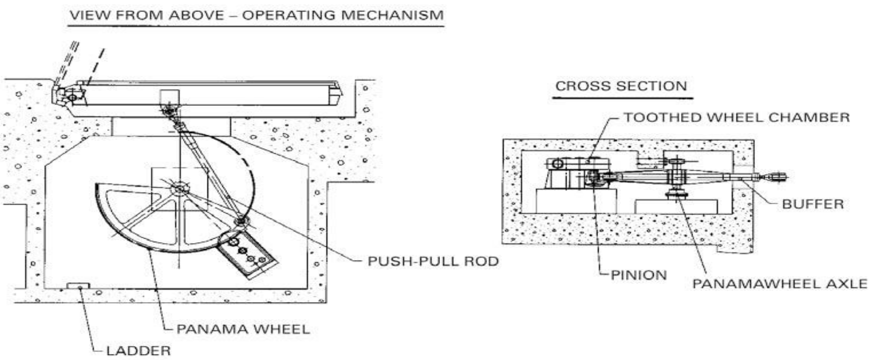


Figure 83: Top and side view Panama Wheel (Vrijburcht, 2000)

The main advantages and disadvantages of a Panama wheel are:

Advantages	Disadvantages
Requires little maintenance	Construction is expensive due to gear wheels, wide chamber and complicated assembly
Insensitive to measurement deviations in gates, therefore also to the exchange of gates	Must be placed above water
Can lock the gate resulting in a (limited) negative retaining structure.	Chamber requires large space in lock head

Table 47: Advantages and disadvantages Panama Wheel

The Panama wheel was mainly applied in the past in medium to large locks and is rarely used in the present. In small locks the width of the chambers would become too large with respect to the lock width, which is why small locks barely contain a Panama wheel.

Rack bar

A rack bar system consists of a horizontally placed rack bar that is directly driven by a pinion and simultaneously acts as a push-pull rod. This operating mechanism is usually placed in a basement chamber next to the gate chamber, where the rack bar sticks out of an opening in the wall.

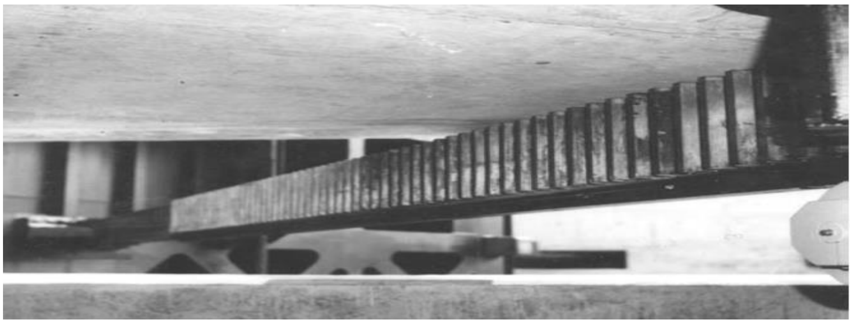


Figure 84: Rack Bar (Vrijburcht, 2000)

The main advantages and disadvantages of a rack bar are:

Advantages	Disadvantages
Simple construction and easy to install	Requires frequent inspections due to high sensitivity to deviations in the horizontal field
Cheaper than a Panama wheel	Must be placed above water
Easy to adapt the system to an operating mechanism that enables negative retention	High susceptibility to ship collisions

Table 48: Advantages and disadvantages Rack Bar

The rack bar is mostly applied in small to medium sized locks. This system is sometimes also found in large locks, although because of the high susceptibility to ship collisions it requires additional protections for the latter.

Appendix C: Unity checks and profile determination

In this appendix the finite element software is checked with the hand calculations.
All the unity checks consider the checks required for the beams as shown in the figure below:

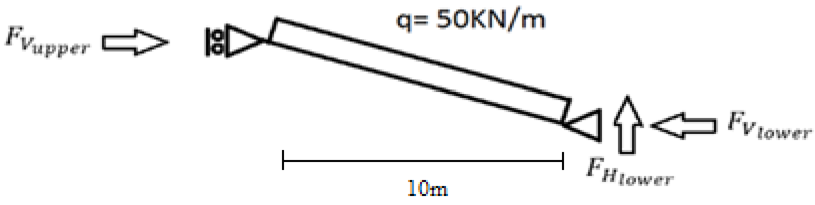


Figure 85: Beam

Forces on beam:

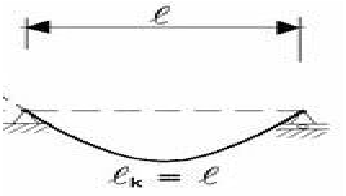
Internal forces	Calculated	Unit
N	-870.03	KN
My	681.25	KNm

Cross-sectional characteristics:

$$A = (W * H) - \left((W-2t)(H-2t)\right) = (570 * 200) - (530 * 160) = 0.0292\ m^2$$

$$I_{yy} = \frac{1}{12} * 200 * 570^3 - \frac{1}{12} * 160 * 530^3 = 0.0011015\ m^4$$

$$W_y = \frac{I_{yy}}{\frac{1}{2} * w} = W_y = \frac{0.00109363}{\frac{1}{2} * 0,57} 0.0038373\ m^3$$



Structural characteristics	Value	Unit
f_y	235000	KN/m^2
E	210000000	KN/m^2
L	10.44000	m
A_{rea}	0.029200	m^2
I_{yy}	0.001094	m^4
$W_{el,min}$	0.003837	m^3
L_k	10.44000	m

Cross-sectional checks

Normal force check:

- $\frac{N}{N_{c,Rd}} \leq 1$
  - $N_{c,Rd} = \frac{A * f_y}{\gamma_{M0}} = \frac{0.0292 * 235000}{1} = 6862KN$
- $\boldsymbol{\frac{N}{N_{c,Rd}} = \frac{870.03}{6862} = 0.1268 \leq 1}$

SCIA Engineer check

Drukcontrole
Volgens EN 1993-1-1 artikel 6.2.4 en formule (6.9)

A	2,9200e-02	m²
Nc,Rd	6862,00	kN
Eenheidscontrole	0,13	-

Bending moment check:

- $\frac{M}{M_{c,Rd}} \leq 1$
  - $M_{c,Rd} = \frac{W_{el,min} * f_y}{\gamma_{M0}} = \frac{0.0038373 * 235000}{1} = 901.8KNm$
- $\frac{\boldsymbol{M}}{\boldsymbol{M_{c,Rd}}} = \frac{\mathbf{681.25}}{\mathbf{901.8}} = \mathbf{0.7555 \leq 1}$

SCIA Engineer check

Controle buigend moment voor My
Volgens EN 1993-1-1 artikel 6.2.5 en formule (6.12),(6.14)

Wel,y,min	3,8650e-03	m³
Mel,y,Rd	908,27	kNm
Eenheidscontrole	0,75	-

Combined normal force and bending moment check:

- $\frac{\boldsymbol{N}}{\boldsymbol{N_{c,Rd}}} + \frac{\boldsymbol{M}}{\boldsymbol{M_{c,Rd}}} = \mathbf{0.1268 + 0.7555 = 0.8823}$
-

SCIA Engineer check:

Controle voor gecombineerde buiging, axiale kracht en Dwarskracht
Volgens EN 1993-1-1 artikel 6.2.1(5) en formule (6.1)

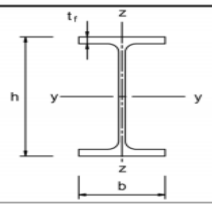
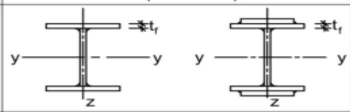
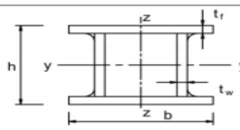
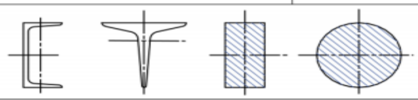
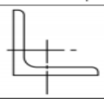
Elastische toetsing		
Vezel	5	
Sigma,N,Ed	29,8	MPa
Sigma,My,Ed	176,3	MPa
Sigma,Mz,Ed	0,0	MPa
Sigma,tot,Ed	206,1	MPa
Tau,Vy,Ed	0,0	MPa
Tau,Vz,Ed	0,0	MPa
Tau,t,Ed	0,0	MPa
Tau,tot,Ed	0,0	MPa
Sigma,von Mises,Ed	206,1	MPa
Eenheidscontrole	0,88	-

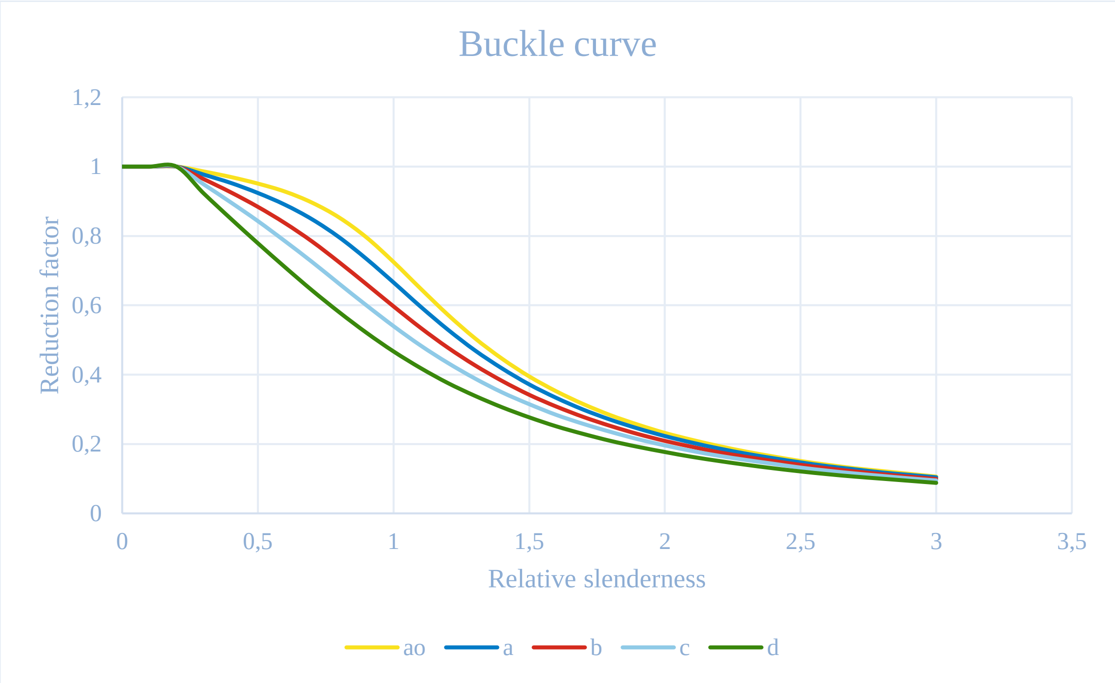
Stability checks

Buckle check (knik):

- $\frac{N}{N_{b,Rd}} \leq 1$
  - $N_{b,Rd} = \frac{\chi * A * f_y}{\gamma_{M1}}$
    - $\chi = \frac{1}{\Phi + \sqrt{\Phi^2 - \overline{\lambda}^2}}$
      - $\overline{\lambda} = \sqrt{\frac{A * f_y}{N_{cr}}}$
        - $N_{cr} = \pi^2 * \frac{EI}{{L_k}^2} = \pi^2 * \frac{210000000 * 0.001094}{10.44000^2} = 20793KN$
      - $\overline{\lambda} = \sqrt{\frac{0.0292 * 235000}{20793}} = 0.57$
      - $\Phi = 0.5\left(1 + \alpha(\overline{\lambda} - 0.2) + \overline{\lambda}^2\right)$
        - α is dependent on the buckle curve

The buckle curve depends on the shape of the cross-sectional profile:

Cross section		Limits		Buckling about axis	Buckling curve S 235 S 275 S 355 S 420	Buckling curve S 460
Rolled sections		h/b > 1,2	$t_f \leq 40$ mm	y – y z – z	a b	a_0 a_0
			40 mm < $t_f \leq 100$	y – y z – z	b c	a a
		h/b ≤ 1,2	$t_f \leq 100$ mm	y – y z – z	b c	a a
			$t_f > 100$ mm	y – y z – z	d d	c c
Welded I-sections			$t_f \leq 40$ mm	y – y z – z	b c	b c
			$t_f > 40$ mm	y – y z – z	c d	c d
Hollow sections			hot finished	any	a	a_0
			cold formed	any	c	c
Welded box sections			generally (except as below)	any	b	b
			thick welds: $a > 0,5t_f$ $b/t_f < 30$ $h/t_w < 30$	any	c	c
U-, T- and solid sections				any	c	c
L-sections				any	b	b



The profile for this experiment classifies as a hollow section. Since the fabrication method is unknown the conservative curve is chosen, namely curve c to which a certain imperfection factor applies:

$Buckling\ curve$	a_0	a	b	c	d
$Imperfection\ factor\ \alpha$	0.13	0.21	0.34	0.49	0.76

- $\Phi = 0.5(1 + 0.49(0.5745 - 0.2) + 0.5745^2) = 0.76$

  - $\chi = \frac{1}{0.76+\sqrt{0.76^2-0.57^2}} = 0.8$

    - $N_{b,Rd} = \frac{\chi * A * f_y}{\gamma_{M1}} = \frac{0.8*0.0292*235000}{1} = 5490KN$

- $\boldsymbol{\frac{N}{N_{b,Rd}} = \frac{870.03}{5490} = 0.158 \leq 1}$

SCIA Engineer check:

Buigingsknikcontrole
Volgens EN 1993-1-1 artikel 6.3.1.1 en formule (6.46)

Knikparameters	**yy**	**zz**	
Zijd. flex. type	Zijdelings stijf	Zijdelings flexibel	
Systeemlengte L	10,440	2,610	m
Knikfactor k	1,00	1,00	
Kniklengte Lcr	10,440	2,617	m
Kritische Euler last Ncr	20946,33	60274,19	kN
Slankheid Lambda	53,75	31,69	
Relatieve slankheid Lambda,rel	0,57	0,34	
Limietslankheid Lambda,rel,0	0,20	0,20	
Knikcurve	c	c	
Imperfectie Alfa	0,49	0,49	
Reductie factor Chi	0,80	0,93	
Knikweerstand Nb,Rd	5500,87	6381,45	kN

Buigingsknikverificatie		
Oppervlakte van de doorsnede A	2,9200e-02	m²
Knikweerstand Nb,Rd	5500,87	kN
Eenheidscontrole	0,16	-

Buckle check (kip):

The way the beam is modelled in this experiment it is susceptible to buckling due to the bending moments. In reality however, the beam is supported by vertical girders connecting all the beams with each other, preventing this type of failure mechanism. The same hold for buckling caused by the normal force in the z-direction. For this the beam is assumed to be uniformly distributed along its length.

Combined bending and axial stress check:

- $\frac{N}{\chi_y N_{c,Rd}} + k_{yy}\frac{M_y}{\chi_{LT} M_{c,Rd}}$
- $\frac{N}{\chi_z N_{c,Rd}} + k_{zy}\frac{M_y}{\chi_{LT} M_{c,Rd}}$

    - $k_{yy} = C_{my} C_{mLT} \frac{\mu_y}{1-\frac{N}{N_{cr}}}$
    - $k_{zy} = C_{my} C_{mLT} \frac{\mu_{zy}}{1-\frac{N}{N_{cr}}}$

        - $\mu_y = \frac{1-\frac{N}{N_{cr,y}}}{1-\chi_y \frac{N}{N_{cr,y}}} = \frac{1-\frac{870.03}{20793}}{1-0.8*\frac{870.03}{20793}} = 1$
        - $\mu_z = \frac{1-\frac{N}{N_{cr,z}}}{1-\chi_y \frac{N}{N_{cr,z}}} = \frac{1-\frac{870.03}{20793}}{1-0.8*\frac{870.03}{20793}} = 1$
        - If $\overline{\lambda_0} \leq 0.2\sqrt{C_1}\sqrt[4]{\left(1-\frac{N}{N_{cr,z}}\right)\left(1-\frac{N}{N_{cr,TF}}\right)}$

$$C_{my} = C_{my0}$$

$$C_{mz} = C_{mz0}$$

$$C_{LT} = 1,0$$

- If $\overline{\lambda_0} > 0.2\sqrt{C_1}\sqrt[4]{\left(1-\frac{N}{N_{cr,z}}\right)\left(1-\frac{N}{N_{cr,TF}}\right)}$

$$C_{my} = C_{my0} + (1 - C_{my,0})\frac{\sqrt{\varepsilon_y}a_{LT}}{1+\sqrt{\varepsilon_y}a_{LT}}$$

$$C_{mz} = C_{mz0}$$

$$C_{LT} = C_{my}^2 \frac{a_{LT}}{\sqrt{\left(1-\frac{N}{N_{cr,z}}\right)\left(1-\frac{N}{N_{cr,T}}\right)}} \geq 1$$

- $C_1 = k_c^{-2} = 0.94^{-2} = 1.1317$
- $C_{mi,0} = 1 + 0.03\frac{N}{N_{cr,i}} = 1 + 0.03\frac{870.03}{6862} = 1.004$
- $\varepsilon_y = \frac{M_y}{N}\frac{A}{W_{el,y}} = \frac{681}{870}\frac{0.0292}{0.003837} = 5,957$
- $a_{LT} = 1 - \frac{I_T}{I_y}$
  - $I_t = \frac{4A_p^2 t}{p}$
    - $p = 2[(W-t)+(H-t)] - 3t(4-\pi)$
    - $p = 2[(570-20)+(200-20)] - 3*20(4-\pi) = 1.4$
    - $A_p = (W-t)(H-t) - (1.5t)^2(4-\pi)$
    - $A_p = (570-20)(200-20) - (1.5*20)^2(4-\pi) = 0.0982$
  - $I_t = \frac{4*0.0982^2*0.02}{1.4} = 0.000548mm^4$

- $a_{LT} = 1 - \frac{0.000548}{0.0011015} = 0.5025$
- $0.2\sqrt{C_1}\sqrt[4]{\left(1-\frac{N}{N_{cr,z}}\right)\left(1-\frac{N}{N_{cr,TF}}\right)}$
- $0.2\sqrt{1.132}\sqrt[4]{\left(1-\frac{870}{20793}\right)\left(1-\frac{870}{960944}\right)} = 0.21$
- $\overline{\lambda_0} = \frac{L_c}{i_{f,z}\lambda_1}$
  - The beam is modelled as being supported by vertical girders preventing buckling due to moments. The vertical girders are positioned once every 1/10th of the beams length.
  - $L_c = \frac{10}{10} = 1$
  - $i_{f,z} = \sqrt{\frac{l_{eff,f}}{A_{eff,f}+\frac{1}{3}A_{eff,w,c}}} = \sqrt{\frac{0.0001991}{0.004+\frac{1}{3}*0.0114}} = 0.16$
  - $\lambda_1 = \pi\sqrt{\frac{E}{f_y}} = \pi\sqrt{\frac{210000000}{235000}} = 93.9$
- $\overline{\lambda_0} = \frac{1}{0.16*93.9} = 0.067 \leq 0.21$

- $C_{my} = 1.004$
- $C_{mz} = 1.004$
- $C_{LT} = 1{,}0$

  - $k_{yy} = C_{my}C_{mLT}\frac{\mu_y}{1-\frac{N}{N_{cr}}} = 1.004 * 1 * \frac{1}{1-\frac{870}{20793}} = 1.048$
  - $k_{zy} = C_{my}C_{mLT}\frac{\mu_{zy}}{1-\frac{N}{N_{cr}}} = 1.004 * 1 * \frac{1}{1-\frac{870}{20793}} = 1.048$

- $\frac{N}{\chi_y N_{c,Rd}} + k_{yy}\frac{M_y}{\chi_{LT}M_{c,Rd}} = \frac{870}{0.8*6862} + 1.048\frac{681}{1*908.27} = 0.94$
- $\frac{N}{\chi_z N_{c,Rd}} + k_{zy}\frac{M_y}{\chi_{LT}M_{c,Rd}} = \frac{870}{0.8*6862} + 1.048\frac{681}{1*908.27} = 0.94$

SCIA Engineer check:

Gecombineerde buig- en axiale drukcontrole
Volgens EN 1993-1-1 artikel 6.3.3 en formule (6.61),(6.62)

Buig- en axiale drukcontrole paramaters		
Interactie methode	alternatieve methode 1	
Oppervlakte van de doorsnede A	2,9200e-02	m^2
Elastische modulus van de doorsnede Wel,y	3,8650e-03	m^3
Ontwerpdrukkracht N,Ed	870,03	kN
Ontwerp buigend moment (maximum) My,Ed	681,25	kNm

Buig- en axiale drukcontrole paramaters		
Ontwerp buigend moment (maximum) Mz,Ed	0,00	kNm
Karakteristieke drukweerstand N,Rk	6862,00	kN
Karakteristieke momentweerstand My,Rk	908,27	kNm
Reductie factor Chi,y	0,80	
Reductie factor Chi,z	0,80	
Reductie factor Chi,LT	1,00	
Interactiefactor k,yy	1,04	
Interactiefactor k,zy	1,04	

Maximum moment My,Ed is afgeleid van balk S39 positie 5,220 m.
Maximum moment Mz,Ed is afgeleid van balk S39 positie 5,220 m.

Interactie methode 1 parameters		
Kritische Euler last N,cr,y	20946,33	kN
Kritische Euler last N,cr,z	60274,19	kN
Elastische kritische last N,cr,T	960944,44	kN
Elastische modulus van de doorsnede Wel,y	3,8650e-03	m^3
Traagheidsmoment Iy	1,1015e-03	m^4
Traagheidsmoment Iz	1,9909e-04	m^4
Torsie constante It	5,2953e-04	m^4
Methode voor equivalente moment factor C,my,0	Tabel A.2 Lijn 4 (Lijnlast)	
Equivalente moment factor C,my,0	1,00	
Factor mu,y	0,99	
Factor mu,z	1,00	
Factor epsilon,y	5,92	
Factor a,LT	0,52	
Kritisch moment voor uniforme buiging Mcr,0	3742215,18	kNm
Relatieve slankheid Lambda,rel,0	0,02	
Limiet relatieve slankheid Lambda,rel,0,lim	0,20	
Equivalente moment factor C,my	1,00	
Equivalente moment factor C,mLT	1,00	

Eenheidscontrole (6.61) = 0,16 + 0,78 + 0,00 = 0,94 -
Eenheidscontrole (6.62) = 0,16 + 0,78 + 0,00 = 0,94 -

To calculate the required eccentricity, half the maximum bending moment should be divided by the vertical support reaction force. For the upper support this would lead to an eccentricity of:

$$\frac{\frac{1}{2} * 681{,}25}{908{,}33} = 0{,}375m$$

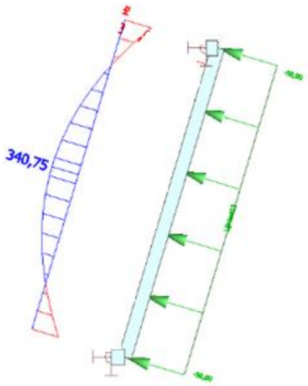
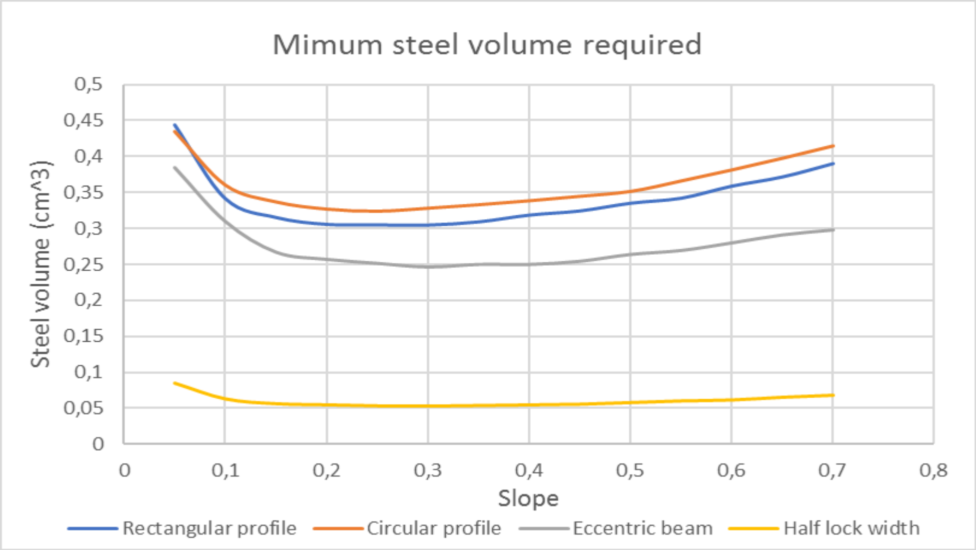


Figure 86: Reduced bending moments

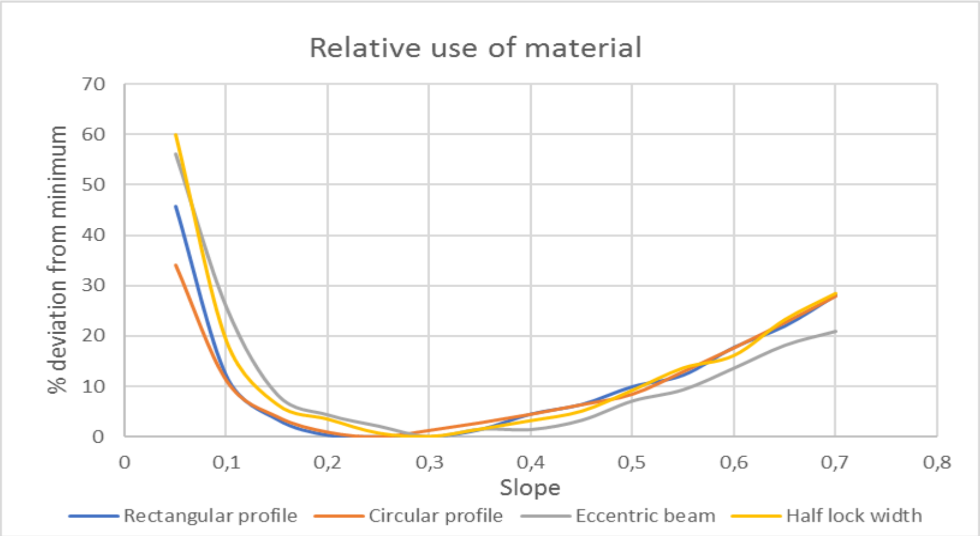
The figure on the right shows the effect of applying this eccentricity. It can be observed that the maximum occurring bending moment is now reduced from 681.3KNm to 340.8KNm.

Having performed the same investigation for the various varying conditions as initially done for the rectangular beam results in the following relation between amount of steel required in the beams versus the slope of the beam.



Graph 24

By dividing the values of the graphs by their minimum value the relative use of material with respect to the optimum angle (minimum volume) is determined.



Graph 25

This graph displays that the optimum slope for the beams in the various conditions are all rather similar. Taking the average it is found the optimum slope is found to be 3:10. This slope is referred to in the rest of this report as the optimal slope.

Appendix D: Relation between $\Delta h_2/\Delta h_1$ and q_2/q_1

In this research it is assumed that $\Delta h_2/\Delta h_1$ and q_2/q_1 are equal to each other (see Section 5.3). In reality this is not completely the case. Considering a lock gate with a inner water depth of 4m and a head difference of 2m we obtain an asymmetric loading factor of $\frac{\Delta h_2}{\Delta h_1} = \frac{2-1}{2+0.5} = 0.4$. To see what the relation between q_2 and q_1 would be, the doors could be schematized as follows:

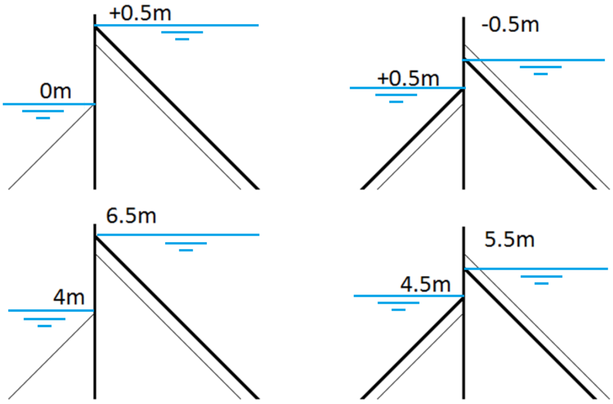


Figure 87: Development of hydrostatic water pressures on lock gate

The upper figures show the change in the water head and the resulting hydrostatic loads on the doors. The bottom figure illustrates the net situation for the doors. Calculating the net force per meter door length of the left situation:

$$\frac{1}{2}\rho g h_r^2 - \frac{1}{2}\rho g h_l^2 = 211.25 - 80 = 131.25\ kN/m$$

For the situation on the right:

$$\frac{1}{2}\rho g h_r^2 - \frac{1}{2}\rho g h_l^2 = 151.25 - 101.25 = 50.00\ kN/m$$

Having calculated the distributed loads we can now determine the asymmetric loading factor:

$$\frac{q_2}{q_1} = \frac{50}{131.25} = 0.38$$

As we can observe that this slightly differs from the value for $\frac{\Delta h_2}{\Delta h_1}$, the reason is that $\frac{\Delta h_2}{\Delta h_1}$ considers the resultant between the hydrostatic loads on the different doors to be uniform, whereas the $\frac{q_2}{q_1}$ relation takes into account the fact that the loads take depth to develop:

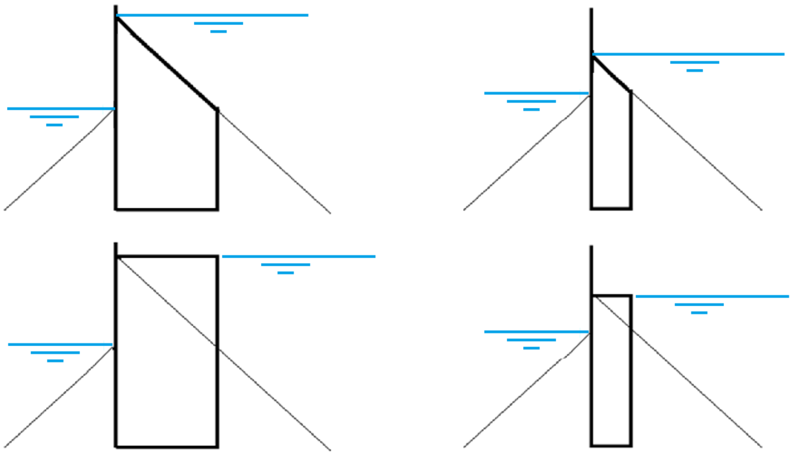


Figure 88: Resulting hydrostatic loads; Top left: schematization of q_1, top right: schematization of q_2, bottom left: schematization h_1, bottom right: schematization h_2.

Appendix E: Profile effects

As mentioned in Section 6.2, the over-dimensioning of the beam is caused by longitudinal and cross-sectional over-dimensioning.
When applying a large beam to a small lock width, the over-dimensioning caused by extra length is inevitable. Since the optimum door slope stays constant for different lock widths, the lock width is directly proportion to the optimum door length.

The optimum cross-sectional area of the beam will vary with varying lock widths. Concerning the required cross-sectional area of the beam it is important to note that:

- Normal force and bending moments $\propto$ $lock\ width^2$
- Profile bending and buckling resistance $\propto$ I_{zz}
- $I_{zz} = \int z^2 dA$

The relation between the moment of inertia I_{zz} and the area of the profile strongly depends on the shape of the profile and what dimensions of the profile are varied. Considering the following three cross-sections the relation between the cross-sectional areas and moment of inertia can be determined:

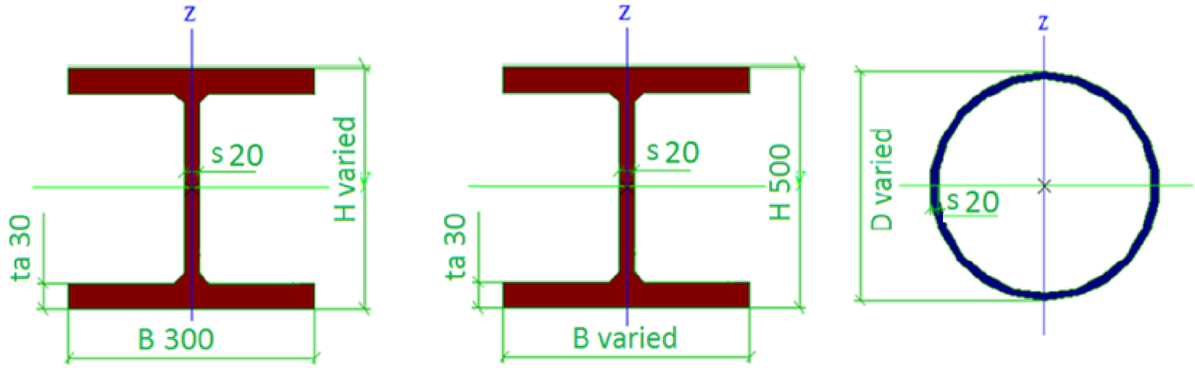


Figure 89: Profile iteration

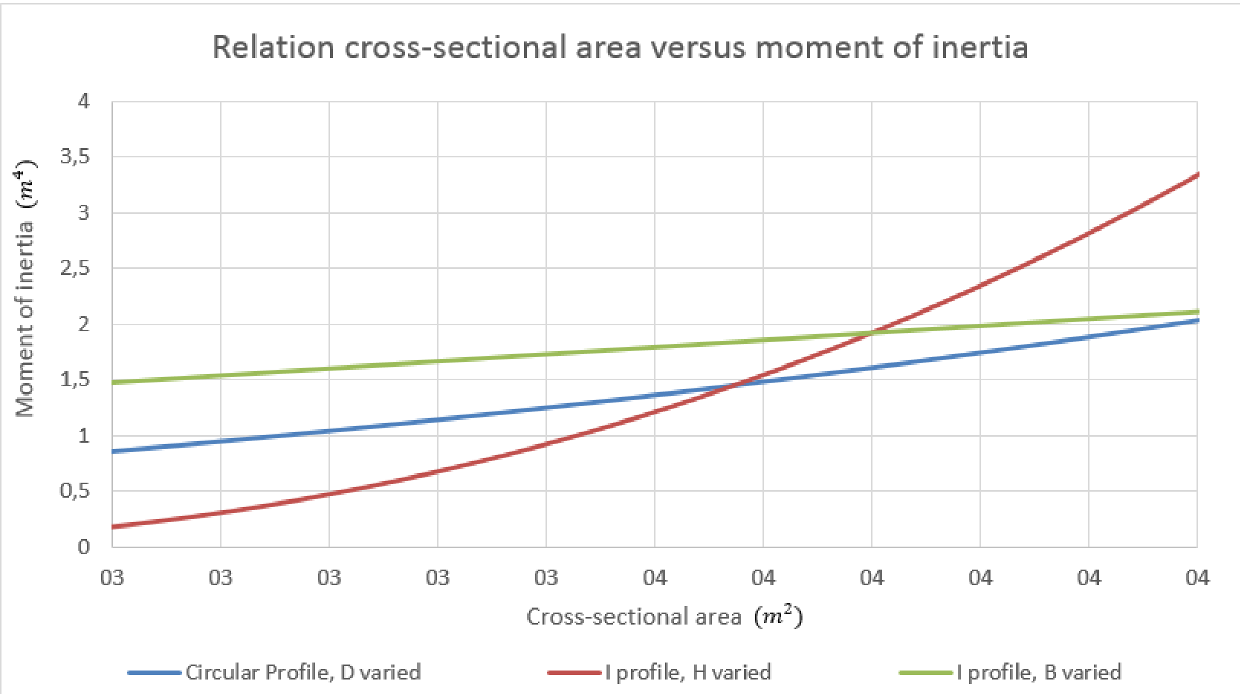


Figure 90: Relation between moment of inertial and cross-sectional area

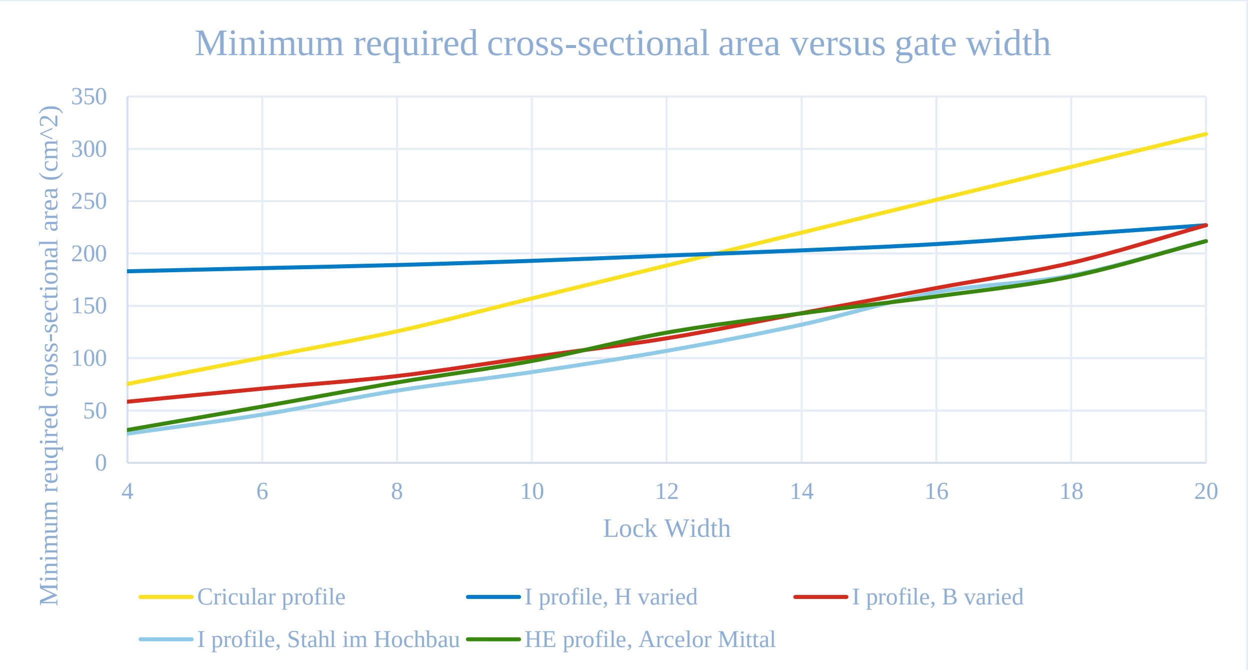
From the graph above we can conclude that the relation between the cross-sectional area and the moment of inertia of the beam more or less can be presented by the following proportionality:

- $I_{zz} \propto A^x$

Where the value of x depends on what characteristics of the profile are varied. Theoretically speaking, the potential values of x range between 1 and ∞. For the I profile where only the width is varied, it can be observed that the relation between the area and moment of inertia is represented by a linear line, so x in this case is equal to 1. For the circular profile the area and the moment of inertia holds the following relation:

- $I_{zz} = 126{,}8A^3$ thus $I_{zz} \propto A^3$

For an imaginary I profile with $s = 0mm$ with H being increased, the cross-sectional area would not increase with increasing H, while the moment of inertia would. For this hypothetical case, the x value would therefore be infinite in the proportionality relation between the moment of inertia and the cross-sectional area of the profile.



The graph above illustrates the required cross-sectional area of the profiles applied in the cases with varying lock widths. From this graph can be concluded that the standardized I and HE profiles provide the optimum amount of material needed for the various lock widths with respect to the profiles evaluated. Due to this optimization, it is chosen to estimate the over-dimensioning with the help of the over-dimensioning curves these profiles give.

Appendix F: Determination of over-dimensioning

Lock width	m	12.00	14.00	16.00	18.00	20.00
Beam length	m	6.26	7.31	8.35	9.40	10.44
25 KN/m						
Optimum profile	HEB	220	240	260	300	320
Cross-sectional area	cm^2	91	106	118	149	161
Unity check	-	0.84	0.90	0.98	0.84	0.91
Non-conforming profile	HEB	200	220	240	280	300
Cross-sectional area	cm^2	78	91	106	131	149
Unity check	-	1.10	1.18	1.21	1.04	1.06
Normalized cross-sectional area	cm^2	83	101	117	135	154
Over-dimensioning	%	85	53	31	14	0
Total normalized steel volume	m^3	0.052	0.074	0.098	0.127	0.161
Total over-dimensioning	%	209	118	64	27	0
50 KN/m						
Optimum profile	HEB	280	320	360	450	500
Cross-sectional area	cm^2	131	161	181	218	239
Unity check	-	0.93	0.9	0.95	0.82	0.85
Non-conforming profile	HEB	260	300	340	400	450
Cross-sectional area	cm^2	118	149	171	198	218
Unity check	-	1.12	1.04	1.06	1.01	1.03
Normalized cross-sectional area	cm^2	127	153	176	199	221
Over-dimensioning	%	75	45	26	11	0
Total normalized steel volume	m^3	0.079	0.112	0.147	0.187	0.231
Total over-dimensioning	%	191	107	57	24	0
75 KN/m						
Optimum profile	HEB	340	400	450	550	650
Cross-sectional area	cm^2	171	198	218	254	286
Unity check	-	0.91	0.92	1	0.92	0.90
Non-conforming profile	HEB	320	360	400	500	600
Cross-sectional area	cm^2	161	181	198	239	270
Unity check	-	1.01	1.12	1.11	1.06	1.02
Normalized cross-sectional area	cm^2	162	191	218	245	273
Over-dimensioning	%	68	43	25	11	0
Total normalized steel volume	m^3	0.102	0.140	0.182	0.230	0.285
Total over-dimensioning	%	180	104	56	24	0

Distributed load	kN/m	60	70	80	90	100
Amount of beams	-	3	3.5	4	4.5	5
18 m wide lock						
Optimum profile	HEB	500	500	550	600	650
Cross-sectional area	cm^2	239	239	254	270	286
Unity check	-	0.83	0.98	0.99	0.99	0.99
Non-conforming profile	HEB	450	450	500	550	600
Cross-sectional area	cm^2	218	218	239	254	270
Unity check	-	1	1.19	1.14	1.13	1.12
Normalized cross-sectional area	cm^2	218	237	253	269	286
Over-dimensioning	%	31	20	13	6	0
Total normalized steel volume	m^3	0.65	0.83	1.012	1.210	1.425
Total over-dimensioning	%	118	72	40	18	0
14 m wide lock						
Optimum profile	HEB	340	400	400	450	500
Cross-sectional area	cm^2	171	198	198	218	239
Unity check	-	0.98	0.86	0.99	0.92	0.87
Non-conforming profile	HEB	320	360	360	400	450
Cross-sectional area	cm^2	161	181	181	198	218
Unity check	-	1.10	1.04	1.20	1.12	1.03
Normalized cross-sectional area	cm^2	169	184	197	210	222
Over-dimensioning	%	31	20	13	6	0
Total normalized steel volume	m^3	0.51	0.65	0.79	0.95	1.10
Total over-dimensioning	%	118	72	41	17	0
10 m wide lock						
Optimum profile	HEB	260	280	300	300	320
Cross-sectional area	cm^2	118	131	149	149	161
Unity check	-	0.93	0.92	0.85	0.98	0.94
Non-conforming profile	HEB	240	260	280	280	300
Cross-sectional area	cm^2	106	118	131	131	149
Unity check	-	1.14	1.10	1.06	1.20	1.09
Normalized cross-sectional area	cm^2	114	126	136	147	156
Over-dimensioning	%	37	25	15	6	0
Total normalized steel volume	m^3	0.34	0.44	0.55	0.66	0.78
Total over-dimensioning	%	128	78	43	18	0

Appendix G: Determination of amount of steel

This appendix demonstrates how the amount of steel required in the MMW locks gates is approximated.

Steel area per specific HEB profile:

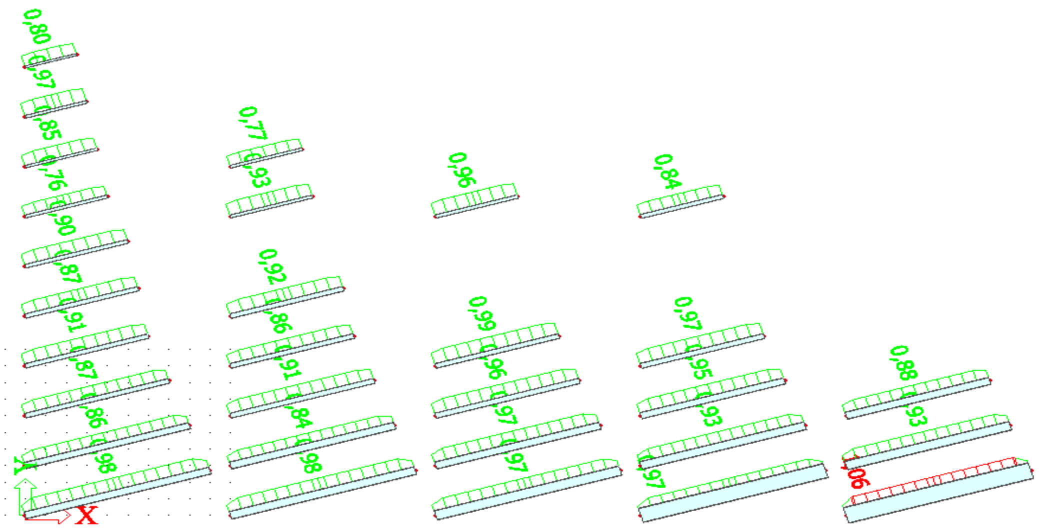
HEB	100	120	140	160	180	200	220	240
Area *10^-3	2,6	3,4	4,3	5,4	6,5	7,8	9,1	10,6
HEB	260	280	300	320	340	360	360	400
Area *10^-3	11,8	13,1	14,9	16,1	17,1	18,1	18,1	19,8
HEB	450	500	550	600	650	700	800	900
Area *10^-3	21,8	23,9	25,4	27,0	28,6	30,6	33,4	37,1
HEB	1000							
Area *10^-3	40,0							

Doors designed such that lock can be set dry:

Minimum required HEB profile in order to conform to Euro codes:

REQUIRED HEB PROFILE		Door height									
		4	5	6	7	8	9	10	11	12	13
Lock width (m)	5		140								
	6					180					
	7	160	180								
	8		200	200		220			260		
	9										
	10			240							
	11				280		300				
	12			280	300	300	320				
	13										
	14		300	320	340		400	450			
	15										
	16			400	450	450	500	550			
	17										
	18			450	500	600			900		1000

Unity checks of optimized beams:



UC	Door height									
Lock width (m)	4	5	6	7	8	9	10	11	12	13
5		0,8								
6					0,97					
7	0,85	0,77								
8		0,76	0,93		0,96			0,84		
9										
10			0,9							
11				0,87		0,92				
12			0,91	0,86	0,99	0,97				
13										
14		0,87	0,91	0,96		0,95	0,88			
15										
16			0,86	0,84	0,97	0,93	0,93			
17										
18			0,98	0,98	0,97			0,97		1

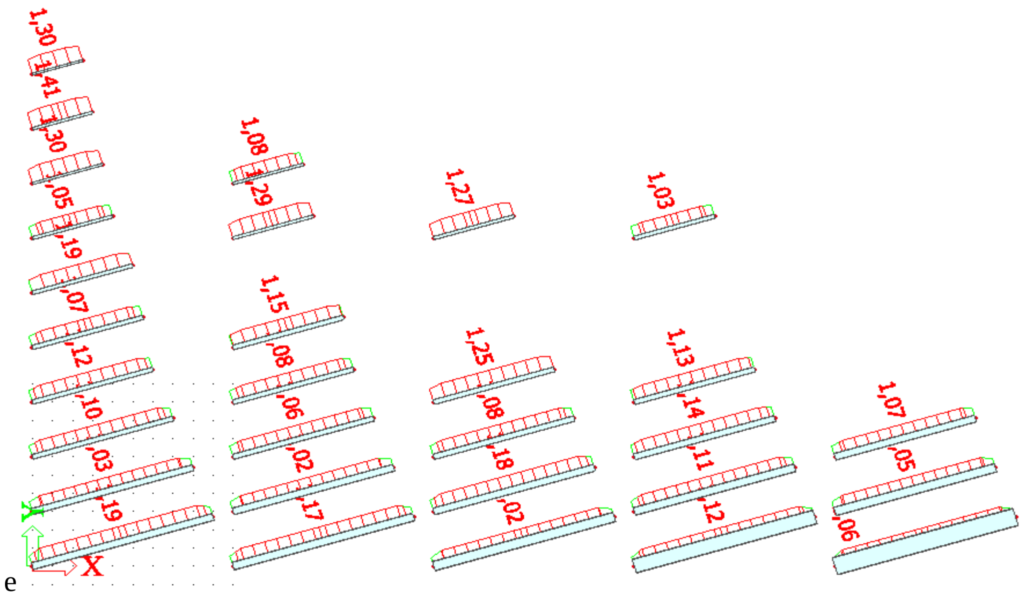
Corresponding cross sectional area in required profiles:

Cross sectional area of profile 10^-3m	Door height									
Lock width (m)	4	5	6	7	8	9	10	11	12	13
5		4,30								
6					6,53					
7	5,43	6,53								
8		7,81	7,81		9,10			11,84		
9										
10			10,60							
11				13,14		14,91				
12			13,14	14,91	14,91	16,13				
13										
14		14,91	16,13	17,09		19,78	21,80			
15										
16			19,78	21,80	21,80	23,86	25,41			
17										
18			21,80	23,86	27,00			37,13		40,00

Minimum required HEB profile in order to fail to Euro codes:

REQUIRED HEB PROFILE	Door height									
Lock width (m)	4	5	6	7	8	9	10	11	12	13
5		120								
6					160					
7	140	160								
8		180	180		200			240		
9										
10			220							
11				260		280				
12			260	280	280	300				
13										
14		280	300	320		360	400			
15										
16			360	400	400	450	500			
17										
18			400	450	550			800		900

Unity checks of optimized beams:



UC		Door height									
		4	5	6	7	8	9	10	11	12	13
Lock width (m)	5		1,3								
	6					1,4					
	7	1,3	1,1								
	8		1,1	1,3		1,3			1		
	9										
	10			1,19							
	11				1,07		1,15				
	12			1,12	1,08	1,25	1,13				
	13										
	14		1,10	1,06	1,08		1,14	1,07			
	15										
	16			1,03	1,02	1,19	1,11	1,05			
	17										
	18			1,19	1,17	1,02			1,12		1,00

Corresponding cross sectional area in required profiles:

Cross sectional area of profile 10^-3m		Door height									
		4	5	6	7	8	9	10	11	12	13
Lock width (m)	5		3,40								
	6					5,43					
	7	4,30	5,43								
	8		6,53	6,53		7,81			10,60		
	9										
	10			9,10							
	11				11,84		13,14				
	12			11,84	13,14	13,14	14,91				
	13										
	14		13,14	14,91	16,13		18,06	19,78			
	15										
	16			18,06	19,78	19,78	21,80	23,86			
	17										
	18			19,78	21,80	25,41			33,42		37,13

Knowing the unity checks and cross sectional area of the profiles for when they just do or do not conform to the Eurocodes it is possible to linearly interpolate the cross sectional area. This interpolation figures out the cross sectional area such that the unity checks are set a 1.

Cross sectional area of profile 10^-3m	Door height									
Lock width (m)	4	5	6	7	8	9	10	11	12	13
5		3,94								
6					6,45					
7	5,05	5,76								
8		6,90	7,57		8,95			10,60		
9										
10			10,08							
11				12,30		14,29				
12			12,58	13,78	14,84	15,90				
13										
14		13,91	15,40	16,77		19,33	20,52			
15										
16			18,36	20,00	21,52	23,06	24,51			
17										
18			21,61	23,64	26,05			36,39		45,69

Determining the amount of beams $\left(\frac{door\ height}{2}\right)$:

AMOUNT OF BEAMS	Door height									
Lock width (m)	4	5	6	7	8	9	10	11	12	13
5		2,5								
6					4,0					
7	2,0	2,5								
8		2,5	3,0		4,0			5,5		
9										
10			3,0							
11				3,5		4,5				
12			3,0	3,5	4,0	4,5				
13										
14		2,5	3,0	3,5		4,5	5,0			
15										
16			3,0	3,5	4,0	4,5	5,0			
17										
18			3,0	3,5	4,0			5,5		6,5

Determining the total combined length of beams $\left(\sqrt{lock\ width^2 + (lock\ width * 0.3)^2}\right)$:

BEAMS LENGTH										
Lock width (m)	4	5	6	7	8	9	10	11	12	13
5		5,2								
6					6,3					
7	7,3	7,3								
8		8,4	8,4		8,4			8,4		
9										
10			10,4							
11				11,5		11,5				
12			12,5	12,5	12,5	12,5				
13										
14		14,6	14,6	14,6		14,6	14,6			
15										
16			16,7	16,7	16,7	16,7	16,7			
17										
18			18,8	18,8	18,8			18,8		18,8

The total use of steel for the beams in the locks $(Beam\ length * amount\ of\ beams * cross\ sectional\ area * volumetric\ weight\ of\ steel)$:

TOTAL BEAM TONS		4	5	6	7	8	9	10	11	12	13
Lock width (m)	5		0,40								
	6					1,27					
	7	0,58	0,83								
	8		1,13	1,49		2,35			3,82		
	9										
	10			2,48							
	11				3,88		5,80				
	12			3,71	4,74	5,84	7,04				
	13										
	14		3,99	5,30	6,73		9,98	11,77			
	15										
	16			7,22	9,18	11,29	13,61	16,07			
	17										
	18			9,56	12,21	15,37			29,52		43,81

(volumetric weight of steel is 7850kg/m3).

__Doors designed such that lock cannot be set dry:__

This exact same method can be applied for the situation where the lock does not have to be set dry, changing the requirement of the gate. In this case the cross sectional area of the profiles become:

Cross sectional area of profile 10^-3m		Retention height									
		1	2	3	4	5	6	7	8	9	10
Lock width (m)	5			2,99							
	6					4,98					
	7	2,60	3,36								
	8	3,21	4,03	5,09		6,77	7,55		8,92		
	9										
	10			6,74							
	11				8,97		11,31				
	12		6,88	8,61	10,12	11,40					
	13										
	14	5,87		10,52	12,25	13,90	15,39	16,79			
	15										
	16		10,16	12,50	14,64	16,58	18,38				
	17										
	18			14,66	17,19			23,65		31,01	

Amount of beams:

AMOUNT OF BEAMS	Retention height									
Lock width (m)	1	2	3	4	5	6	7	8	9	10
5			3,50							
6					5,50					
7	3,50	4,00								
8	3,50	4,00	4,50	5,00	5,50	6,00		7,00		
9										
10			4,50							
11				5,00		6,00				
12		5,00	5,50	6,00	6,50					
13										
14	4,50		4,50	5,00	5,50	6,00	6,50			
15										
16		5,00	5,50	6,00	6,50	7,00				
17										
18			4,50	5,00			7,50		8,50	

Total amount of tons of steel:

TOTAL BEAM TONS	Retention height									
Lock width (m)	1	2	3	4	5	6	7	8	9	10
5			0,43							
6					1,35					
7	0,52	0,77								
8	0,74	1,06	1,50		2,44	2,97		4,09		
9										
10			2,49							
11				4,04		6,12				
12		3,38	4,66	5,97	7,29					
13										
14	3,03		5,43	7,03	8,77	10,60	12,52			
15										
16		6,66	9,01	11,52	14,14	16,87				
17										
18			9,73	12,68			26,17		38,88	

Appendix H: Matlab code

This appendix goes into more detail about the calculations performed to determine the dimensioning of the gate modules. The boundary conditions of the vertical beam are presented below:

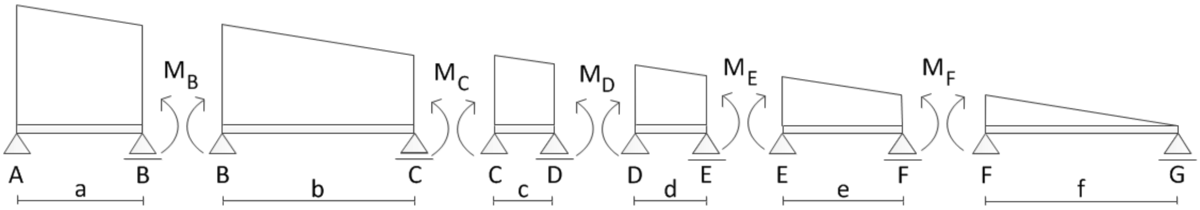


Figure 91: Splitting up the statically indeterminate beam into sections

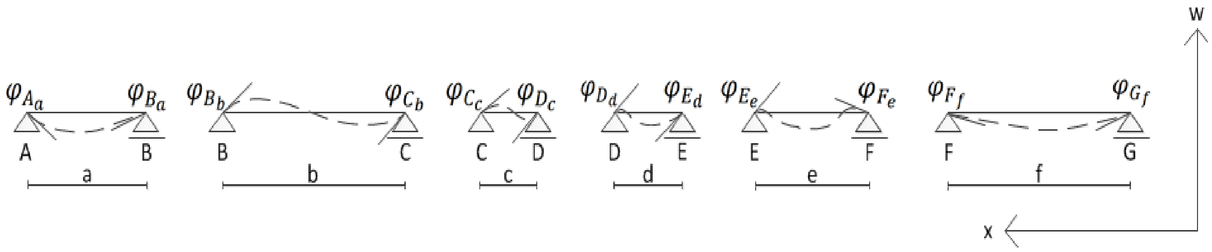


Figure 92: Angle rotations at the ends of the sections due to the loads and bending moments

$$\varphi_{Ba} = \varphi_{Bb} \qquad \varphi_{Cb} = \varphi_{Cc} \qquad \varphi_{Dc} = \varphi_{Dd} \qquad \varphi_{Ed} = \varphi_{Ee} \qquad \varphi_{Fe} = \varphi_{Ff}$$

Determining the equations for the rest of the rotations at the ends of the sections and taking into account the boundary conditions as presented above results in the following equations:

$$\varphi_{Ba} = -\frac{10(b+c+d+e+f)a^3}{24EI} - \frac{7a^4}{36EI} - \frac{M_B a}{3EI} \quad = \quad \varphi_{Bb} = \frac{10(c+d+e+f)b^3}{24EI} + \frac{2b^4}{9EI} + \frac{M_C b}{6EI} + \frac{M_B b}{3EI}$$

$$\varphi_{Cb} = -\frac{10(c+d+e+f)b^3}{24EI} - \frac{7b^4}{36EI} - \frac{M_C b}{3EI} - \frac{M_B b}{6EI} \quad = \quad \varphi_{Cc} = \frac{10(d+e+f)c^3}{24EI} + \frac{2c^4}{9EI} + \frac{M_D c}{6EI} + \frac{M_C c}{3EI}$$

$$\varphi_{Dc} = -\frac{10(d+e+f)c^3}{24EI} - \frac{7c^4}{36EI} - \frac{M_D c}{3EI} - \frac{M_C c}{6EI} \quad = \quad \varphi_{Dd} = \frac{10(e+f)d^3}{24EI} + \frac{2d^4}{9EI} + \frac{M_E d}{6EI} + \frac{M_D d}{3EI}$$

$$\varphi_{Ed} = -\frac{10(e+f)d^3}{24EI} - \frac{7d^4}{36EI} - \frac{M_E d}{3EI} - \frac{M_D d}{6EI} \quad = \quad \varphi_{Ee} = \frac{10fe^3}{24EI} + \frac{2e^4}{9EI} + \frac{M_F e}{6EI} + \frac{M_E e}{3EI}$$

$$\varphi_{Fe} = -\frac{10fe^3}{24EI} - \frac{7e^4}{36EI} - \frac{M_F e}{3EI} - \frac{M_E e}{6EI} \quad = \quad \varphi_{Ff} = \frac{2f^4}{9EI} + \frac{M_f f}{3EI}$$

The set of equations can be presented in a matrix notation of $AX = Y$ where A is the multiplication factor of the bending moments, X the bending moments and Y the sum of the terms not containing any moments:

$$\begin{bmatrix} \frac{a+b}{3} & \frac{b}{6} & 0 & 0 & 0 \\ \frac{b}{6} & \frac{b+c}{3} & \frac{c}{6} & 0 & 0 \\ 0 & \frac{c}{6} & \frac{c+d}{3} & \frac{d}{6} & 0 \\ 0 & 0 & \frac{d}{6} & \frac{d+e}{3} & \frac{e}{6} \\ 0 & 0 & 0 & \frac{e}{6} & \frac{e+f}{3} \end{bmatrix} * \begin{bmatrix} M_B \\ M_C \\ M_D \\ M_E \\ M_F \end{bmatrix} = \begin{bmatrix} -\frac{10(b+c+d+e+f)a^3}{24EI} - \frac{7a^4}{36EI} - \frac{10(c+d+e+f)b^3}{24EI} - \frac{2b^4}{9EI} \\ -\frac{10(c+d+e+f)b^3}{24EI} - \frac{7b^4}{36EI} - \frac{10(d+e+f)c^3}{24EI} - \frac{2c^4}{9EI} \\ -\frac{10(d+e+f)c^3}{24EI} - \frac{7c^4}{36EI} - \frac{10(e+f)d^3}{24EI} - \frac{2d^4}{9EI} \\ -\frac{10(e+f)d^3}{24EI} - \frac{7d^4}{36EI} - \frac{10fe^3}{24EI} - \frac{2e^4}{9EI} \\ -\frac{10fe^3}{24EI} - \frac{7e^4}{36EI} - \frac{2f^4}{9EI} \end{bmatrix}$$

The solution of the bending moments can be found by solving the function $X = A^{-1}Y$, this is however not yet possible since the centre to centre distances c, d, e and still have to be determined. As mentioned earlier these have to be determined such that the vertical support reactions in points D, E and F are equal to each other:

$$F_D = F_E = F_F.$$

The support reactions can be found by using the principles of moment and force equilibrium. Taking the bending moment around point F of section f:

$$F_G = \left(\frac{10}{6}f^3 + M_f\right)/f$$

Then considering section $e + f$, taking the bending moment around point E:

$$F_F = \left(\frac{10}{6}(e+f)^3 - F_G(e+f) + M_E\right)/f$$

Continuing this method leads to the following set of equations:

$$F_E = \left(\frac{10}{6}(d+e+f)^3 - F_G(d+e+f) - F_F(d+e) + M_D\right)/d$$

$$F_D = \left(\frac{10}{6}(c+d+e+f)^3 - F_G(c+d+e+f) - F_F(c+d+e) - F_E(c+d) + M_C\right)/c$$

$$F_C = \left(\frac{10}{6}(b+c+d+e+f)^3 - F_G(b+c+d+e+f) - F_F(b+c+d+e) - F_E(b+c+d) - F_D(b+c) + M_B\right)/b$$

$$F_B = \left(\frac{10}{6}(a+b+c+d+e+f)^3 - F_G(a+b+c+d+e+f) - F_F(a+b+c+d+e) - F_E(a+b+c+d) - F_D(a+b+c) - F_C(a+b)\right)/a$$

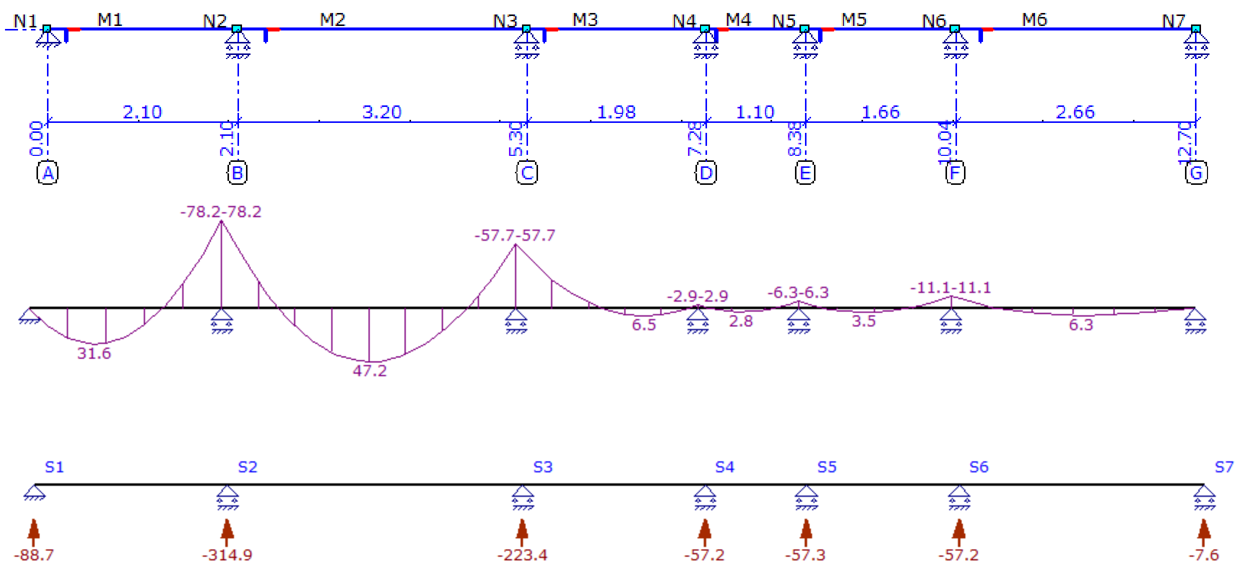
$$F_A = \frac{10}{2}(a+b+c+d+e+f)^2 - F_B - F_C - F_D - F_E - F_F - F_G$$

```
clear all
close all

%hth distances
for i=0:0.02:2.5
    a=2+i;
    for ii=0:0.02:3
        b=1+ii;
        for iii=0:0.02:2
            c=1+iii;
%             for iv=0:0.2:2;

                d=12.7-3.2-2.1-a-b-c;
 %               for v=0:0.2:2
                e=3.2;

                f=2.1;


                %solutions
                A2=(2*10*a^4)/90+(10*a*b^3)/24+(7*10*b^4)/360;
                C2=(10*a*b^3)/24+(2*10*b^4)/90+(10*(a+b)*c)*c^2/24+7*10*c^4/360;
                E2=((10*(a+b)*c)*c^2)/24+2*10*c^4/90+((10*(a+b+c)*d)*d^2)/24+7*10*d^4/360;;
                G2=(10*(a+b+c)*d)*d^2/24+2*10*d^4/90+(10*(a+b+c+d)*e)*e^2/24+7*10*e^4/360;
                I2=(10*(a+b+c+d)*e)*e^2/24+2*10*e^4/90+(10*(a+b+c+d+e)*f)*f^2/24+7*10*f^4/360;

                %Matric solver
```

```
                 X=[(a+b)/3 b/6 0 0 0;b/6 (b+c)/3 c/6 0 0; 0 c/6 (c+d)/3 d/6 0; 0 0 d/6 (d+e)/3
e/6; 0 0 0 e/6 (e+f)/3];
                 Y=[A2;C2;E2;G2;I2];

                 %Moments
                 M=inv(X)*Y;
                 Mb=M(1);
                 Mc=M(2);
                 Md=M(3);
                 Me=M(4);
                 Mf=M(5);

                 %Support reactions
                 Fa=(10*a^3/6-Mb)/a;
                 Fb=((a+b)^3*10/6-Fa*(a+b)-Mc)/b;
                 Fc=((a+b+c)^3*10/6-Fa*(a+b+c)-Fb*(b+c)-Md)/c;
                 Fd=((a+b+c+d)^3*10/6-Fa*(a+b+c+d)-Fb*(b+c+d)-Fc*(c+d)-Me)/d;
                 Fe=((a+b+c+d+e)^3*10/6-Fa*(a+b+c+d+e)-Fb*(b+c+d+e)-Fc*(c+d+e)-Fd*(d+e)-Mf)/e;
                 Ff=((a+b+c+d+e+f)^3*10/6-Fa*(a+b+c+d+e+f)-Fb*(b+c+d+e+f)-Fc*(c+d+e+f)-
Fd*(d+e+f)-Fe*(e+f))/f;
                 Fg=(a+b+c+d+e+f)^2*10/2-Fa-Fb-Fc-Fd-Fe-Ff;

                 F=[Fa Fb Fc Fd Fe Ff Fg];
                 M=[Mb Mc Md Me Mf];
                 hth=[a b c d e f];

                 z=0.1;
                 if abs(Fb-Fc)<z && abs(Fc-Fd)<z && abs(Fd-Fb)<z && d>0


                    break
                 end
                  end
         end
end
```

Point	**A**	**B**	**C**	**D**	**E**	**F**	**G**
Distance (m)	12.7	10.6	7.4	5.42	4.32	2.66	0
Bending moment (KNm)	0	78.3	57.7	3.0	6.4	11.1	0
Support reaction (KN)	88.7	314.9	223.4	57.2	57.3	57.2	7.6

The findings can now be checked with the program Matrix Frame in order to make sure the calculations are performed correctly:



Section 1.6 illustrated that the upper modules of the door consist of one upper horizontal girder and vertical beams going down to connect with the module bellow. According to this type of modularization

the height of the modules is equal to the centre to centre distances of the horizontal girders as calculated above.
With these modules it is possible to create combinations for various door heights. The table below shows how the height of different possible modular combinations meets the height of the existing doors:

Module combinations	a b d	a b e	a b c	a b f	a b d	a b c d	a b e f	a b c d f	a b c e f	a b c d e f
Door height (m)	6,4	7,0	7,3	8,0	8,4	8,9	9,6	11,0	11,6	12,7
Actual door heights (m)	6,4	6,8	7,1	7,6	8,3 8,4	8,5 8,7	9,2	10,1	11,4	12,7
Exceedence (m)	0,1	0,2	0,2	0,4	0,1	0,4 0,0	0,5 0,3	1,0	0,3	0,0

From the table above it can be seen that the module combinations match the existing door heights pretty well although it is clear there is room for improvement. Slightly altering the height of the modules can lead to the following result:

Module combinations	a b d	a b e	a b c	a b f	a b d	a b c d	a b e f	a b c d f	a b c e f	a b c d e f
Door height (m)	6,5	6,9	7,3	8,0	8,5	8,9	9,2	10,1	11,6	12,8
Actual door heights (m)	6,4	6,8	7,1	7,6	8,3 8,4	8,5 8,7	9,2	10,1	11,4	12,7
Exceedence (m)	0,2	0,2	0,2	0,5	0,2 0,1	0,4 0,2	0,0	0,0	0,2	0,1