General Comments

This revised version contains only the correction of Structural Mechanics part which means that Design Method and Strategy was left as it was before. The changes made for the structural part were:

- Implementation of structural models introducing the system (top view and front view of the lock gates (see Section 14.2).
- Explanation of Macaulay's method and its respective models to make it more understandable (see Appendix I.1).
- Implementation of models for deflections in the lock gate and bridge (Appendix I.5 and I.7.5).
- Implementation of models for the diagonal (see Appendix I.9).
- Implementation of complete calculation process regarding the miter gates (see Appendix I.1,I.2,I.4 and I.5).
- Implementation of complete calculation process regarding the second order calculations (see Appendix I.3).
- Implementation of complete calculation process regarding the bridge design (see Appendix I.7).
- Implementation of complete calculation process regarding the diagonal beam (see Appendix I.9).

MID-TERM INTEGRATED REPORT

Module 6 : Sustainable Civil Engineering (2019-1B)

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Management summary

This mid-term integrated report was done by a group of students as a requirement to complete module 6 of Civil Engineering at the University of Twente. It consists of a complete design of miter gates and a pedestrian bridge on top of them which are located at Eefde, the Netherlands. In the aforementioned location there is a lock chamber which was built in 1993 and declared a National Monument in 2003; due to the increasing ships every year this lock chamber is not enough to deal with that increasing amount. Therefore the construction of another lock chamber next to the old one is the solution to cope with the increased and future demand. However there will not be described the complete lock chamber because the main focus of this report is on the design of a pair of miter gates and a bridge located at the IJssel side of the lock.

The first half of this report consists of the description and application of the complete steps of Nigel Cross method. The main idea of the method is to split the overall problem into subproblems to find sub-solutions which will be used to the overall design solution. Therefore, during that process the stakeholders, objectives, functions, objects, requirements, characteristics and alternatives will be explained and analysed. These steps are clearly visible in the following table of contents to facilitate the reading of this report.

The second half of the report consists of the structural design which means that the different forces, loads, and moments acting on the gates and the bridge are analysed, calculated and optimized. To do that there were considered the extreme water levels because if the system is stable with this conditions it will be stable to other conditions. The different steps to have a complete structural design can be found in the table of contents as well as the first part to facilitate the reading of the report.

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1.Introduction

The existence of shipping locks contributes to the navigability of the ships by the waterways. Because the Eefde lock represents an important connection between Germany and the east of The Netherlands, it is required to have an optimal functioning. Which is specially focused on the reduction of the loss of water from the Twente Canal to the IJssel. Therefore, the miter gates at the IJssel side will be designed in order to reduce water losses and waiting time.

For the design process, the Nigel Cross method is applied. First, the problem will be defined and the objectives which the system should be able to achieve. Because as Nigel Cross method will be applied it is important to have a clear overview of what is required and what is desired to be achieved at the end of the project. Furthermore, a description of the different characteristics, functions and requirements of the different components will be explained.
The Nigel Cross method will be compared with another method which is also feasible to understand why it is an acceptable method. By following the steps of the mentioned method the stakeholders and their desires should be considered. Then, it is possible to deduce the principal objectives by means of an objective tree. After the elaboration of the objectives, it is necessary to examine the functions which can help to achieve the proposed objectives with a function tree. The function tree is connected to an object tree and together are a basis for the design of the miter gates and the footbridge.
After that, a performance specification will be realized, with all this information the Engineering Characteristics(ECs) that the system should be analysed in a house of quality. A morphological chart will be created by considering the mentioned characteristics and criteria. At that point, the different alternatives should be clearly defined. By using a multicriteria analysis the best alternatives will be selected and the verification will be done in order to check if the system is able to achieve the defined objectives. Then the validation will be realized in order to know if the system fulfils the desires of the stakeholders.
The second part of this report consists of the structural part in which there is an introduction which gives a clear overview of the design. The dimensions of the lock gate and footbridge will be clearly defined in order to calculate the forces and moments which are acting on the structure. Then, the strength of the components can be analysed and the deflections that the system should be able to handle. The optimization will be done in order to reduce the usage of steel for both the miter gates and the footbridge. Finally, the discussions and conclusions will be elaborated.

2.Problem definition and objective analysis

The Eefde lock which was built in 1993, is located in Eefde (The Netherlands) and connects the Twente Canal and IJssel river. In addition, this lock is essential in terms of mobility and economic growth in the zone because several goods transports are executed through this inland waterway. Also, it is important to mention that the Eefde lock is a National Monument since 2003.
Due to the passage of time, several things have changed. For instance, the number of ships crossing the lock is higher than it was in the past. Therefore, the Eefde lock’s capacity is no longer enough to handle this increasing number which leads to a much longer waiting time that can generate negative consequences.
Another problem is that the lock can not allow fully charged ships to pass through because it has a depth of 2.8 meters that means that only not-fully loaded vessels can pass through it. In other words, if the vessels are not fully loaded there will be less amount of transported goods which lead to an increase in cost due to less efficiency in transportation. In addition, there is another problem which is the existence of only one lock chamber at this location which means that if an accident occurs or if maintenance needs to

be done the mobility that occurs there will be interrupted. Therefore this situation will cause inconvenience in the shipping going through the lock.

In order to solve the aforementioned problems, another lock system will be designed. However, the complete lock system will not be discussed because the focus of this report is the description of the design process of the miter gates located at IJssel river side. The miter gates will have a pedestrian bridge which will be constructed on the top of them. In order to start the design process, it is necessary to clarify the objectives that are aimed to be achieved by the end of the project.

The first main objective is that the system (doors and bridge) will be as convenient as possible which means a reduction in waiting time and an increase of fully-loaded vessels going through the lock. The second objective is that the miter gates and bridge will be safe. In other words, the system will ensure the safety of people that might cross through the bridge and also the system will ensure that the material damage that might occur will be as low as possible.

Another objective is to make an efficient system which means that there will be less water loss which will lead to improved water levels. Finally, there is another objective that is important and is to make the whole system as sustainable as possible. This means that the gates and the bridge will have a minimum environmental impact, also the system will be economic sustainable in terms of cost of construction and maintenance and it will have social acceptance.

Therefore, to ensure convenience, efficiency, safety, sustainability and economic growth in the region it is necessary to build a new lock chamber. This new lock will comply with all policies and regulations that are necessary to have an adequate structure which will help with the development of the zone.

3.Description of characteristics, functions and requirements of the lock components designed.

It is important to know which are the characteristics, functions and requirements that the designed system has and can perform. Therefore the main characteristic of the complete system (miter gates and bridge) is that it is made of steel. Another one is that it is sustainable, stable, safe, efficient and not annoying for people working and living in the zone. The functions that this lock and bridge perform are: regulating water levels, allowing crossing the ships in an efficient way that means less waiting and crossing time, bearing all the loads, forces and momentum acting on them without collapsing, ensure safety for people and being sustainable in terms of environment, economy and society. Lastly, the requirements for the system were: minimum lock width of 12.2 meters and the minimum depth of the lock chamber of 4 meters.

4.Design methods

In order to enhance the established ways of working in design, some methods have been developed. Such methods surged due to the growing complexity of the modern design. Which is caused by the development of new materials and devices. Therefore, it is necessary to have a team work which should be coordinated. In order to ensure that the specialists collaborations are made appropriately an organised approach to design should be elaborated. There is a method which allows this and is the Design method which can be any procedure, technique, tool or aids to design. Indeed the general body of these methods are classified into two groups: Creative and Rational methods which will be explained below.

- The Creative Method has played an important role in the stimulation of creative thinking. It works by making a better flow of ideas and removing mental blocks. When there are problems the creative methods will help to increase the possible solutions.

- The Rational Method promotes the systematic approach to design. Its main idea is to serve as a checklist to know if everything is done or not, therefore it formalizes the process by recording the different items that need to be checked-off as they are achieved or collected until everything is complete. All of this is achieved by widening the searching space for possible solutions and facilitating teamwork.

4.1.Nigel Cross method

Nigel Cross method is within the Rational method and essentially outlines the nature of the design thinking. The product development and design process management are placed within a broader context. The Nigel Cross Method makes the design process more flexible and essentially considers the potential desires and necessities of the clients. Furthermore, provides a step by step advice for the implementation of a design method as it can be visualized in figure 1.

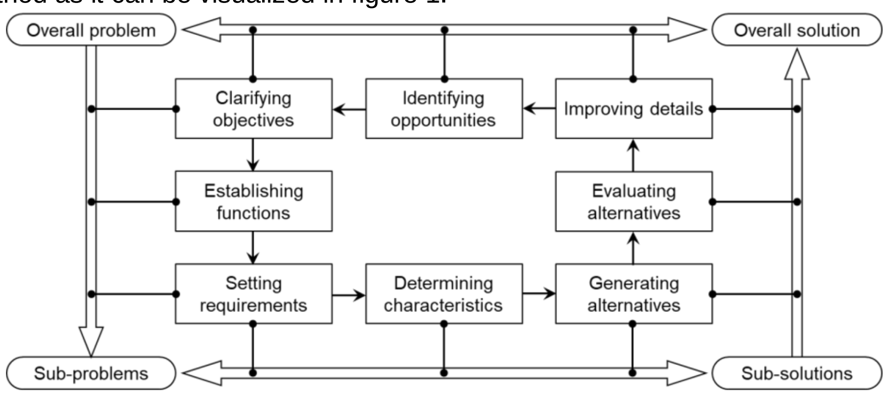


Figure 1. Nigel Cross method diagram

All the steps have a great correlation with each other and this assures that the objectives are met in the final phase. The problem is subdivided into sub-problems in order to have a better understanding of the actual situation. The objectives are derived from the problem which will be used to make a function tree. In the end, these functions should be connected with some objects. From the functions is also possible to deduce the requirements of the different stakeholders.

In order to find sub-solutions to the sub-problems, it is necessary to consider the requirements, which are essential to determine the client attributes(CAs) and engineering characteristics(ECs). This will be done in order to avoid conflicts and misunderstandings. The mentioned characteristics will lead to the generation of alternatives. These will be expressed in a morphological chart which widens the alternatives of possible solutions. The mentioned chart generates different components or sub-solutions which can be combined to generate the solution.

In order to obtain an overall solution from the sub-solutions, the different alternatives should be evaluated. The mentioned evaluation will examine the different requirements, stakes and functions. This especially confirms if the alternatives meet the objectives. After evaluating all alternatives one final design can be generated. It is feasible to improve some details in order to enhance the performance of the product in the future. Then, it is possible to have the final solution to the established problem. Finally, it is important to check if the proposed solution can solve the problem.

After the explanation of the different methods, it can be distinguished some differences between them, such as the creative method is carried out in a disorganized way. For instance, brainstorming in which a large number of ideas are generated and no criticism is allowed. Furthermore, the feasibility of the ideas is not considered. Whereas Nigel Cross method is developed in a more organized way. For example, there is implemented a solution-problem approach where all the different ideas need to be considered and analysed carefully before decision making.

Another difference is that in the creative method there are not a checklist or something which records the progress of the project. While Nigel Cross method as part of the rational method documents everything that needs to be achieved or collected to finalize a project.
Both methods also differ in the time in which the solutions could appear. For instance, in the creative method there is a creative process. In the mentioned process the experts experience a sudden illumination which suggests a solution for the problem. While Nigel Cross method states several steps to find a solution.

5.Stakeholder analysis

A project will be a complete success if it meets the different wishes and demands that each stakeholder may have. A stakeholder is a person, group of persons or organization that is affected by the project. Therefore by taking into account the demands as much as possible of the different stakeholders the project will be supported in a better way.
It is important to know the different interests, objectives, expected situations regarding the project and its possible solutions. So, the table below describes them by taking into account each stakeholder involved in the project.

Table 1. Stakeholder Inventory

Stakeholder	**Interest**	**Desired Situation & objectives**	**Existing or expected situations**	**Causes**	**Solutions**
Rijkswaterstaat	To allow the navigation of large ships	Build and place an efficient lock gate to regulate water levels	Water loss during door opening	Delay in locking process	Construct a set of lock gates
Shipping companies	Count with necessary water levels	Transport the different goods in an efficient way	Variation of water levels during the year Only vessels with a draught of 2.8 meters can pass	High and low discharge periods and water loss	Construct a set of lock gates
Nearby residents	A noise free environment	A quiet place to develop their daily activities	During the construction there would be possible disturbance	Noise due to machinery	There will not be any worker or machinery working during peak hours and weekends
Construction companies	Collaborate with the infrastructural development of a specific place	Build a sustainable and appropriate infrastructure	The infrastructure might not be as appropriate as expected	Lack of communication Misunderstanding of the main purpose that the structure must fulfil	Manage the construction of the structure
Environmental groups	The protection of the local flora and fauna	Avoid as much as possible the environmental destruction	Some species might be loss during the construction process	The contamination of water, therefore the death of some species	Reduce the impact that the construction of the lock can cause to the local species
Electricity companies	Provide a safe and functioning system	Simultaneous work with construction companies to have a smooth functioning of the structure	Problematic connections might appear if the infrastructure does not have an appropriate design	Lack of communication with the construction companies	To organize meetings periodically and to communicate what is required from the electricity companies
Government	Regulate the system and the different activities that will be carried out	Make sure that every system complies with the established standards	The system might not fulfil the regulations	Lack of communication of the different regulations that needs to be fulfilled	Improved communication ways such as checklists to check if everything has been meet
Maintenance staff	Make sure that the system is repaired (if necessary) and maintained adequately	Ensure the proper functioning of the system after it has been completed	The system might not meet the necessary requirements for its maintenance	Misunderstanding of the different requirements needed to finish the system	Make explicit what needs to be done and achieved by the system

Business companies	Transport of products	Uninterrupted transport of products	Fully loaded ships are not allowed to pass the lock	Low water levels and water loss	Build the lock to allow the ships to transport
Experts	The implementation of their demands in the construction of the structure	Implement their knowledge through demands to improve the system	The system does not meet the demands	Lack of communication of the different demands	Improved communication methods to satisfy the requests
Municipality	Control the proper functioning of the system	Establish policies which will allow to regulate the proper functioning of the structure	The system does not take into account the current policies	Deficiency in the revision of the current policies	Apply different policies to ensure a legal performance
Workers	Have a good working environment	Perform their daily activities normally	Reduced mobility during construction process	Obstruction of the pedestrian crossing	Habilitate another bridge to cross from side to side

5.1.Position of stakeholders

The different stakeholders and its respective interests were listed before, therefore it is important to know their position in relation to the system. This implies the estimation of the power and interest of each stakeholder.
This estimation will be done by using The Power-Interest diagram as a tool. The objective of this tool is to map the position of the stakeholders in a graphical way, so this will be represented in a Power-Interest grid which is shown below.

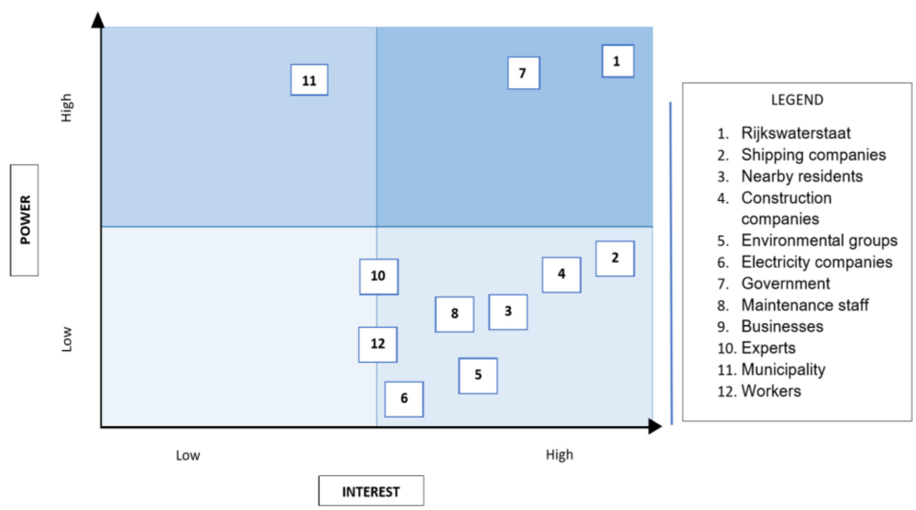


Figure 2. Power interest grid

As the figure shows, the graph is divided into four quadrants. The first one is located at the upper right side and represents the group of stakeholders which has a lot of power and interest, this group is called “Key players” and it is very important to keep them satisfied and involved in the project. The second quadrant is located at the upper left side of the graph and represents the group “subjects”, this group has a lot of power but their interest is low, therefore keeping them satisfied during the project is important. The third quadrant located at the lower left side depicts a group of people called “crowd” which interest and power are the lowest in the graph, therefore they are monitored during the project’s development. Finally, the fourth quadrant which represents people with high interest but low power, they are called “context setters”. Due to its reduced power but high interest keeping them informed about the project’s development is sufficient.

6.Objective analysis

In order to start the design process, it is important to define the different objectives that the system should meet at the end of this process, this is done with the aim to have a clear path to follow when designing the system. Therefore it is necessary to make sure that all the objectives are met, this is achieved by creating an objective tree, that is a diagram which will be used to have an overview of the different objectives that the complete system should comply. In this case, the objective tree of the miter gates and the footbridge can be found in Appendix A. It is important to mention that the objective should be specific and clear, so the main objective of the system is "A convenient, safe, efficient and sustainable system conformed by miter gates and a footbridge", this is located in the upper middle part of the diagram.

In addition, this main objective is divided into four categories that are: convenience, safety, efficiency and sustainability. Then the different sub-objectives are stated which are located below the name of each category and below them there are sub-sub-objectives. Also, in the category of sustainability, there is a split in three parts that are: environmental, economic and social. In the whole system there is How-Why structure which means that from top to bottom there is applied the question "How" and from bottom to top should be asked the question "Why".

7.Function analysis

In order to design a system, certain functions should be analysed. The function analysis method considers essential functions and the level at which the problem will be focused on. In order to have a clear overview of the functions, a function tree was elaborated. The function tree can be visualized in Appendix B. The main task in the function tree is to allow the navigation of fully loaded ships and the reduction of the waiting time of 30 minutes. Furthermore, to allow people to pass to the other side. Then, the main function is decomposed in basic functions which are: optimise navigability, control water level. The supportive functions are: ensure safety, manage structure, support economic sustainability, support environmental sustainability and support social sustainability. Then, secondary basic functions, secondary supportive functions and so on are stated in the diagram.

The technique How-Why is also applied in order to understand the system in a better way. Which means that from the left to right the question "How" will be asked and from right to left "Why" will be questioned. Furthermore, the allocation of functions is made in such a way that existing products can perform the functions. Then, it is possible to identify the objects which fulfil the proposed functions. The objects together make the whole system that will be developed. They are linked to functions in an object tree and this is a model of the system, not a design. The mentioned object tree can be found in Appendix B. By working with this method the designers avoid the selection of a premature solution. Along this process, the functions and objects are in constant development.

8.Performance specification

Once the different objectives are clear and the functions which meet the objectives are stated it is necessary to specify the aimed performance of the system. In order to have a clear vision and to identify each of the different performance specifications, a table was created which can be found in appendix C. These performance specifications are the requirements of the design. It is important to mention that the requirements are formulated following the SMART criteria which means that every single requirement is specific, measurable, acceptable, realistic and timebound. These criteria are followed in order to know in detail the required performance of the system.

Furthermore, as it was stated previously to have SMART requirements the table includes: element or object, description of each performance, the criterion which refers to the terms in which each requirement

can be measured, the performance that is aimed to be achieved and a possible bandwidth, priority and the source of the requirement.
In addition, the different requirements that are present in the table were formulated by taking into account the different objectives, functions, sub-functions and objects that were shown previously in the different diagrams (objective, function and object tree). This was done with the aim to have cohesion between the different diagrams and the table with the requirements which will lead to another step that will be explained below.

9.Client Attributes (CAs) and Engineering Characteristics (ECs)

The relationship between client attributes and engineering characteristics should be properly understood in order to satisfy the customer's needs. Engineering characteristics (ECs) define the design of the structure and the Client attributes (CAs) represent needs and requirements. If they are not satisfied, the entire system is useless. The most feasible way to assess the relationship between attributes and characteristics is to represent them in a matrix. The mentioned matrix is called 'house of quality' which can be found in Appendix D . In practice, the 'house of quality' is used to know the most important characteristics.

In order to construct a 'house of quality', several steps were performed. First, the requirements and needs of the client were identified. Then, it was necessary to determine the importance of each client attribute. Therefore, the customer importance was expressed with numbers from 0 to 14 depending on the importance of the attributes. For instance, in the case of more fully loaded ships, more ships in less time and safety received a score of 14. This occurred due to the fact that they are of high importance to the client. Furthermore, the relative weight expressed as a percentage was added. It is important that all the engineering characteristics should be real and measurable. In order to identify the relations between CAs and ECs some symbols were used, which represent a strong, moderate and weak relationship. Furthermore, it is necessary to identify relationships between ECs. These interactions were divided into positive, negative and no correlation. Finally, it was important to establish a target value based on previous projects and engineering judgement.

10.Morphological chart

In the design process, it is important to not only think about the first solution but beyond. Therefore the morphological chart is used to look for alternatives to the functions which were previously stated in the function tree. This chart consists of a column which first details the features of the system and the means that can be used to achieve these features. The means are the different alternatives which can be used to create a system. Then the best alternatives are chosen, in other words, the best mean to perform the function is selected for each category (features) which leads to a composition of alternatives. This morphological chart can be found in Appendix E.

11.Alternatives

By taking into account the morphological chart previously elaborated it is important to choose more alternatives to have a better insight of which should be the best alternative. This was done by choosing one mean to every function which ended up in four alternatives. The first two are using steel as the main material while the third one uses timber and the last one utilizes concrete. Each different choice for every feature of the four alternatives is shown in Appendix F.

11.1.Steel

As it was mentioned before, there are two alternatives which use steel as the main material. There are some differences between both alternatives, for example, the first alternative uses LED lighting to reduce energy consumption and to increase its lifespan. While the second alternative uses energy-saving lamps which will reduce the energy consumption and the cost of lighting. Another important difference between these alternatives is that the first one will perform material optimisation to reduce costs but alternative two will work with a simple structure that also will reduce the costs, however, simple structures are not always convenient in terms of stability. There are also other differences between alternative one and two which can be seen in Appendix F.

11.2.Timber

The third alternative uses timber as its main material which compared to steel has a lower material cost because steel is more expensive than timber. It will use bulbs to illuminate, however, bulbs consume more energy than LED lighting and saving lamps. Therefore in terms of lighting, this alternative has the lowest performance and increased the cost. Also to reduce costs this alternative will use low-quality material which will reduce the costs a lot but it can put safety at risk which is not desired because one of the main objectives of this project is to have a safe system. There were also chosen another means for each feature for this alternative which can be seen in Appendix F.

11.3.Concrete

The fourth alternative includes concrete as the main material. This material is cheaper than steel but a bit more expensive than timber because its price depends on where it was obtained. Another difference is that this fourth alternative will use CLF for illumination which means that this will consume a lot of energy which will result in an increase in costs. In addition, concrete needs reinforcement to cope with tension forces, therefore it is necessary to take into account the cost of steel. Also, this alternative will work with a simple structure which might affect the stability of the whole system while the alternatives with steel are more stable. The different choices for this alternative can be found in Appendix F.

12.AHP

In order to make decisions, it is necessary to state the preference order of the alternatives, which facilitates the selection of the best alternative. Frequently, there are conflicting criteria and Multi-criteria decision-making (MCDM) helps to evaluate and quantify the criteria. The Analytical Hierarchy Process (AHP) is part of this and is currently applied in different fields such as government and business. It is a structured method for organizing and evaluating complex decisions. Furthermore, it is principally based on psychology and mathematics. This technique considers the objective and the different alternatives to reach it. After the execution of several steps, a final decision will be taken.

12.1.Hierarchy Tree

As it was mentioned before the goal will be considered and some alternatives were elaborated. Therefore, it is necessary to define the criteria which will evaluate the alternatives. Even though, the criteria can be subdivided in subcriteria for the sake of this project the hierarchy tree will only consist of criteria. The main goal is to have ‘ Efficient miter gates and footbridge design’ and will consist of five criteria which are: safety, stability, sustainability, convenience and costs. Then, the hierarchy tree is connected to the four alternatives: Steel(1), Steel(2), Timber and Concrete.

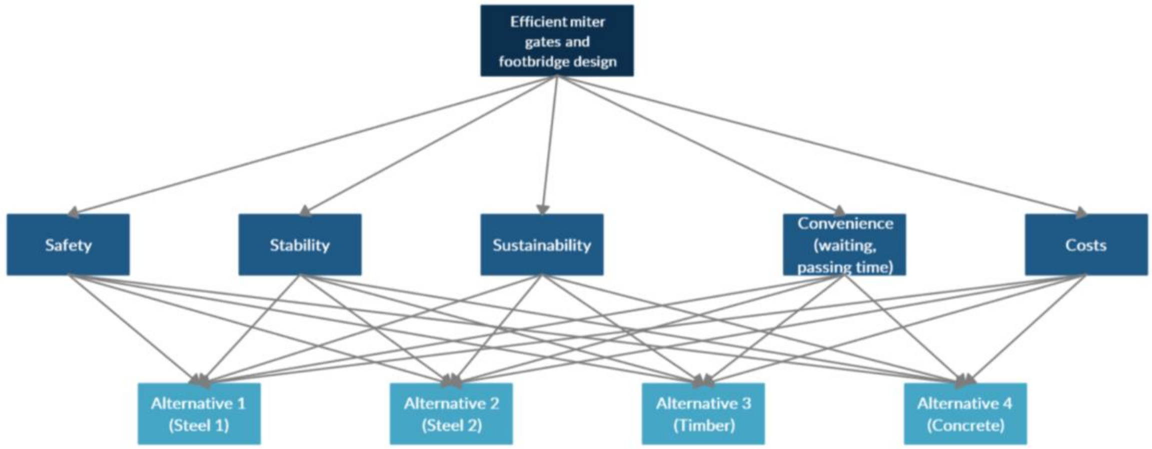


Figure 3. Hierarchy tree

12.2.Relative weights of criteria

In order to obtain the relative weight of each criterion, a pairwise comparison should be performed. This eventually will show which criteria has more priority among the rest. Therefore, a table was created which can be found in Appendix G. These criteria were shown in figure 3. This table has the importance and intensity columns in which two criteria are compared and then the most important criteria will be located. Then, it is necessary to define the intensity of importance. The Saaty scale of comparison was used in which numbers from 1 to 9 are used. Low numbers indicate that both criteria have more or less the same importance. On the other hand, high values represent the favouring of one element over another (Bukhsh, et al., 2017).

12.3.Comparison matrix

Each alternative was analysed with the mentioned criteria. Moreover, the measuring units were included. For the criteria of safety, each alternative was measured using score cards because they can not be quantified easily. This is the same case for stability and sustainability. Convenience was quantified using minutes and costs in euros. After the evaluation of each alternative with the stated criteria, it is necessary to sum all the columns as table 12 shows in appendix G.

12.4.Ranking the criteria

As it was mentioned before the criteria were compared and the intensities defined. Then, the scores for the intensity of each criterion were represented in another table shown in Appendix G. In order to obtain the priority vector, it is necessary to normalize the columns, which basically consists of the division of the entry of the columns by its sum. The normalized table served to calculate the mean of each row which gave the priority vector. The mean vector of each row was multiplied by the normalized table of the criteria giving as a result the final score which serves to know which criteria are more important, in our case stability had a score of 0.32 therefore it is more relevant than the cost which resulted in a value of 0.1. The detailed process can be found in Appendix G.

12.5.Ranking the alternatives

After obtaining the final score of the criteria, the final score for the alternatives can be found. The mentioned scores determine the best alternative. First, the comparison matrix is normalized as it was explained before. Then the normalized matrix is multiplied by the priority vector. Which gives the final scores that should be considered in order to select the best alternative. The alternative that has the lowest score is the best. As it can be appreciated in Table 14, concrete has the highest score and steel the lowest. Therefore, the first alternative which implies the use of steel is the best with a score of 0.16. This could be due to the fact that the most important criterion was stability and steel contributes significantly to this. The detailed calculations can be found in Appendix G.

13.Sensibility discussion

It can be deduced from previous steps that the criteria weights or priority vector strongly influences the ranking of the alternatives. Stability is valued as an important criterion with a score of 0.32, therefore the alternative which contributes the most to stability should have the lowest final score. On the other hand, it is also important to consider the other criteria. For instance, convenience which is related to the travelling time of the ships. It is also important because convenience is part of the basic functions that the system should perform. In Table 14 of appendix G the scores can be visualized with their respective raking. The second option is the alternative of steel with a final score of 0.24. But, it does not seem to be very safe and convenient as in the case of alternative 1. That could lead to the score of alternative 1 as the best instead of alternative 2.

14.Structural Design

14.1.Introduction to the structural system

During the development of this chapter, the structural design of the miter gates and the pedestrian bridge located at Eefde will be elaborated and described. The material that was used during the elaboration of the design was steel, that means that the gates and the bridge were analysed and calculated by using the different properties that steel includes. Therefore by the end of this chapter, a proven stable and optimised design of the system which consists of miter gates and bridge will be finished. The optimisation consisted of using less material as possible, this was done by calculating the total steel volume of the gate and the bridge because the idea is to reduce costs in the construction process.
Firstly, the forces acting on the gate and its respective calculations are elaborated. After that, the calculations and elaboration of a gate design are done by taking into account the steel plates and beams and the respective forces, loads, moments, stresses and deflections acting on them. Then the optimisation of the angle, number of beams and HEA profiles are determined.
Then, the forces acting on the bridge are calculated and used to elaborate on a design with steel plates and beams. Later, the optimisation of the aforementioned design is executed. After that, the calculations of a diagonal beam located in the gates are made. Finally, the elaboration and calculation of two connections are performed.

14.2.Forces acting on the miter gate

First of all, it was necessary to know what was the pressure generated by the water. The water level which was used to calculate these pressure was equal to 10.8 meters that was the extremely high water level that the Twente Canal could have which means that this is the worst scenario that might occur. Therefore if the gates are able to withstand this pressure generated by such water level, the gates are strong enough to cope with any lower water level. For security reasons it was decided to increase the height of the gates by 2.7 meters given a final height of 13.5 meters.

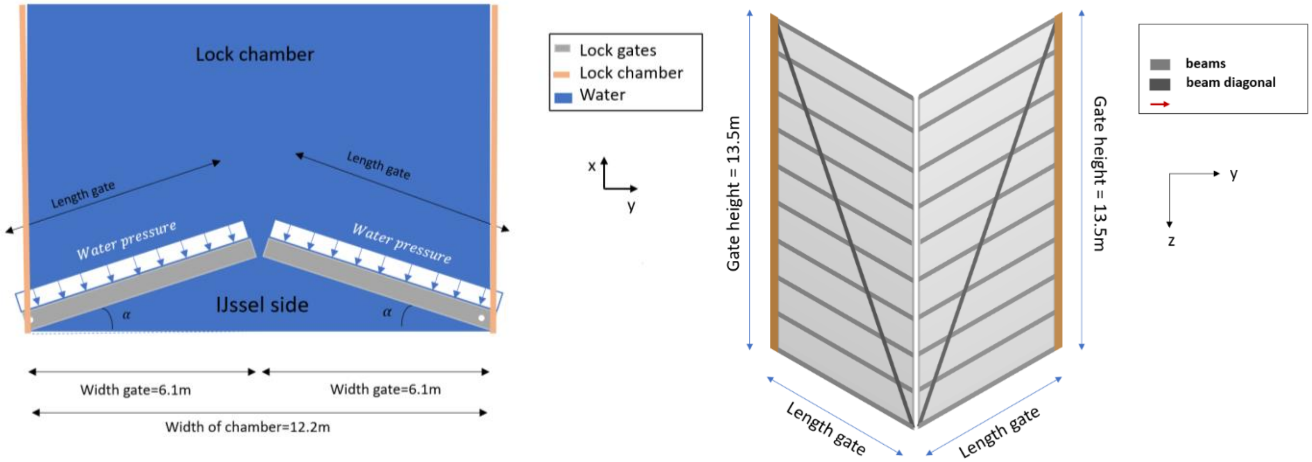


Figure 4. Top view and Front view of the miter gates

Other forces that act on the gate are represented in figure 5, where N represents the force that is delivered by the other door lock, H and V are its components and all these forces will have a reaction forces on the other side of the gate. The load of water acting on the gate is represented as q_{beam} and it has the value of the highest reaction force (that was calculated using Macaulay's Method) per meter, this load is in equilibrium with the aforementioned forces. Alpha is the angle that will be optimised later. It is important to mention that the same calculations for one gate apply to the other gate. The formulas for the calculation of those forces can be found in appendix I.1 and the MATLAB code in appendix J.

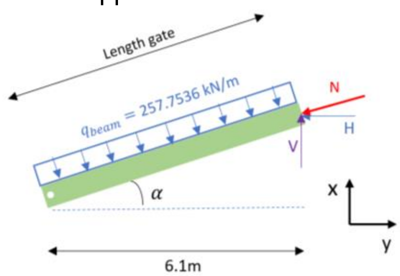


Figure 5. Forces acting on the lock gate

Plate and beams for the lock gate

Firstly, the thickness of the steel plate needed for the design was calculated and its formulas can be found in appendix I.2. After that the strength of the beams in the lock gate was calculated. These beams needed to bear the moment caused by the water load and the second order which is caused by the normal force acting on the gate, so the equations to calculate them can be found in appendix I.3.

After that, the formulas for the calculation of maximum allowed and actual deflections were established (see appendix I.4-1.5). Due to the optimization that needs to be done all the different calculation processes were performed in MATLAB which can be found in appendix K. It was realised that the various formulas were dependent on the angle, HEA profile and number of beams, therefore by having this in mind the optimisation process can start and will be described below.

14.3.Optimization lock gate

In order to optimize the lock gate, a Matlab code was elaborated and can be found in appendix K. First, the optimization of the angle was done by plotting a graph of the angle against the minimum strength. The angles from 1 to 25 were proved for the profiles from HEA 100 to HEA 400 and that yielded in figure 24 of appendix I.6.1. According to Rizards and Paulus (2019), the optimal angle should lie in a range from 16 to 20. The angle 18.4 had a balanced proportion between the normal force and the bending moment and it was taken as a reference. Therefore, it was decided to take the angle 18 as optimum. The actual values for the angle and length of the gate can be visualized in figure 6.

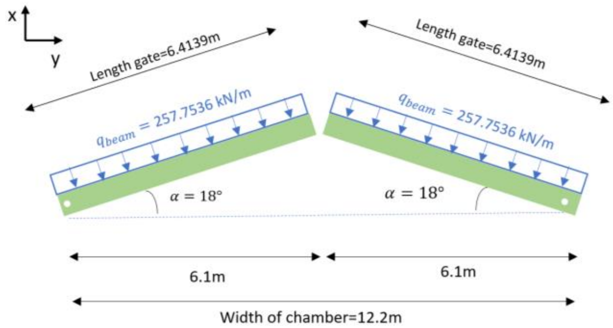


Figure 6. Top view lock gate

With the graph 16 of appendix I.6.1 from the last step the profiles which can be used were defined. Therefore, only the profiles from HEA 220 to HEA 400 would be taken into account. Due to the fact that they were below the values of the yield strength of the steel. The optimization of beams is also very important because if there are more beams the profiles can be smaller and that means less steel used to build the gate. What is important in the optimization is less usage of material. The profiles from HEA 300 to HEA 240 were proved with a different number of beams. Some criteria were considered in order to get the most plausible number of beams. For instance, the plate thickness, the strength of the beams and total volume were considered. The principal factor which allowed to select the number of beams was the volume. The optimised number of beams is shown in table 2.

Table 2. Results from the optimization of the lock gate

Number of beams	HEA profile	Plate thickness(m)	S/R strength beams	Total volume(m^3)
10	**240**	**0.0219**	**0.74680**	**2.5943**

As it can be appreciated the selected number of beams was 10 due to the fact that the total volume will be lower compared with the other profiles the complete table can be visualized in Appendix I.6.2. In the table will also be appreciated that as the number of beams increases the required thickness of the plate is smaller. Furthermore, for the value of S/R the result should be below 1 which is the case for all the beams. But, a requirement for S/R is that also should be above 0.8. Therefore, the group decided to consider the volume above S/R which is related to with the strength of the beams(based on the Rankine Gordon).

A diagonal beam will be placed on the lock gate, therefore it was optimized. The different calculations and optimization can be found in Appendix I.9. As it can be appreciated in Table 19 the optimal profile was HEA 180 and the length of the beam was 14.9m.

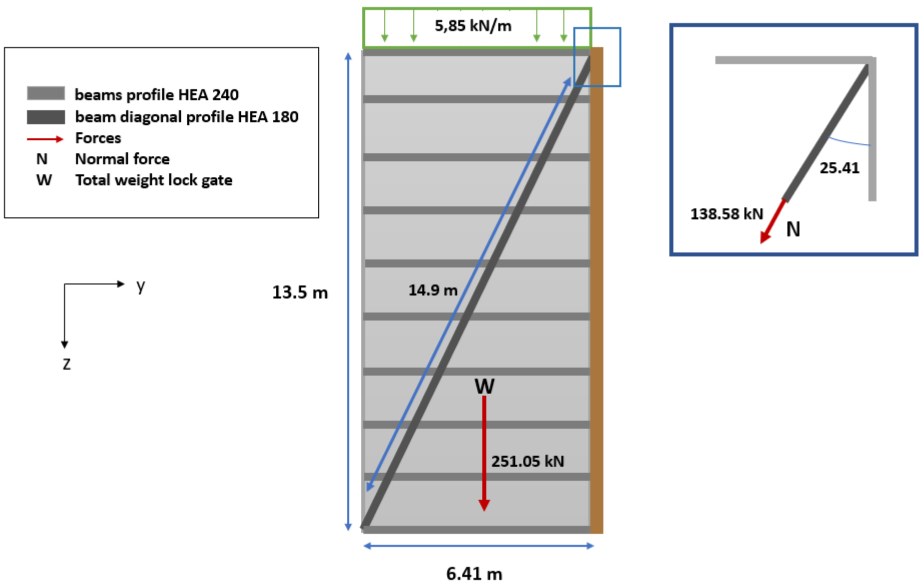


Figure 7. Design of lock gate

14.4.Design footbridge

When designing the pedestrian bridge a similar process of gate design was followed. Which means that the first step was to analyse the forces and loads acting on the bridge. After the respective calculations were done (see appendix I.7.1) it was decided that the design stress of the bridge is equal to $5.85 kN/m^2$ because it is the highest stress acting on the footbridge. Knowing this value the plate thickness of the bridge, load, moment and deflection can be calculated. The equations used to perform each calculation can be found in appendix I.7.2-I.7.5. All these calculations were performed by MATLAB and can be found in Appendix L. This MATLAB code was created with the aim to make the optimisation process less time consuming and more efficient.
Figure 8 shows a schematization of the bridge, where can be seen that the upper beam of the lock gate serves as a base for the bridge. In addition, perpendicular beams to the plate will be placed there. The exact beam profile, number of beams and plate thickness will be known after the optimisation of the system is done. In addition, it is important to mention that the bridge will have handrails of 1.5 meters high to ensure the safety of the people crossing it.

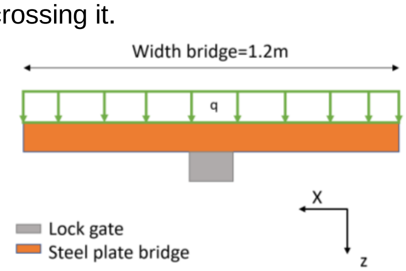


Figure 8. Schematization of bridge

14.5.Optimisation footbridge

As it was mentioned before, all the formulas used were applied in MATLAB with the purpose of optimising the system, this code can be found in Appendix L. The optimization process started by plotting the deflection against the different HEA steel profiles(see figure 28 of appendix I.8), with this graph it was possible to realise which HEA profile was optimum, therefore the optimum HEA profile for this system is

HEA 100. Once the optimum profile was known, then it was possible to calculate for which number of beams the system will be optimum. In appendix I.8 there is a table which compares the different number of beams and the plate thickness, S/R deflection and total volume caused by the variation in the number of beams. Therefore the optimum number of beams was equal to 3 because it uses less amount of material and its respective values can be seen in table 3.

Table 3. Results from the optimization of the bridge

Number of beams	HEA profile	Plate thickness (m)	S/R deflection beams	Total volume (m^3)
3	**100**	**0.0077**	**0.2071**	**0.1003**

Once the optimum HEA profile and number of beams is known it is possible to have a clear scheme of how the bridge look like which is shown in the figure below.

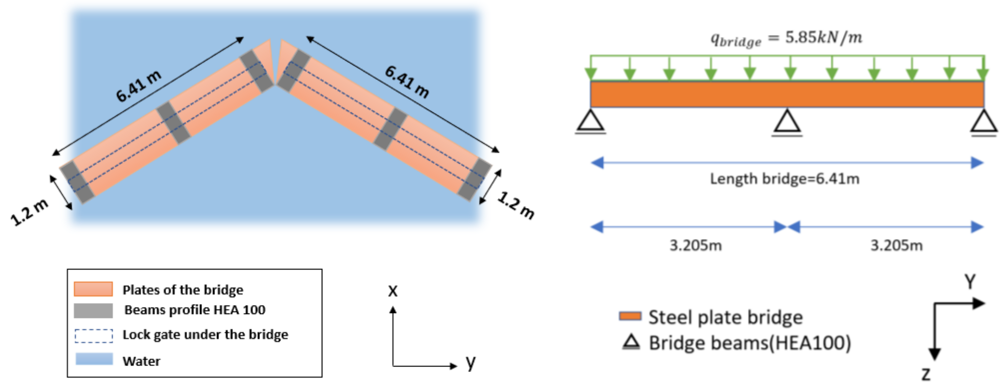


Figure 9. Design of pedestrian bridge

14.6.Connections

After the optimisation of the complete system is finished, two connections were implemented to make the system more stable. The first connection consists of 4 bolts with M12 dimensions and 4.6 class. In this connection, the beam of the bridge with a profile HEA 100 will be connected to the upper beam of the lock gate with a profile of HEA 240. The detailed calculations can be found in appendix I.11.1. While the second one is a welded connection between the beams and a plate of the bridge which resulted in a weld width of 3mm and a weld length of almost 7mm. The calculations to obtain the aforementioned values can be found in appendix I.11.2.

15.Verification

The aim of the verification of this system is to check if it works or not. This can be done by comparing results and requirements with similar systems. Another verification option is to check if all the requirements were satisfied. The verification of this system was done by putting all objects, the functions that it needs to perform and the execution of them that was or will be done in the future. In some cases, there were also added the price of the object. Therefore a verification matrix was created and can be seen in appendix H.

16.Validation

It was decided that the most feasible option to validate the system is to have a meeting with each stakeholder that is involved because the success or failure of the project depends on them, therefore

during the design process the requirements, interests and wishes were taken into account as much as possible.
Firstly Rijkswaterstaat's interest was to have more ships crossing the lock gate which will improve inland waterway transport, therefore the system fulfilled that because the waiting and crossing time were reduced. Then shipping companies wanted to count with necessary water levels to allow fully charged ships to cross, this was also fulfilled by the system because it was designed taking into account the minimum required water level. Then the nearby residents wanted a noise-free environment which was not fulfilled at all because during the construction process there will be some noise, but some measures were done which were planting trees that will reduce noise and will improve the landscape of the zone. Also with this measure environmental groups can be satisfied. On the other hand construction companies' interest was to collaborate with the infrastructural development which of course was achieved by the complete system. Other stakeholders are electricity companies which wanted adequate connections to provide electricity to the system, this interest was as well fulfilled by taking into account the illumination and operation of the gates into account while designing. Then the government and municipality wanted to regulate the system, which also was fulfilled by taking into account the different policies that apply to the system. Then maintenance staff and experts wanted to make sure that the system meets the necessary requirements. For maintenance, however, this can be done at least one year after completion. Also, business companies' interest was uninterrupted transport of products which can be fulfilled because the system is efficient and allows more loaded ships to cross in less time. Finally, workers wanted to perform their activities normally, therefore by having stairs, handrails and signage they can do their daily activities in a safe environment.
After the different interests of the stakeholders and the means and ways to fulfil them it can be said that the system meets almost all the different requirements which means that it is a feasible option to them.

17.Discussion

First of all the different objectives and functions would have been done in a better way if there would be a meeting with the different stakeholders and the client to know what exactly do they want because in the project there were some unclear things. Therefore the design team had to guess and interpret according to their insight some wishes that the stakeholders had.
Another point of improvement could be regarding the client and engineering characteristics because some wishes were too vague to transform them into engineering characteristics, therefore it was done by interpreting in the best possible way. Then the alternatives could have been chosen in another way than choosing different elements from the morphological chart. There were compared four alternatives with different materials and performance which is not fair enough because each system is unique and has its own objectives, functions, objects, etc. Therefore it would have been better if there were a comparison having the same parameters. After that, by using multi-criteria analysis there could be some inaccuracies because some of the values are based on assumptions.
Regarding the structural design, it is not as realistic as it wanted because there were several factors which were not taken into account, for example the wind loads, the vibrations occurring when a person is crossing the bridge, snow loads, temperature effects. In addition, the gates were analysed when they are standing still but in reality, this is not the case because the gates tend to rotate due to the water. Also due to the lock gate needs to bear water level from both sides it could have been considered both sides of the lock gate when analysing and designing it.
After that when calculating the optimisation there were some values of S/R which were below 0.8 and it is because the main optimisation idea of this project was to have less amount of material because one of the ideas were material optimisation to reduce costs. Also, this S/R values could have been improved by taking into account not only the deflection but also the stresses.

In the case of the connections, the arm of the bolt was taken with a value of 0.18 m because it was assumed that the tensile force will act in the centre of the bolt.

18.Conclusion

After completing the different steps of Nigel Cross method that were: stating objectives, then making those objectives into functions, after that find an object which performs that function. Then those functions served as a basis for the performance specifications and engineering specifications. Then a morphological chart was created and with this chart different alternatives were chosen. After that, these alternatives were analysed using multicriteria analysis and the best alternative (design) was chosen. So, the verification was done to know if the system worked and the validation of the design was performed by taking into account the stakeholders involved in the project. After all this process was done it can be concluded that the design satisfies and fulfils the different requirements and interests that the client and stakeholders had.

Once all the analysis and calculations of the different forces, loads, stresses and moments acting on the gate and the pedestrian bridge were done. The optimisation process started and the optimum amount of beams and steel profiles were found; always taking into account the maximum allowed deflection and the value of S/R that were within the safety limit. Therefore it can be concluded that the mechanical design is strong enough, safe and stable.

Bibliography

Bukhsh, Z. A., Oslakovic, I. S., Klanker, G., Hoj, N. P., Imam, B., & Xenidis, Y. (2017). *Multi-criteria decision making: AHP method applied for network bridge prioritization.*

Daniel, R., & Paulus, T. (2019). *Lock Gates and Other Closures in Hydraulic Projects.* Oxford: Elsevier.

EnergyUseCalculator. (2019). *EnergyUseCalculator*. Retrieved from http://energyusecalculator.com/about.htm

Escamilla, E. Z. (2015). *Global or local construction materials for post-disaster reconstruction? Sustainability assessment of 20 post-disaster shelter designs.* Retrieved from https://www.researchgate.net/publication/278299995_Global_or_local_construction_materials_for_post-disaster_reconstruction_Sustainability_assessment_of_20_post-disaster_shelter_designs/figures?lo=1

FLIR. (n.d.). *Thermal imaging for.* Retrieved from https://www.flirmedia.com/MMC/THG/Brochures/T820484/T820484_EN.pdf

ISSF. (2015). *Stainless Steel and CO2.* Retrieved from http://www.worldstainless.org/Files/issf/non-image-files/PDF/ISSF_Stainless_Steel_and_CO2.pdf

Shi, J. (2017). *Optimum enlargement of the Eefde lock using a simulation model.* Delft University of Technology, TU Delft Civil Engineering and Geosciences. Retrieved from http://resolver.tudelft.nl/uuid:a39cf2d0-cbff-4e2a-8473-b8f894984138

APPENDIX

Appendix A. Objective tree

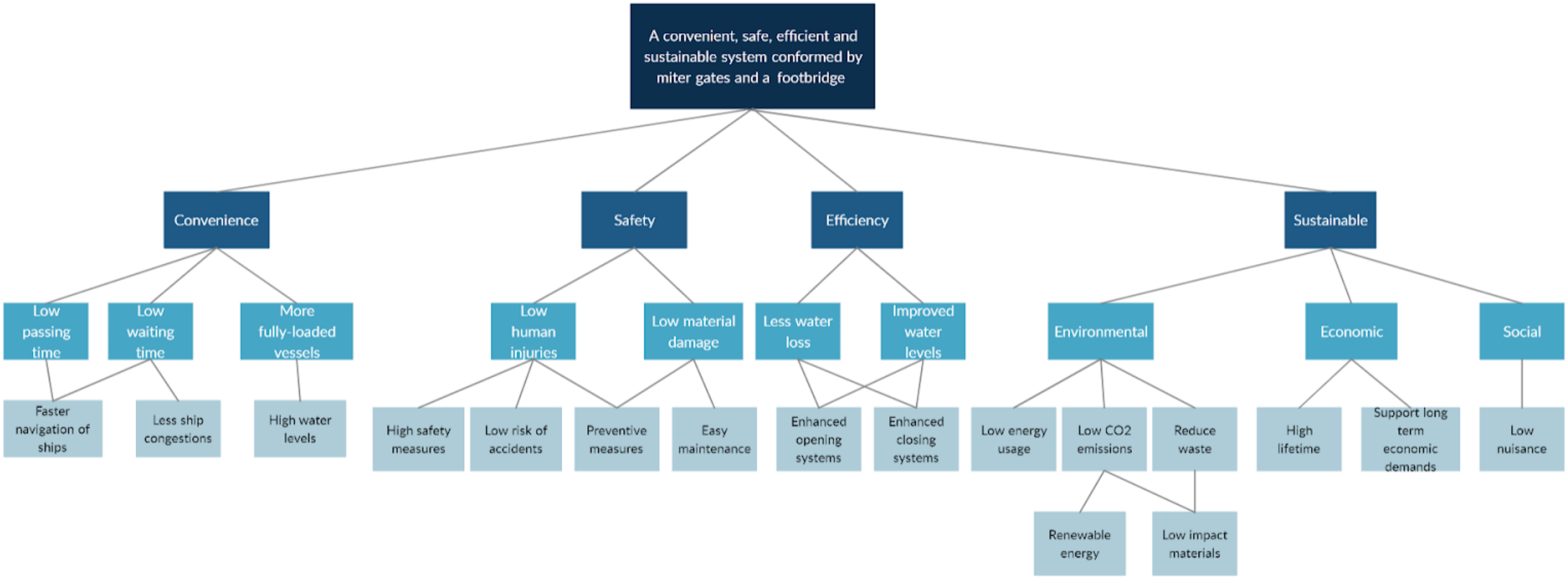
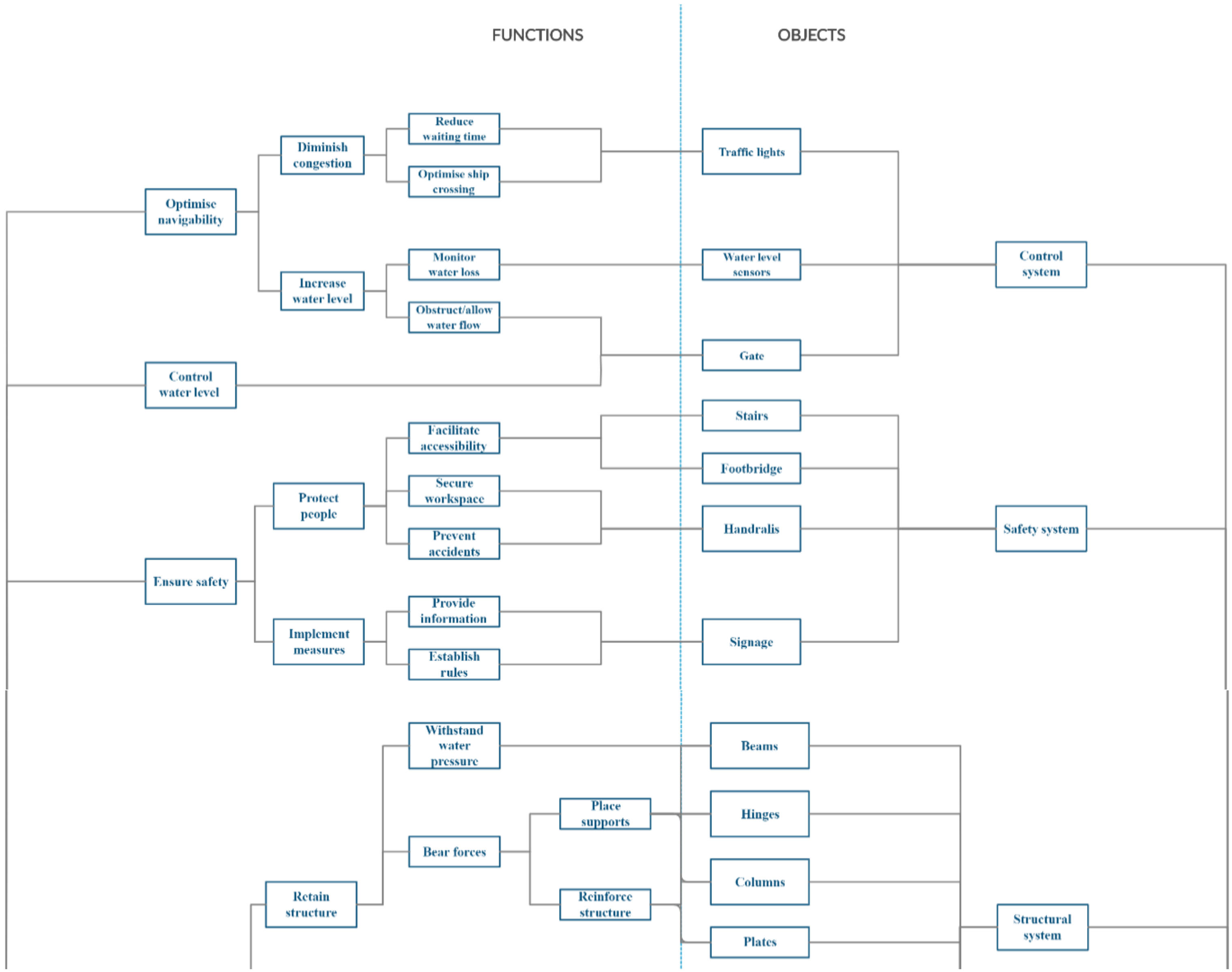
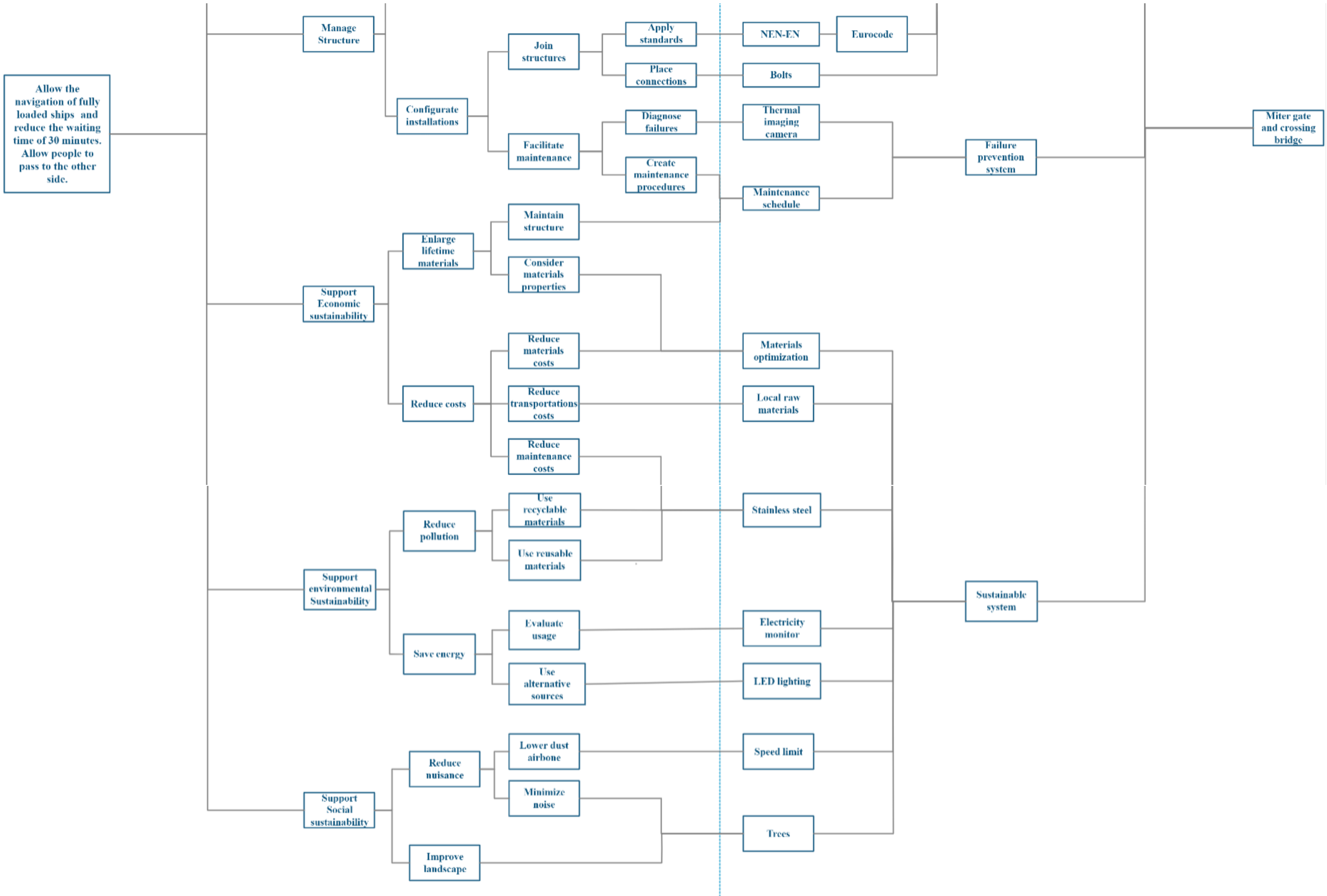


Figure 10. Objective tree

Appendix B. Function and object tree

Figure 11. Function and Object tree





Allow the navigation of fully loaded ships and reduce the waiting time of 30 minutes. Allow people to pass to the other side.
Manage Structure
Configurate installations
Join structures
Facilitate maintenance
Apply standards
Place connections
Diagnose failures
Create maintenance procedures
NEN-EN
Eurocode
Bolts
Thermal imaging camera
Maintenance schedule
Failure prevention system
Miter gate and crossing bridge
Support Economic sustainability
Enlarge lifetime materials
Maintain structure
Consider materials properties
Reduce costs
Reduce materials costs
Reduce transportations costs
Reduce maintenance costs
Materials optimization
Local raw materials
Support environmental Sustainability
Reduce pollution
Use recyclable materials
Use reusable materials
Stainless steel
Save energy
Evaluate usage
Use alternative sources
Electricity monitor
LED lighting
Sustainable system
Support Social sustainability
Reduce nuisance
Lower dust airbone
Minimize noise
Improve landscape
Speed limit
Trees

Appendix C. Requirements (Performance Criteria)

Table 4. Requirements

ID	Object or element	Description	Criterion	Performance	Bandwidth	Priority	Source
1	Control system						
1.1	Gate	Regulate water level	meters	11.65	min.10.8	requirement	client
1.1.1		Material	Type	Steel	-	requirement	client
1.1.2			Type	Miter gate	-	requirement	client
1.1.3		Width gate	meters	12.2	12.5	requirement	client
1.1.4		Length per gate	meters	6.41	-	requirement	client
1.2	Traffic lights	Manage crossing time	minutes	<50	50	wish	client
1.2.1		Manage waiting time	minutes	<30	30	wish	client
1.3	Water level sensors	Precise measurement	meters	accuracy	Should be accurate	wish	owner
2	Safety system						
2.1	Stairs	Facilitate accessibility	Accessibility level (5-point scale)	5	min.4	requirement	user
2.2	Footbridge	Facilitate the crossing from one side to the other	Crossing level (5-point scale)	5	min.4	requirement	user
2.2.1		Width bridge	meters	1.20	min.1.20	condition	policy
2.3	Handrails	Safe for	Safety	5	min.5	requireme	user

		people	level (5-point scale)			nt	
2.3.1		Height	meters	1.5	-	wish	client
2.4	Signage	Informative for workers and users	Information level (5-point scale)	5	min.5	requirement	user
2.4.1		Adequate number of signages	number	16	4	condition	policy
3	Structural system						
3.1	Beams Pates	Bear water pressure	kN/m^2	108	-	requirement	client
3.2	Beam Columns	Hold load of footbridge	kN/m	5.85	-	requirement	client
3.3	Bolts	Connect the different parts	Material	Steel	-	requirement	client
4	Failure prevention system						
4.1	Thermal image camera	Monitoring and diagnosing the structure	Thermal image	Accurate diagnostic	Should be accurate	wish	owner
4.2	Maintenance schedule	Adequate planning	Adequacy level (5-point scale)	5	min.	wish	owner
5	Sustainable system						
5.1	Material optimization	Reduction of costs	Percentage	15%	10%	wish	client
5.2	Local raw materials	Minimize transportation distance	Percentage	20%	-	wish	client

5.2.1		Maximum transportation distance	Km	1000	100	wish	client
5.3	Stainless steel	Reduce pollution	Percentage to be recycled	95%	min. 80 %	wish	client
5.3.1		Reduce maintenance costs	Percentage of construction cost	1%	0.2%	wish	client
5.4	Electricity monitor	Measure energy consumption	Yes/No	Yes	-	wish	owner
5.5	LED lighting	Reduce energy consumption	KW/h	0.24 per day	Max. 0.24 per day	wish	client
5.5.1		High lifespan	Hours	10000	min.9500	wish	client
5.5.2		Life cycle	Long life	yes	-	wish	client
5.6	Speed limit	Reduce dust airborne	$\frac{Km}{h}$	20	Max. 30	demand	policies
5.7	Trees	Minimize noise	Decibel (dB)	50	Max. 85	wish	user
5.7.1		Improve landscape	number	10	-	wish	users

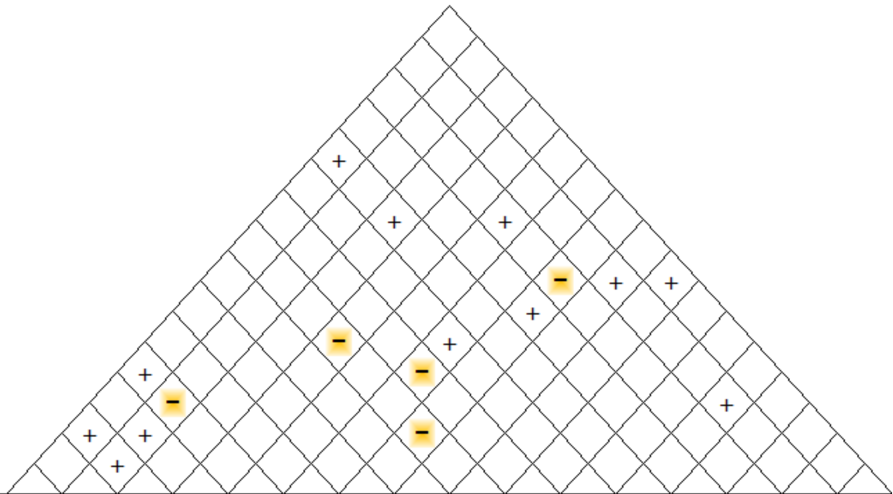
Appendix D. House of quality Client Attributes (CAs) and Engineering Characteristics (ECs)

Figure 12. House of quality

Correlations	
Positive	+
Negative	−
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼



Row #	Weight Chart	Relative Weight	Customer Importance	Maximum Relationship	Functional Requirements / Clients Attributes	Loads	Moment acting on the system	Forces	Connections	Dimensions	Opening / Closing door	Material properties	Water flow	Safety standards	Noise	Power	Water pressure	CO2 emissions	Material optimisation	Water level	Signage
					Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
					Direction of Improvement																
1		5%	10	9	Less waiting time						●		○							○	○
2		7%	14	9	More fully-loaded ships								○				▽			●	▽
3		4%	7	9	Eco-friendly system							○						●	▽		
4		7%	14	9	More ships in less time						●		○							○	○
5		7%	14	9	Safety				●					●							○
6		5%	9	9	Reduction of costs				▽			○							●		
7		4%	7	9	Increase lifetime							●									
8		6%	11	9	Stable structure	●	●	●	●	●		○								○	
9		4%	7	9	Less energy consumption						○					●					
10		4%	7	9	No disturbances						▽				●						
11			100																		
					Target				2	12.2 x	10	Reusable, recyclable and resistent	4.88	yes	50	150 000		5000		10.8	16
					Units	KN / m	KN m	KN	number	m	minutes	class	m^3 / s	yes	dB	KW	Pa	Kt	quantity	m	number
					Max Relationship	9	9	9	9	9	9	9	3	9	9	9	1	9	9	9	3
					Technical Importance Rating	49.5	49.5	49.5	117	49.5	122	72	57	63	31.5	31.5	7	31.5	44	115.5	64
					Relative Weight	5%	5%	5%	12%	5%	13%	8%	6%	7%	3%	3%	1%	3%	5%	12%	7%
					Weight Chart																

Appendix E. Morphological chart

Table 6. Morphological chart

Features	Means				
Obstruct/allow water flow	Miter gates	Swinging gates	Sliding gates	Guillotine gates	Vertically rotating gates
Material	Steel	Stainless steel	Wood	Concrete	
Facilitate accessibility	Steel bridge	Wood bridge	Suspension bridge		
Prevent falling	Barriers	Handrails	Rope over bridge	Fences	
Provide illumination	CFL	Bulbs	LED lights	Energy saving lamp	
Bear forces	I-shape Beams	Bars	Tubes		
Minimize noise	Fence	Trees	Noise-cancelling headphones for workers	Earplugs for workers	
Reduce material costs	Low quality material	Material optimization	Simple structure		
Optimise ship crossing	Traffic signs	Timer	Traffic lights		
Provide information	Signage	Information point	booklet		
Recyclable material	Precast concrete	Stainless steel	Plastics	Glass	Timber
Evaluate energy usage	Electricity monitor	Voltmeter	Wattmeter	Ammeter	
Diagnose failures	Infrared thermometers	Thermal imaging camera	Radars		
Connect different parts	Bolts	Nails	Glue		
Reduce transportation costs	Short distances	Green trucks	Gas-saving trucks	Local raw materials	
Ascend to the bridge	Elevator	Stairs	Ramp		

Monitor water loss	Water level sensor	Multiscan	Wireless passive sensor		
Manage maintenance	Planners	Maintenance schedule	Supervisor		
Reduce dust airborne	Fine water sprays	Speed limit	Soil stabilizers	Silt fence	

Appendix F. Alternatives

The different alternatives are shown below. Each alternative has a different colour and each cell is coloured if it differs from the other alternatives. If a cell is not coloured that means that the alternative has the same mean as other alternatives.

Table 7. Alternative choices

	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Material	Steel	Steel	Timber	Concrete
Obstruct/allow water flow	Miter gates	Miter gates	Miter gates	Miter gates
Facilitate accessibility	Steel bridge	Steel bridge	Wood bridge	Suspension bridge
Prevent falling	Handrails	Fences	Rope over bridge	Concrete barriers
Provide illumination	LED lights	Energy saving lamp	Bulbs	CFL
Bear forces	I-shape beams	I-shape beams	Tubes	Bars
Minimize noise	Trees	Trees	Noise-cancelling headphones for workers	Concrete fence
Reduce material costs	Material optimization	Simple structure	Low quality material	Simple structure
Optimise ship crossing	Traffic lights	Traffic signs	Timer	Traffic signs
Provide information	Signage	Information point	Information point	Booklet
Recyclable material	Stainless steel	Stainless steel	Timber	Precast concrete
Evaluate energy usage	Electricity monitor	Ammeter	Wattmeter	Voltmeter
Diagnose failures	Thermal imaging camera	Infrared thermometer	Radars	Infrared thermometer
Connect different parts	Bolts	Bolts	Nails	Anchorage of reinforcement

Reduce transportation costs	Local raw materials	Gas-saving trucks	Short distances	Gas-saving trucks
Ascend to the bridge	Stairs	Stairs	Stairs	Stairs
Monitor water loss	Water level sensor	Water level sensor	Wireless passive sensor	Multiscan
Manage maintenance	Maintenance schedule	Planners	Supervisor	Planners
Reduce dust airborne	Speed limit	Silt fence	Soil stabilizers	Fine water sprays

Appendix G. Multi-criteria decision analysis (MCDA) calculations

It consists in the selection of the best solution from different alternatives by analyzing different criteria and giving weights to them. This is done to know which criteria is the most and less important. There exist several MCDA methods for this purpose but during the development of this project there was applied the Analytical Hierarchy Process (AHP) which integrates quantitative and qualitative criteria to make a decision.
Therefore it is necessary to weight the criteria in order to know which one is the most and less important. So, in table 8 it can be seen five criteria which is compared to each other. For example if safety and sustainability are compared it can be seen that safety is 4 times more important than sustainability. This is visible by looking at the column of intensity which has the number 4 and the letter A for importance means that it is about safety. The intensity has values from 1 to 5 being 5 the most important and 1 the less important.

Table 8. Importance and intensity criteria

Criteria		Importance and intensity	
A	B	Importance	Intensity
Safety	Stability	B	2
Safety	Sustainability	A	4
Safety	Convenience	A	1
Safety	Costs	A	2
Stability	Sustainability	A	4
Stability	Convenience	A	2
Stability	Costs	A	3
Sustainability	Convenience	B	5
Sustainability	Costs	B	2

Convenience	Costs	A	4

After the different criteria and its respective weights are stated there can be made an importance and intensity matrix with each criteria and its assigned weights.

Table 9. Importance and intensity matrix

	Safety	**Stability**	**Sustainability**	**Convenience**	**Costs**
Safety	1	0.5	4	1	2
Stability	2	1	4	2	3
Sustainability	0.25	0.25	1	5	2
Convenience	1	0.5	5	1	4
Costs	0.5	0.33	2	0.25	1
SUM	4.75	2.58	16	9.25	12

Then, table 9 is normalized which means that each column is divided by its sum. Which resulted in the following table:

Table 10. Normalized importance and intensity matrix

	Safety	**Stability**	**Sustainability**	**Convenience**	**Costs**	**Priority vector**
Safety	0.21	0.19	0.25	0.11	0.17	0.19
Stability	0.42	0.39	0.25	0.22	0.25	0.30
Sustainability	0.05	0.10	0.06	0.54	0.17	0.18
Convenience	0.21	0.19	0.31	0.11	0.33	0.23
Costs	0.11	0.13	0.13	0.03	0.08	0.09
SUM	1.00	1.00	1.00	1.00	1.00	

After that, by using the normalized matrix there was calculated the average of each row which resulted in the priority vector. This vector is shown in table 9. It is important to mention that the higher the value is in the priority vector the important criteria is.

Then the priority vector was multiplied by each row which resulted in the final score of the criteria which is shown below:

Table 11. Final score of criteria

Final score
0.18
0.32
0.19
0.21
0.10

Before doing any calculation with the final score it is necessary to have a comparison matrix which is shown below:

Table 12. Comparison matrix

Criteria	Safety	Stability	Sustainability	Convenience	Costs
Measuring unit	Score card	Score card	Score card	Minutes	Euros(€)
Alternative 1	1	1	2	20	700
Alternative 2	1.5	2	2.7	30	750
Alternative 3	4	2.5	3	25	600
Alternative 4	2.5	3	3.5	30	625
SUM	9	8.5	11.2	105	2675

As it can be seen in table 12 there were stated the different alternatives with the criteria and assigned the performance of each one. The measuring unit for each criteria is shown in the aforementioned table and are: score cards which means the less the value the better the alternative, minutes because it is aimed to have reduced waiting times and euros which of course are aimed to be as less as possible.
After the comparison matrix is done, the normalization of this matrix needs to be executed. It was done in the same way as the normalized importance and intensity matrix. The normalized comparison matrix is shown below:

Table 13. Normalized comparison matrix

Criteria	Safety	Stability	Sustainability	Convenience	Costs
Measuring unit	Score card	Score card	Score card	Minutes	Euros(€)
Alternative 1	0.11	0.12	0.18	0.19	0.26
Alternative 2	0.17	0.24	0.24	0.29	0.28
Alternative 3	0.44	0.29	0.27	0.24	0.22
Alternative 4	0.28	0.35	0.31	0.29	0.23
SUM	1.00	1.00	1.00	1.00	1.00

When the final score vector and the normalized comparison matrix is done, the final score vector is multiplied by each row to obtain the scores of the alternatives. As it was mentioned before the lower the score the better the alternative which resulted in the following rankings:

Table 14. Alternative scores and ranking

Final	Score	Ranking
Alternative 1	0.16	1
Alternative 2	0.24	2
Alternative 3	0.30	3
Alternative 4	0.31	4

Appendix H. Verification

Table 15. Verification

ID	Description	Function	Execution
1	Gate	Regulate water level	To allow ships going through the gate the doors will be opened and closed

1.1		Width gate	This was a given requirement which has the value of 12.2meters
1.2		Length per gate	This value was calculated by taking into account the angle and the width of the gate
2	Traffic lights	Manage crossing time	This lights will help ships to know when they can cross, therefore the crossing time will be less than 50 minutes
2.1		Manage waiting time	Once the ships are aware of when they can cross, this will reduce the waiting that will be less than 30 minutes
3	Water level sensors	Precise measurement	This sensors will be placed strategically in the water to know if there is or not enough water to allow the crossing of ships
4	Stairs	Facilitate accessibility	To allow people to reach the bridge this stairs will be placed in the ground which is below and next to the bridge Cost: 1000 euros
5	Footbridge	Facilitate crossing from one side to the other	Due to the dimensions of the lock chamber it is important to facilitate accessibility from one side to the other because it will improve accessibility. This will be done by placing the footbridge on the top of the lock gate
5.1		Width bridge	According to ivp Delft (2015) the minimum width is 1.2 meters to allow the crossing of two people at the same time
6	Handrails	Safe for people	The handrails will be placed in order to ensure that people do not fall into the water.
6.1		Height	According to ivp Delft (2015) the minimum height is 1m. For safety reasons it was decided to have a 1.5 m height for the handrails. Cost: 90 euros per meter
7	Signage	Informative for workers and users	The signs should provide information for emergency cases. The maximum number of people which can cross the footbridge.
7.1		Adequate number of signages	There should be signages that communicate the actual water level inside the chamber. Signages that could help to know if the ships can pass or if they have to stop.
8	Beams	Bear water pressure and forces	The used beams must bear all the forces acting on the system. 3 beams HEA100 for the bridge. 10 beams HEA240 for the gate and 1 beam HEA180 for the diagonal were the beam profiles used for the complete system. Costs:

			44.65 euros per HEA100 109.18 euros per HEA240 72.59 euros per HEA180
9	Plates	Bear water pressure and forces	Plates with different dimensions will be placed in the bridge and gate because each design requires a different amount and dimensions of plates.
10	Bolts	Connect the different parts	The bolts should allow to have a strong connection between the footbridge and the lock gate. Therefore 4 bolts of M12 dimensions and 4.6 class will be implemented.
11	Thermal image camera	Monitoring and diagnosing structure	They serve to identify early problems in the construction. It is useful for building inspections because the problem can be corrected before becoming more serious and costly. Depending on the quality of the resolution the costs can vary. Cost: 1 200 euros (FLIR E4) - Average quality
12	Electricity monitor	Measure energy consumption	Because it is wanted to know how much energy is the complete system consuming this will be placed strategically to measure each device.
13	LED lighting	Reduce energy consumption	To ensure safety as well in the nights and dark days by save money and be friendly with the environment. Cost: 2.25 euros per bulb
13.1		High lifespan	The aim is to have a lifespan as long as possible which in this case is 10000 hours
14	Trees	Minimize noise	To avoid discomfort caused by noise there will be planted several trees around the lock chamber
14.1		Improve landscape	To create a nice feeling of harmony and well-being with nature while looking at the lock chamber. At the same time contributing to the environment.

Appendix I: Structural Mechanics

The sluice which is located at the IJssel side of the lock chamber has to be designed. In order to do that the different forces acting on the miter gates should be considered. Essentially, the water pressure acting on the gate located at the IJssel side. In the graph 13 the extremely high water level and the low water level of the Twente Canal are represented . The extremely high water level at the Twente Canal side was considered to act in the gate which will be designed. Because the water level increases through the years and it was decided to increase the height of the gate by 2.7m. The resulting height of the gate was 13.5 m. It is important to mention that the minimum water depth should be 4 m in order to allow the navigation of fully loaded ships.

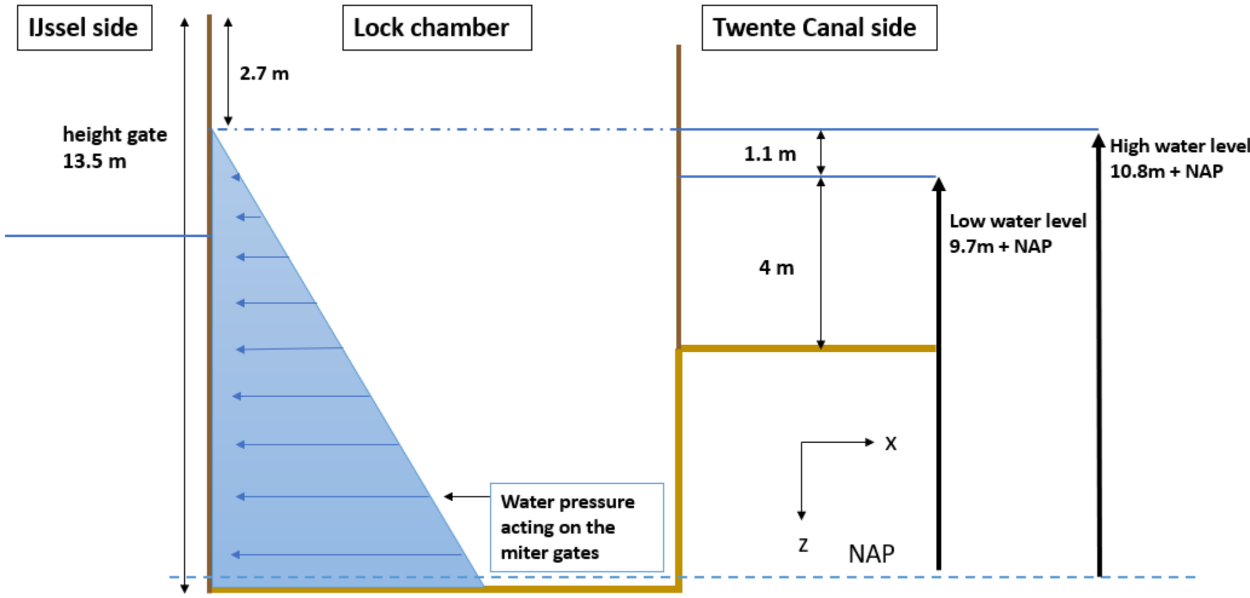


Figure 13. Cross section of the lock chamber and water levels from the Twente Canal

I.1. Forces acting in the lock gate

In order to calculate the forces acting on the gate a Matlab code was created. The mentioned code use the Macaulay's Method for continuous beams and can be found in Appendix J. As it can be seen in figure 14 there is the schematization of Macaulay's Method which was used to calculate the reaction forces due to the stress of water which in this case is equal to $108kN/m^2$.
The application of such method gave as a result the reactions forces acting on each beam which are detailed below.

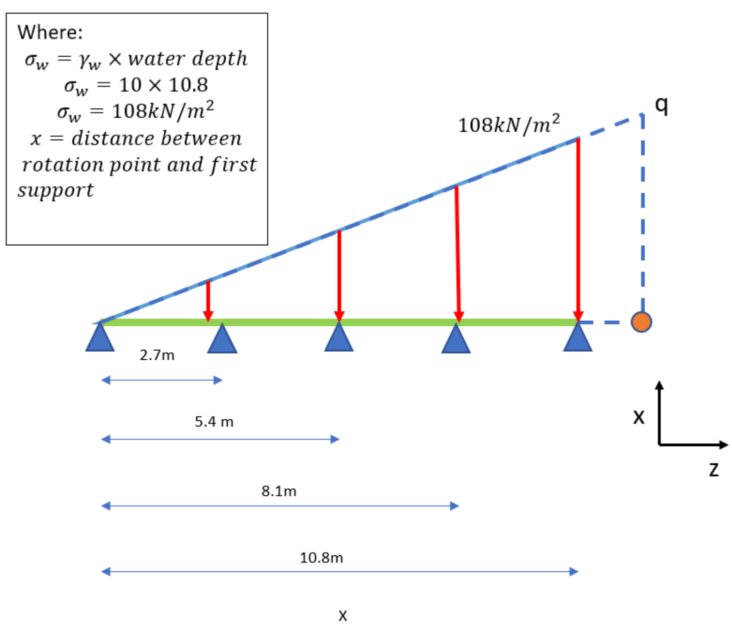


Figure 14. Schematization of Macaulay's Method

Calculation of reaction forces

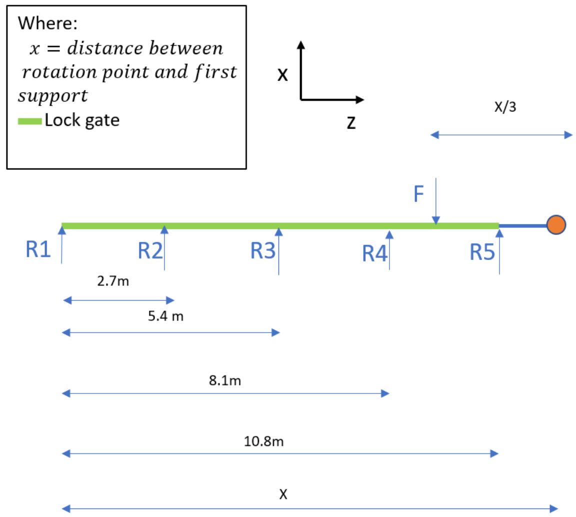


Figure 15. Forces involved in the calculations

$$\sum M = 0$$

$$M(x) = R1(X-0) + R2(X-2.7) + R3(X-5.4) + R4(X-8.1) + R5(X-10.8) - F(\frac{X}{3})$$

$$M(X) = R1(X) + R2(X-2.7) + R3(X-5.4) + R4(X-8.1) + R5(X-10.8) - \frac{5X^3}{3}$$

Then we integrate the moment equation.

$$EI\varphi(X) = \frac{R1X^2}{2} + \frac{R2(X-2.7)^2}{2} + \frac{R3(X-5.4)^2}{2} + \frac{R4(X-8.1)^2}{2} + \frac{R5(X-10.8)^2}{2} - \frac{5X^4}{12} + C1$$

After that the rotation equation is integrated.

$$-EI\delta(X) = \frac{R1X^3}{6} + \frac{R2(X-2.7)^3}{6} + \frac{R3(X-5.4)^3}{6} + \frac{R4(X-8.1)^3}{6} + \frac{R5(X-10.8)^3}{6} - \frac{5X^5}{60} + C1X + C2$$

$$\sum V = 0$$

$$R1 + R2 + R3 + R4 + R5 - F = 0$$

Boundary conditions

$X = 0$ $\delta = 0$

$X = 2.7$ $\delta = 0$

$X = 5.4$ $\delta = 0$

$X = 8.1$ $\delta = 0$

$X = 10.8$ $\delta = 0$

$X = 10.8$ $M = 0$

$\sum V = 0$

Then it is necessary to fill in the above equations by replacing each unknown with the correspondent boundary condition. It is important to mention that in this method negative values and zero values are not taken into account. After that we will end up with six equations with R1,R2,R3,R4,R5,C1 and C2 as unknows.

After solving the different equations the resulting values for C2 was zero and for C1 was -2.4252 . In addition the values of the support unknowns(R1,R2,R3,R4,R5) are shown in the following table.

Table 16. Results of the reaction forces

Support 1 $(\frac{kN}{m^2})$	Support 2 $(\frac{kN}{m^2})$	Support 3 $(\frac{kN}{m^2})$	Support 4 $(\frac{kN}{m^2})$	Support 5 $(\frac{kN}{m^2})$
5.6411	75.5036	135.3857	257.7536	108.9161

Then it was necessary to calculate other forces that act on the lock gate. First some values for the width, length and x height were calculated in order to calculate the other forces acting on the lock gate. Figure 16 shows the schematization of the calculated values.

Assumptions

- The angle of 15° was assumed in order to perform the calculations the mentioned angle will change after the optimization.
- It is important to mention that for the value of F the highest force from table 16 was taken because if the system can handle this force it is feasible to assume that will support lower forces.

$$width(m) = \frac{width\ of\ chamber}{2} = \frac{12.2}{2} = 6.1\ m \qquad \text{(equation 1)}$$

$$length\ gate(m) = \frac{width}{\cos(\alpha)} = \frac{6.1}{\cos(15)} = 6.315\ m \qquad \text{(equation 2)}$$

$$x\ height(m) = \sqrt{length\ gate^{2} - width^2} = \sqrt{6.315^2 - 6.1^2} = 1.63\ m \qquad \text{(equation 3)}$$

$$q_{beam}\left(\frac{kN}{m}\right) = F_{support\ 4} \times 1 = 257.7536 \times 1 = 257.7536\,\frac{kN}{m} \qquad \text{(equation 4)}$$

$$\sum M = 0 \qquad \text{(equation 5)}$$

$$M_{plate} - V_{force} * length\ gate - H_{force} * x\ heigth = 0 \qquad \text{(equation 6)}$$

$$M_{plate}(kNm) = q_{beam} \times \frac{lenght\ gate^2}{2} = 257.75 \times \frac{6.315^2}{2} = 5139.44\ kNm \qquad \text{(equation 7)}$$

$$V_{force} = H_{force} * \sin(\alpha) \qquad \text{(equation 8)}$$

$$M_{plate} - H_{force} * \sin(\alpha) * length\ gate - H_{force} * x\ heigth = 0 \qquad \text{(equation 9)}$$

$$H_{force}(kN) = \frac{M_{plate}}{length\ gate \times \sin(\alpha) + x\ height} = \frac{5139.44}{6.315 \times \sin(15) + 1.63} = 1574.37\ kN \qquad \text{(equation 10)}$$

$$N_{force}(kN) = H_{force} \times cos(\alpha) = 1574.37 \times \cos(15) = 1520.72\ kN \qquad \text{(equation 11)}$$

$$V_{force}\ (kN) = H_{force} \times sin(\alpha) = 1574.37 \times \sin(15) = 407.48\ kN \qquad \text{(equation 12)}$$

All these values can be visualized in the following figure:

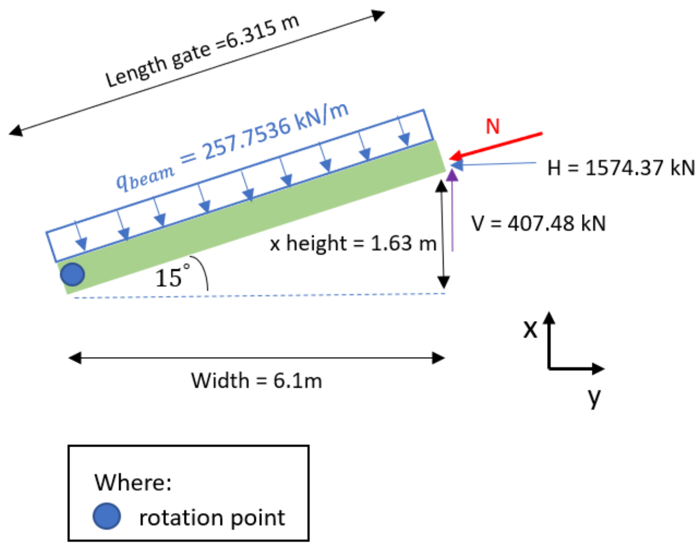


Figure 16. forces acting on the lock gate

Where:

$width = width\ of\ one\ miter\ gate$

$M_{plate} = Moment\ caused\ by\ \ the\ rotation\ point$

I.2. Plate thickness calculations

As it was mentioned before the highest force was used. Therefore, the moment for the calculation of the thickness of the plate will consider the force F. The value of the moment was obtained by plotting a graph in Matlab using the support forces calculated before as figure 17 shows.

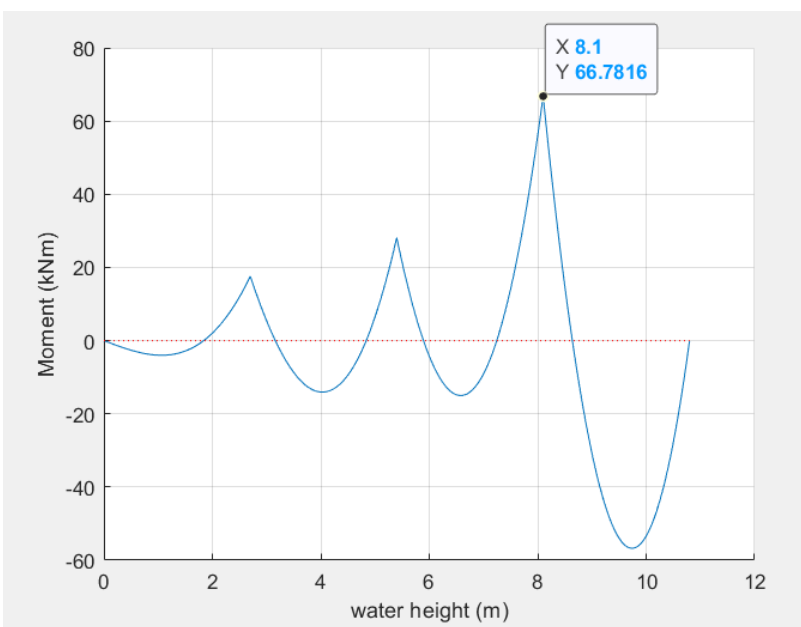


Figure 17. Moment Diagram due to the reaction forces

The thickness of the plate is calculated as follows:

$W(mm^3) = \frac{I}{e}$ (equation 13)

$I(mm^{4)} = \frac{1}{12} \times l \times h^3$ (equation 14)

$e(mm) = \frac{1}{2} h$ (equation 15)

$\sigma_{plate}\left(\frac{N}{mm^2}\right) = \frac{M}{W} = \frac{M_{plate} \times e}{I} \leq fyd$ (equation 16)

$\frac{M_{plate} \times e}{I} = fyd$

$\frac{M_{plate} \times \frac{1}{2} h}{\frac{1}{12} \times l \times h^3} = fyd$

After the respective calculations an equation for h was obtained and is shown as follows:

$h(mm) = \sqrt{\frac{M_{plate}}{\frac{1}{6} * b * fyd}}$ (equation 17)

$h(mm) = \sqrt{\frac{66.7816 \times 10^6}{\frac{1}{6} * (1 \times 10^3) * 235}}$

$h = 41.29mm = 0.041m$

Where:

$I = moment\ of\ inertia$

$e = distance\ to\ the\ center\ of\ gravity$

$h = plate\ thickness$

$fyd = 235\ N/mm^2$

$l = b = 1m(Assumption)$

$W = moment\ of\ resistance$

$\sigma_{plate = stress}$

$M_{plate} = 66.7816\ kNm = 66.7816 \times 10^6\ Nmm(This\ value\ was\ obtained\ from\ figure\ 17)$

I.3. Second order calculations

It is important to consider all the forces acting on the gate. In previous steps only the loads in the beams and plate caused by the water were taken into account. The second order effect will consider the other forces acting on the door. The normal force caused by the contact with the other door should be taken into account in order to obtain $\frac{S}{R}$, which should be smaller than 1. The Rankine Gordon was used and the following formulas were applied for the different calculations:

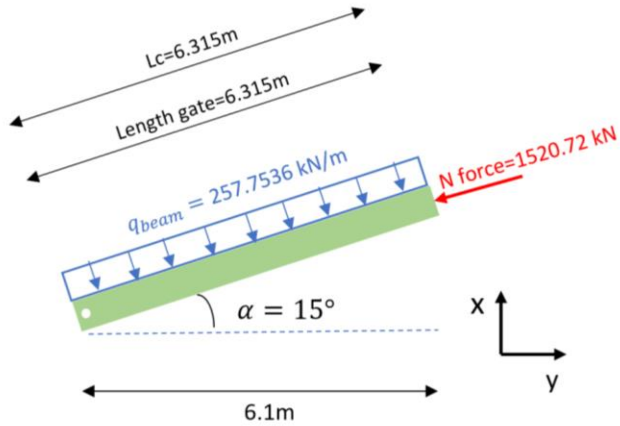


Figure 18. Schematization of Second Order Effect

Assumptions:

- It is important to mention that the chosen profile for these calculations was HEA 100, but after the optimization the most accurate profile will be used in the calculations. In the meantime the group worked with the values regarding profile HEA 100 which are:
  $I = 3.492 \times 10^{-6}\ m^4$
  $A = 2.124 \times 10^{-3}\ m^2$
  $W_{el,y} = 7.276 \times 10^{-5} m^3$

$$M_{beam}(kNm) = \frac{1}{8} * q_{beam} * length\ gate^{2} = \frac{1}{8} * 257.75 * 6.315^2 = 1283.859\ kNm \qquad \text{(equation 18)}$$

$$F_c(kN) = \frac{\pi^{2} * EI}{L_c^{2}} = \frac{\pi^2 * 2.1\times10^8 * 3.492\times10^{-6}}{6.315^2} = 181.49\ kN \qquad \text{(equation 19)}$$

$$F_v(kN) = N_{force} = 1520.72\ kN \qquad \text{(equation 20)}$$

$$n = \frac{F_c}{F_v} = \frac{181.49}{1520.72} = 0.119 \qquad \text{(equation 21)}$$

$$\sigma_{beam}\left(\frac{kN}{m^2}\right) = \frac{N_{force}}{A} + \left(\frac{n}{n-1} * \frac{M_{beam}}{W_{el,y}}\right) \leq fyd \qquad \text{(equation 22)}$$

$$\sigma_{beam}\left(\frac{kN}{m^2}\right) = \frac{1520.72}{2.124\times10^{-3}} + \left(\frac{0.119}{0.119-1} * \frac{1283.859}{7.276\times10^{-5}}\right) = -1.667 \times 10^6\ \frac{kN}{m^2}$$

$$\sigma_{ED}(kN/m^2) = \frac{N_{force}}{A} = \frac{1520.72}{2.124\times10^{-3}} = 715969.87\frac{kN}{m^2} \qquad \text{(equation 23)}$$

$$f_c\left(\frac{kN}{m^2}\right) = \frac{F_c}{A} = \frac{181.49}{2.124\times10^{-3}} = 85447.27\ \frac{kN}{m^2} \qquad \text{(equation 24)}$$

$$\frac{1}{fsys} = \frac{1}{f_c} + \frac{1}{fyd} = \frac{1}{85447.27} + \frac{1}{235000} = 1.596 \times 10^{-5} \qquad \text{(equation 25)}$$

$$\frac{1}{fsys} = \frac{1}{1.596 \times 10^{-5}} = 62656.6416$$

$$\frac{S}{R} = \frac{\sigma_{ED}}{fsys} = \frac{715969.87}{62656.6416} = 11.427 \qquad \text{(equation 26)}$$

As it can be seen the result of $\frac{S}{R}$ is not less than 1 but it is not a problem now because as it was mentioned before this values are the result of assumptions that means that all the results will change when the optimization is done.

Where:
$E = 2.1 \times 10^{8}\ (kN/m^{2})$
$I = moment\ of\ inertia\ (depends\ on\ HEA\ profile)$
$A = cross\ section\ beam\ (depends\ on\ HEA\ profile)$
$W_{el,y} = moment\ of\ resistance\ (\ depends\ on\ HEA\ profile)$
$fyd = 235000 kN/m^{2}$
$L_c = length\ gate$
$F_c = critical\ force$
$F_v = normal\ force$
$n = factor\ of\ critical\ force\ over\ normal\ force$
$\sigma_{ED} = stress\ caused\ by\ the\ Normal\ force$
$N_{force} = Normal\ force$

I.4. Maximal Deflections in lock gate

According to Gulvanessian et al.(2004,pp. 11-12) the maximum allowed deflections can be calculated with the following equations. By using them, the values for the maximum deflections of the plate and the beam can be calculated.
Assumption:
Even though, the plate and beams have differences in the way that they deflect the mentioned source states that the values for the beams and plates deflections should be less than $\frac{l}{300}$.
The calculations were performed as follows:

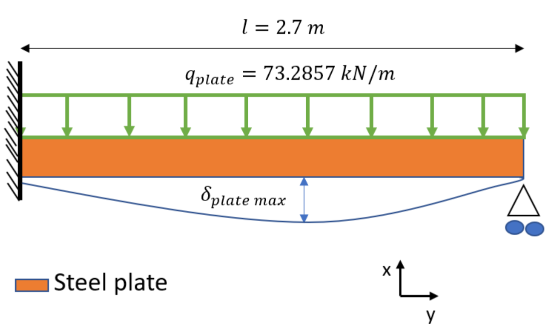


Figure 19. Maximal deflection plate

$$\delta_{Max,plate}(m) = \frac{l}{300} = \frac{2.7}{300} = 0.009\ m \quad \text{(equation 27)}$$

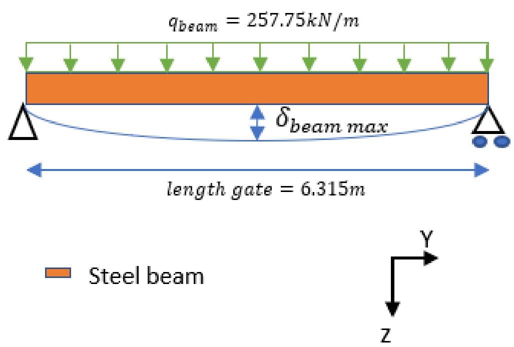


Figure 20. Maximal deflection beam

$$\delta_{Max,beam}(m) = \frac{length\ gate}{300} = \frac{6.315}{300} = 0.02105\ m \qquad \text{(equation 28)}$$

Where :
$l\ =\ distance\ between\ beams$
$length\ gate = 6.316\ m$
$\delta_{Max}\ (m) = \frac{l}{300}$ $\quad retrieved\ \ from\ a\ handbook\ (Gulvanessian\ et\ al.,2004, pp. 11 - 12)$

I.5. Actual deflections in the lock gate

In the previous step the maximal allowed deflection was calculated. Then, it is possible to calculate the real deflections that the beams and plates will experience and to notice if they fall within the limits.

Assumption

- As it was mentioned before the value of the moment of inertia is assumed with the profile HEA 100.

$$I_{beam} = 3.492 \times 10^{-6}\ m^4$$

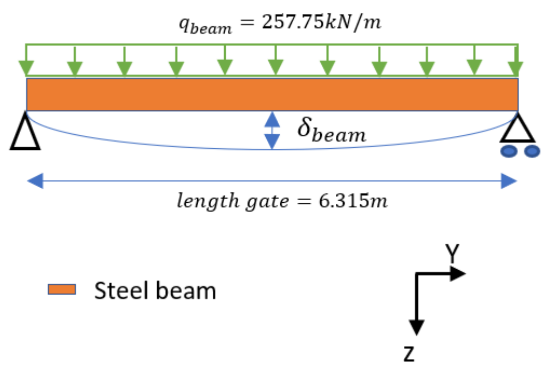


Figure 21. Deflection of the beam

$$\delta_{beam}(m) = \left(\frac{n}{n-1}\right) \times \frac{5}{384} \times \frac{q_{beam} \times length\ gate^4}{EI,beam} \qquad \text{(equation 29)}$$

$$\delta_{beam}(m) = \left(\frac{0.12}{0.12-1}\right) \times \frac{5}{384} \times \frac{257.75 \times 6.315^4}{2.1 \times 10^8 * 3.49 \times 10^{-6}} = -0.99\ m$$

$$M_{plate}(kNm) = \frac{1}{8} * q_{plate} * l^2 \qquad \text{(equation 30)}$$

$$q_{plate}\left(\frac{kN}{m}\right) = \frac{M_{plate} * 8}{l^2} = \frac{66.7816 * 8}{2.7^2} = 73.2857\ \frac{kN}{m} \qquad \text{(equation 31)}$$

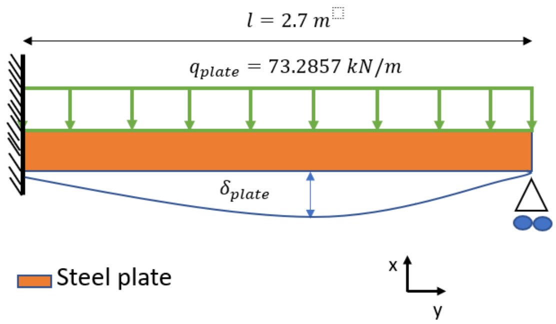


Figure 22. Deflection of the steel plate

$$\delta_{plate}(m) = \frac{1}{192} \times \frac{q_{plate} x l^4}{EI, plate} \qquad \text{(equation 32)}$$

$$\delta_{plate}(m) = \frac{1}{192} \times \frac{73.2857 \times 2.7^4}{2.1 \times 10^8 * 0.067} = 1.44 \times 10^{-6} m$$

For the calculation of the I_{plate}:

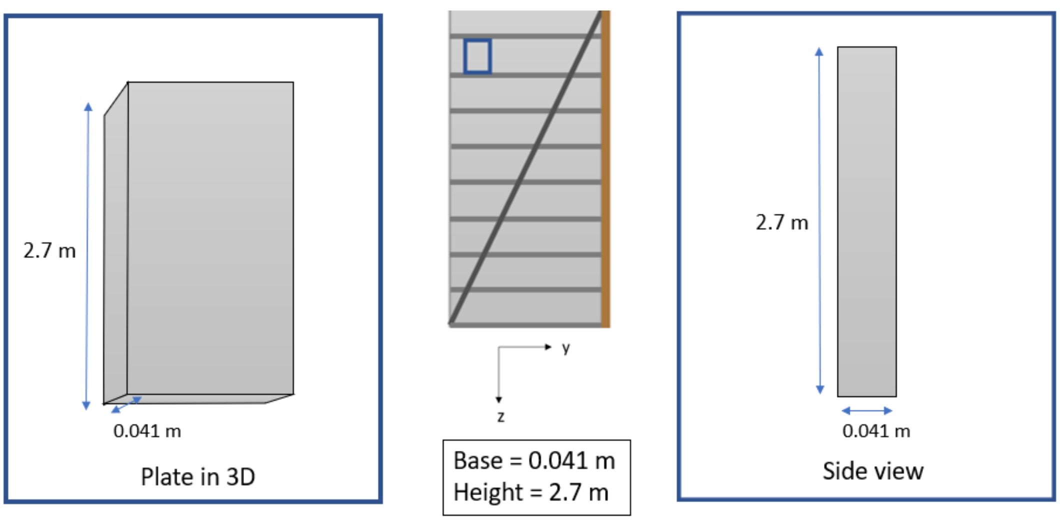


Figure 23. Steel plate from different views

$$I_{plate}\,(m^4) = \frac{1}{12} \times b \times h^3 = \frac{1}{12} \times 0.041 \times 2.7^3 = 0.06725\ m^4 \qquad \text{(equation 33)}$$

$$\frac{S}{R} beam = \frac{\delta\ \ _{beam}}{\delta_{Max,beam}} \qquad \text{(equation 34)}$$

$$\frac{S}{R} beam = \frac{-0.99}{0.02105} = -47.0309$$

Where:

$l = distance\ between\ beams$

$n = calculated\ in\ appendix\ I.3$

$I\ \ _{beam} = moment\ of\ inertia\ (depends\ on\ HEA\ profile)$

$I\ \ _{plate} = moment\ of\ inertia\ of\ the\ plate$

$\frac{S}{R} beam = factor\ of\ actual\ deflection\ over\ maximum\ deflection$

I.6. Optimization of the lock gate

It is important to mention that all the equations stated in the previous steps were introduced in Matlab in order to develop the optimization of the lock gate.

I.6.1. Optimization profiles and angle

As mentioned before the angle of 15 and the HEA 100 profile will be optimized in this part of the project. For this sake, it was decided to consider the angles from 1 to 25 and the profiles from HEA 100 to HEA 400. For instance, the Matlab code uses the first HEA 100 profile and then perform the calculations for each one of the angles with this profile. Which means for that profile 25 calculations are performed and then the calculations will be performed with the next HEA profile with the 25 angles. This is repeated successively. Until the profile HEA 400 is reached which will also result in 25 calculations due to the 25 angles. Each angle and profile was used to calculate all the previous steps (see appendix I.1 to I.5), the difference is that the angle and HEA profile will change. This lead to the figure 25, in which only the angles from 15-20 can be visualized. For the graph, the angle is plotted in the x-axis and in the y-axis the minimum strength of the steel. The Matlab code can be visualized in Appendix J. Only the values below the minimal strength of steel were considered.

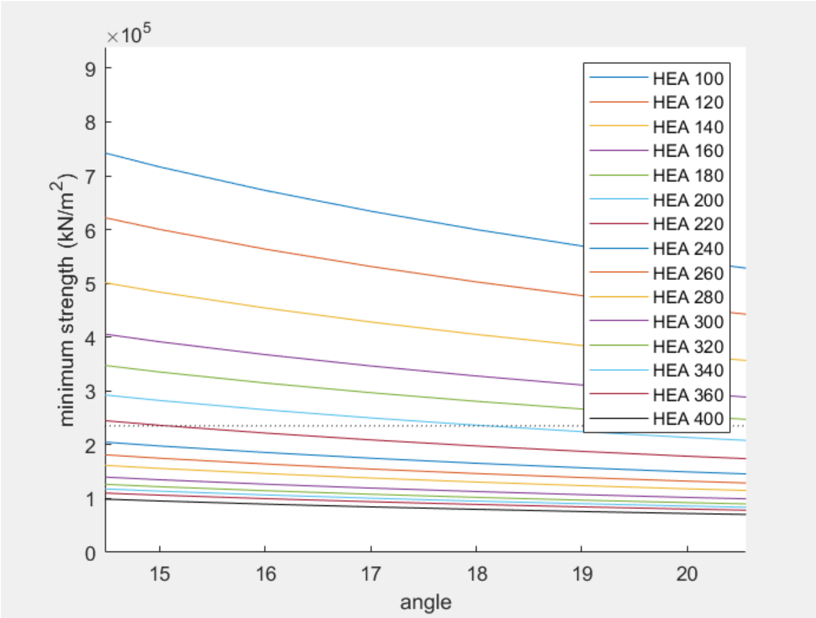


Figure 24. Graph of the angle against minimum strength

I.6.2. Optimization of the beams

The number of beams was optimized by considering the profiles from HEA 300 to HEA 240. For the optimization some parameters were calculated. The Matlab code was proved with each of the following parameters “number of beams” and “HEA profile” will lead to the following results given in Table(). The number of beams which used less steel is considered optimal. Therefore, the optimal number of beams should be 10.

Table 17. Optimization of the lock gate

Number of beams	HEA profile	Plate thickness(m)	S/R strength beams	Total volume(m^3)
3	300	0.1436	0.93430	12.9577
4	300	0.0734	0.87590	6.9485
5	280	0.0527	0.89420	5.1398
6	280	0.0413	0.74100	4.2126
7	260	0.0334	0.73130	3.514
8	260	0.0286	0.63120	3.1591
9	240	0.0245	0.83840	2.7751
10	**240**	**0.0219**	**0.74680**	**2.5943**

I.7. Appendix Bridge Design

I.7.1.Mandatory loads on the pedestrian bridge

According to ipv Delft (2016) this mandatory loads needs to be taken into account when designing a footbridge and are calculated below:

$$\sigma_{bridge,length} = 2.0 + \frac{120}{length\ bridge + 30} \qquad \text{(equation 35)}$$

$$\sigma_{bridge,length} = 2.0 + \frac{120}{6.41+30} = 5.30\ kN/m^2$$

$$\sigma_{bridge,width} = 2.0 + \frac{120}{width\ bridge + 30} \qquad \text{(equation 36)}$$

$$\sigma_{bridge,width} = 2.0 + \frac{120}{1.20+30} = 5.85 kN/m^2$$

After the respective calculations are done, the values for the stresses are known and it was decided to work with the highest stress value which in this case is $5.85 kN/m^2$ to ensure that the bridge is strong enough.

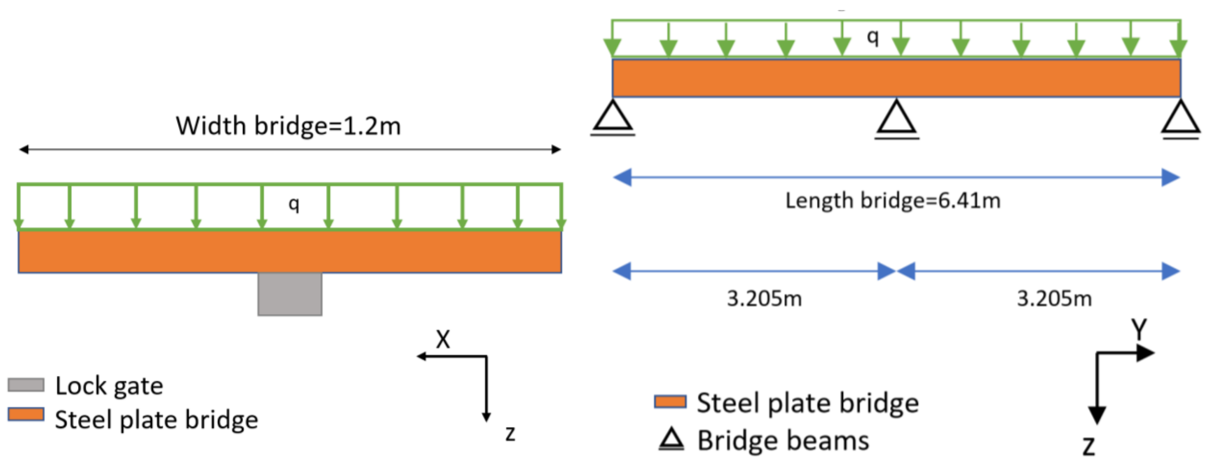


Figure 25. Schematization of the bridge

I.7.2. Plate thickness calculations

When the design stress is known, then it is possible to calculate the load, moment and thickness of the steel plate. The different formulas that were used to calculate them are shown below. It is important to mention that the calculations were performed with the assumption of 3 beams placed in the bridge.

$q_{plate}(kN/m) = \sigma_{bridge} \times 1$ (equation 37)

$q_{plate}\left(\frac{kN}{m}\right) = 5.85 \times 1 = 5.85\ kN/m$

$M_{plate}(kNm) = \frac{1}{8} \times q_{plate} \times l^2$ (equation 38)

$M_{plate}(kNm) = \frac{1}{8} \times 5.85 \times 3.205^2 = 7.51\ kNm$

$W(m^3) = \frac{I}{e}$ (equation 39)

$I(m^{4)} = \frac{1}{12} \times l \times h^3$ (equation 40)

$e(m) = \frac{1}{2} h$ (equation 41)

$\sigma_{bridge}\left(\frac{kN}{m^2}\right) = \frac{M}{W} = \frac{M_{plate} \times e}{I} \leq fyd$ (equation 42)

$\frac{M_{plate} \times e}{I} = fyd$

$\frac{M_{plate} \times \frac{1}{2} h}{\frac{1}{12} \times l \times h^3} = fyd$

After the respective calculations an equation for h was obtained and is shown as follows:

$h(m) = \sqrt{\frac{6 \times M_{plate}}{fyd \times l}}$ (equation 43)

$h(m) = \sqrt{\frac{6 \times 7.51}{235000 \times 3.205}} = 7.73 \times 10^{-3} m = 7.73mm$

Where:

$\sigma_{bridge = 5.85 kN/m^2}$

$l = distance\ between\ beams\ (depends\ on\ number\ of\ beams, but\ in\ this\ case\ it\ was\ assumed\ 3\ beams)$

$I = moment\ of\ inertia$

$e = distance\ to\ the\ center\ of\ gravity$

$h = plate\ thickness$

$fyd = 235000 kN/m^2$

I.7.3. Forces acting on the beams of the footbridge

In this section the assumption that was made is that there are no normal forces acting on the beam. Therefore the below formulas were used to calculate the uniform distributed load and the moment acting on the beams. This formulas were again introduced in MATLAB because of the optimisation.

$q_{beam\ (kN/m) = \sigma_{bridge} \times l}$ (equation 44)

$q_{beam\ (kN/m) = 5.85 \times 3.205} = 18.75\ kN/m$

$M_{beam}(kNm) = \frac{1}{2} \times q_{beam} \times w^2$ (equation 45)

$M_{beam}(kNm) = \frac{1}{2} \times 18.75 \times 1.2^2 = 13.5\ kNm$

Where

$\sigma_{bridge=5.85kN/m^2}$

$l = distance\ between\ beams\ (depends\ on\ number\ of\ beams)$

$w = width\ bridge\ (m)$

I.7.4. Maximum deflections in the bridge

The maximum deflection factor is essential because it determines if a structure is stable or not. To calculate the maximum deflection of the plate and the beams in the bridge, the following formulas were used. Once again this formulas were implemented in MATLAB due to the optimisation.

$\delta_{Max,plate}(m) = \frac{l}{300}$ (equation 46)

$\delta_{Max,plate}(m) = \frac{3.205}{300} = 0.011m$

$\delta_{Max,beams}(m) = \frac{\frac{1}{2}w}{300} = \frac{w}{600}$ (equation 47)

$\delta_{Max,beams}(m) = \frac{1.2}{600} = 2 \times 10^{-3}m$

Where

$l = distance\ between\ beams\ (depends\ on\ number\ of\ beams)$

$w = width\ bridge\ (m)$

I.7.5. Actual deflections in the bridge

In the previous section (Appendix I.7.4) the maximum allowed deflections in the bridge were calculated. However it is pivotal to know the actual deflections that will occur in the plate and beams. This was calculated with the following formulas that were implemented in MATLAB. This formulas were taken from the Reader Structural Mechanics Module 4 because the forget me not was applied.

Plate deflection

$EI, plate = E \times I$ (equation 48)

$EI, plate = 2.1 \times 10^8 \times \frac{1}{12} \times h \times l^3$ (equation 49)

$EI, plate = 2.1 \times 10^8 \times \frac{1}{12} \times (7.73 \times 10^{-3}) \times 3.205^3$

$EI, plate = 4453501.923\ kNm^2$

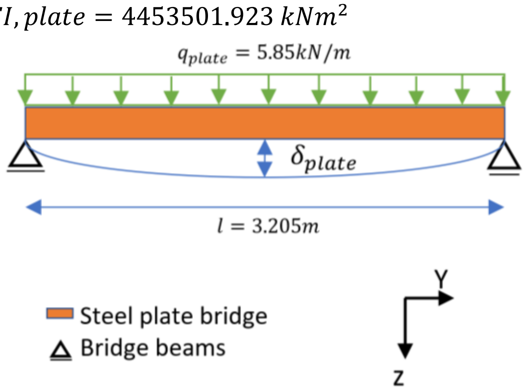


Figure 26. Deflection of the plate

$$\delta_{plate}(m) = \frac{5}{384} \times \frac{q_{plate} \times l^4}{EI,plate} \qquad \text{(equation 50)}$$

$$\delta_{plate}(m) = \frac{5}{384} \times \frac{5.85 \times 3.205^4}{4453501.923} = 1.80 \times 10^{-6} m = 1.80 \times 10^{-3} mm$$

Beams deflection

$$EI, beams = E \times I \qquad \text{(equation 51)}$$

$$EI, beams = 2.1 \times 10^8 \times 3.492 \times 10^{-6}$$

$$EI, beams = 733.32\ kNm^2$$

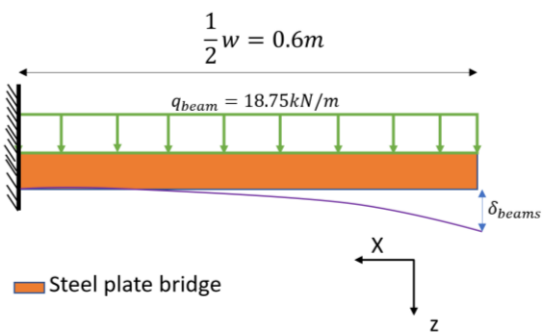


Figure 27. Deflection of the beams

$$\delta_{beams}(m) = \frac{1}{8} \times \frac{q_{beam} \times (\frac{1}{2}w)^4}{EI,beams} \qquad \text{(equation 52)}$$

$$\delta_{beams}(m) = \frac{1}{8} \times \frac{18.75 \times 0.6^4}{733.32} = 4.14 \times 10^{-4} m = 0.41mm$$

Where

$l = distance\ between\ beams\ (depends\ on\ number\ of\ beams)$

$w = width\ bridge\ (m)$

$E = 2.1 \times 10^8\ (kN/m^2)$

$I = moment\ of\ inertia\ (depends\ on\ HEA\ profile, in\ this\ case\ it\ was\ assumed\ HEA100 = 3.492 \times 10^{-6}\ m^4)$

$q_{plate} = see\ appendix\ I.7.2$

$q_{beam} = see\ appendix\ I.7.3$

I.8. Optimisation footbridge design

The main idea of the whole optimisation process is to find a balance between number of beams, plate thickness and HEA profile and also taking into account the allowed deflection. Therefore, as it was mentioned before the different formulas needed for the project that were explained before (see appendix I.7.1 - I.7.5) were introduced in MATLAB to do several calculations until the optimal design was found. The figure below shows a plot of deflection against HEA profile. The different lines that are plotted with several colours represent the number of beams used which were from 2 beams till 10 beams. This multiple beams were implemented to have a better insight between the deflection and HEA profiles. Therefore as it can be seen in figure 28 all of the lines and profiles are within the accepted limits, therefore it was decided that HEA=100 was the optimum profile which means that the previous assumption regarding the profile of the beam was correct (see appendix I.7.5).

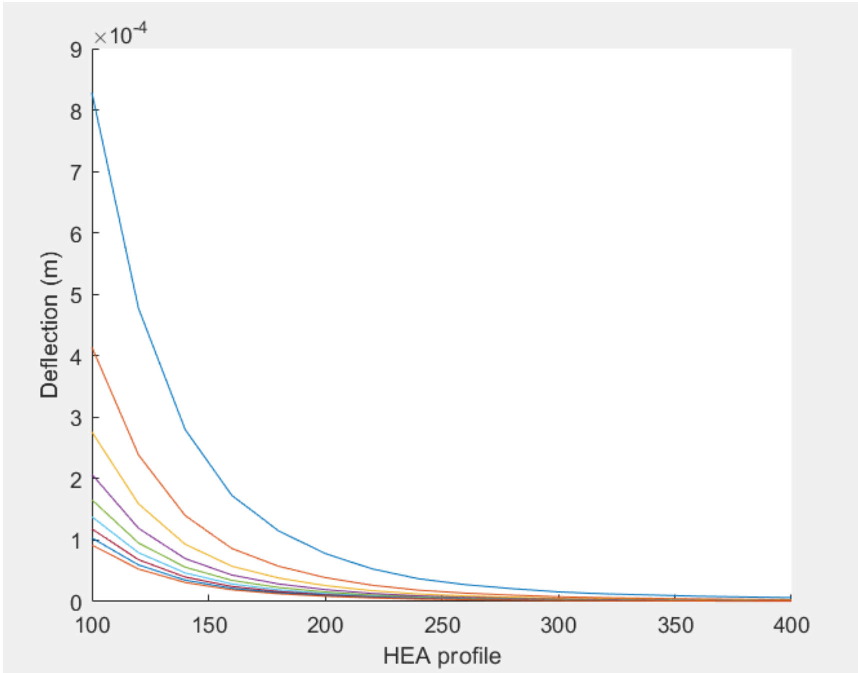


Figure 28. Graph of HEA profiles against deflection

When the HEA optimum profile is known, then it is necessary to compare different number of beams using only HEA=100 to know which exact number of beams is the optimum. Which resulted in the following table:

Table 18. Optimisation for number of beams

Number of beams	Plate thickness (m)	S/R deflection beams	Total volume (m^3)
2	0.0109	0.4142	0.1114
3	**0.0077**	**0.2071**	**0.1003**
4	0.0063	0.1381	0.103
5	0.0055	0.1035	0.1101
6	0.0049	0.0828	0.1192
7	0.0045	0.069	0.1296
8	0.0041	0.0592	0.1406
9	0.0039	0.0518	0.1521
10	0.0036	0.046	0.164

The optimum design is considered to be the one which is stable and uses less amount of material. Therefore Table 18 shows that the optimum number of beams is 3 because by using this amount of beams the bridge will need less amount of steel. Therefore the assumed 3 beams for the previous calculations were correct.

When knowing the optimum number of beams and HEA profile it is possible to know the exact maximum deflections allowed in the bridge which are:

$$\delta_{Max,plate}(m) = \frac{l}{300} = \frac{3.205}{300} = 0.011m$$

$$\delta_{Max,beams}(m) = \frac{\frac{1}{2}w}{300} = \frac{w}{600} = \frac{1.2}{600} = 2 \times 10^{-3}m$$

I.9. Diagonal beam

A diagonal beam was included in each gate to ensure the stability of the whole structure. The different formulas used in the diagonal calculations were implemented in MATLAB to optimise it. The calculations with the optimised values of this beam are shown below.

$$weight\ gate = \frac{volume\ gate \times steel\ density}{102} = \frac{2.5943 \times 7800}{102} = 198.39kN \qquad \text{(equation 53)}$$

$$weight\ bridge = \frac{volume\ bridge \times steel\ density}{102} = \frac{0.1003 \times 7800}{102} = 7.67kN \qquad \text{(equation 54)}$$

$$load\ bridge = L \times w \times \sigma_{bridge} = 6.4139 \times 1.2 \times 5.85 = 44.99kN \qquad \text{(equation 55)}$$

$$Total\ weight\ lock\ gate = weight\ gate + weight\ bridge + load\ bridge = 198.39 + 7.67 + 44.99 = 251.05kN \qquad \text{(equation 56)}$$

$$load\ column = \frac{Total\ weight\ lock\ gate}{2} = 125.53kN \qquad \text{(equation 57)}$$

Where
$volume\ gate = optimum\ volume = 2.5943m^3$
$volume\ bridge = optium\ volume = 0.1003m^3$
$steel\ density = 7800\ kg/m^3$
After that the normal force acting on the diagonal was calculated, this formulas and calculations shown below were also done in MATLAB.

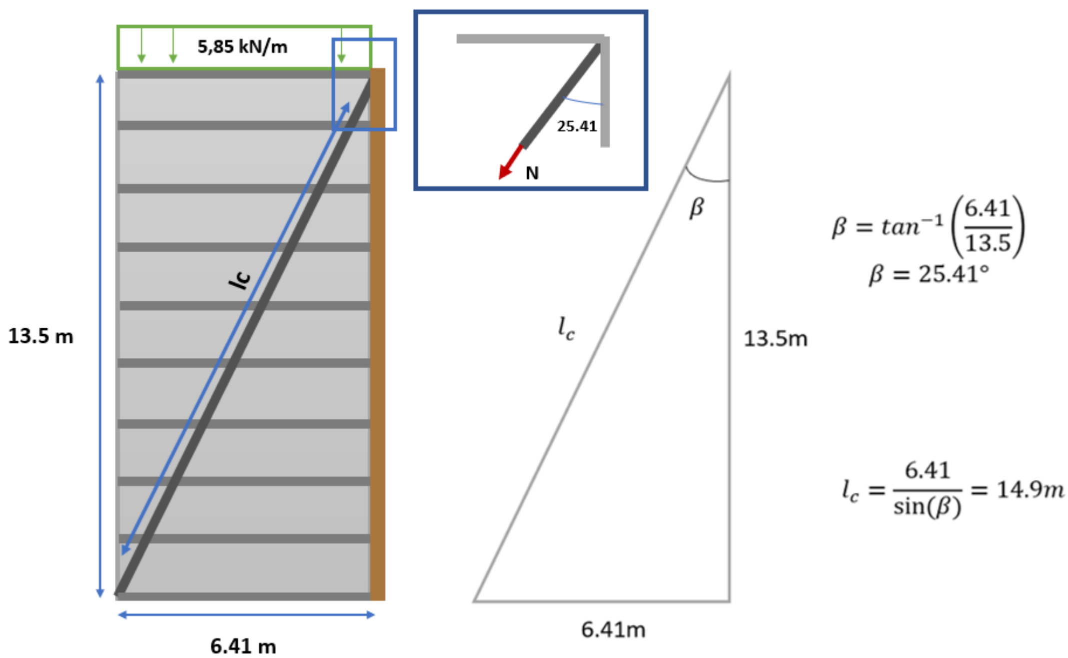


Figure 29.Calculation angle and length of diagonal beam

$$N_{diagonal} = \frac{load\ column}{cos(\beta)} = \frac{125.53}{cos(25.07)} = 138.58kN \qquad \text{(equation 58)}$$

Where
$\beta = angle\ between\ diagonal\ and\ column = 25.41$

Then, there was necessary to make more calculations, however the following formulas depend on the HEA profile which needs to be chosen after the optimisation is done. Therefore there will be shown only the formula without any values because the optimisation process is not done yet.

$$\sigma_{diagonal,ED}(kN/m^2) = \frac{N_{diagonal}}{A} \qquad \text{(equation 59)}$$

$$fc_{diagonal} = \frac{\pi^2 \times E \times I}{lc^2 \times A} \qquad \text{(equation 60)}$$

$$\frac{1}{fsys} = \frac{1}{fc_{diagonal}} + \frac{1}{fyd} \qquad \text{(equation 61)}$$

$$\frac{S}{R} = \frac{\sigma_{diagonal,ED}}{fsys} \qquad \text{(equation 62)}$$

Where:
$A = cross\ section\ beam\ (depends\ on\ HEA\ profile)$
$E = 2.1 \times 10^8\ (kN/m^2)$
$I = moment\ of\ inertia\ (depends\ on\ HEA\ profile)$
$lc = length\ of\ the\ diagonal = 14.9m$
$fyd = 235000kN/m^2$

I.10. Optimisation diagonal beam

As it was mentioned before, all the formulas that were shown previously for the diagonal calculations were implemented in MATLAB. This code can be found in appendix M.
The table below is what resulted after the respective calculations were done by using each HEA profile.

Table 19. Optimisation diagonal

HEA profile	S/R
100	4.5291
120	2.6819
140	1.6248
160	1.0393
180	**0.7216**
200	0.5117
220	0.3661
240	0.268
260	0.21
280	0.1692
300	0.1337
320	0.1121
340	0.0996
360	0.0862
400	0.07

As it can be seen in table 19 there was a comparison between HEA profiles and their respective S/R values. Therefore the optimal profile that was chosen was HEA=180 because by using this profile it gave an acceptable S/R value.

I.11. Connections

I.11.1. Connection one, bolt connection

The first connection will consider the beam from the footbridge with the beam from the lock gate. The actual deflection in the footbridge causes a rotation point therefore the bolts will experience a tension force as it can be visualized in figure 30. Therefore the bolts will be placed in order to handle this force.

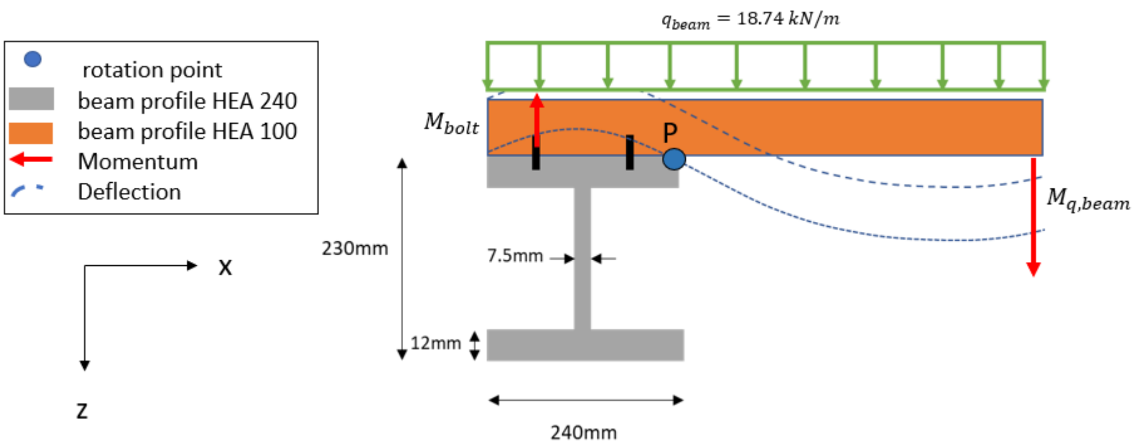


Figure 30. Graph of the moment due to the load of the footbridge

$\Sigma M = 0$ (equation 63)

$M_{q,beam} = M_{bolt}$ (equation 64)

$$M_{q,beam}(kNm) = \frac{1}{2} \times q_{beam} \times (arm_{q,beam})^2 = \frac{1}{2} \times 18.7484 \times 0.48^2 = 2.16\ kNm$$

$M_{bolt}\,(kNm) = F_{bolt} \times arm_{bolt}$ (equation 65)

$F_{bolt}\,(kN/bolt) = \frac{M_{qbeam}}{arm_{bolt}} = \frac{2.16}{0.180} = 12\frac{kN}{bolt}$ (equation 66)

$As(mm^2) = \frac{F_{bolt} \times \gamma_{M2}}{k_2 \times f_{ub}} = \frac{12 \times 1.25}{0.9 \times 0.4} = 41.667 mm^2$ (equation 67)

Where:

$q_{beam} = 18.7484\ \frac{kN}{m}$

$arm_{q,beam} = 0.48m$

$arm_{bolt} = 0.180\ m$

$As = shaft\ area$

$\gamma_{M2} = 1.25$

$k_2 = 0.9$

$$f_{ub} = 400\ \frac{N}{mm^2} = \frac{0.4kN}{mm^2}$$

For this calculations the bolt class of 4.6 was considered. With the As value obtained it is possible to know the dimensions of the bolts that should be used. The area of the shaft should be around 42 mm^2. The group looked at the tables provided in the connections lecture the shaft area which is more approximated to that value was M12. Therefore, it was decided to work with this dimensions for the bolts. It is important to mention that the deflection would not look like figure 31 in reality but this was done in order to obtain a better visualization of what is happening.

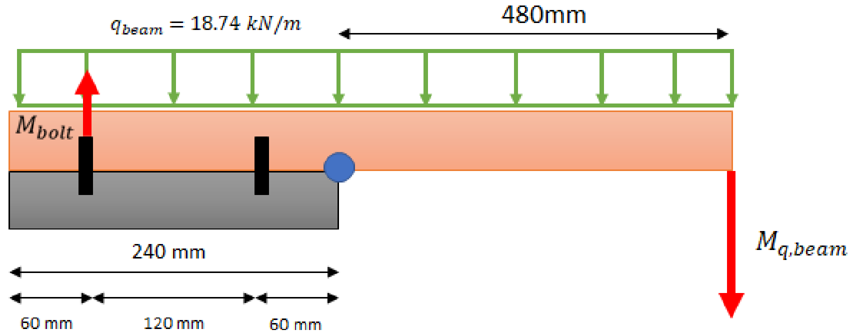


Figure 31. Arms of the bolt and q_{beam}

In figure 32 a top view of the connection can be visualized with four bolts

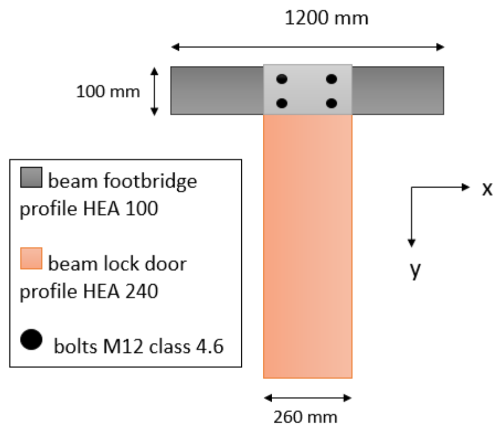


Figure 32. Top view of the bolts

I.11.2. Connection two, welded connection

The second connection that was done to join two elements of the system is the welded connection. This connection was done between the beams and a plate of the bridge. Figure 33 shows a schematization of the parts that were connected and the forces acting on them. It was assumed that the weld width was equal to 3mm because it is the minimum weld width. Then the calculation process to obtain the weld length was performed which can be seen below.

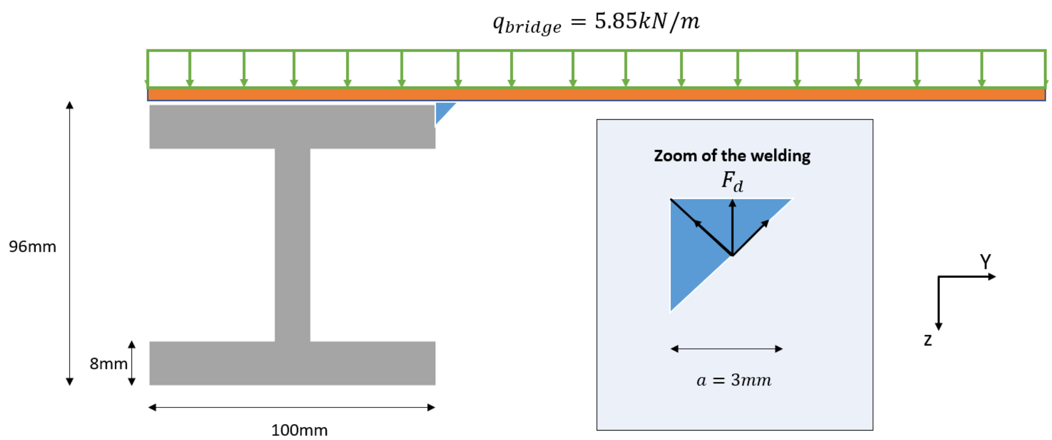


Figure 33. Welded connection

$$F_d = \frac{q_{bridge} \times width,plate\ bridge}{number\ of\ suppots} = \frac{5.85 \times 3.21}{2} = 9.38925kN \times 1000 = 9389.25N \qquad \text{(equation 68)}$$

$$\sigma = \frac{\frac{(1/2)Fd}{\sqrt{2}}}{a \times l} = \frac{\frac{(1/2)(9389.25)}{\sqrt{2}}}{3 \times l} = \frac{1106.53}{l} N/mm^2 \qquad \text{(equation 69)}$$

$$\tau = \frac{\frac{(1/2)Fd}{\sqrt{2}}}{a \times l} = \frac{\frac{(1/2)(9389.25)}{\sqrt{2}}}{3 \times l} = \frac{1106.53}{l} N/mm^2 \qquad \text{(equation 70)}$$

$$\sigma_c = \sqrt{\sigma^2 + 3\tau^2} = \sqrt{(\frac{1106.53}{l})^2 + 3(\frac{1106.53}{l})^2} = \frac{2213.067}{l} N/mm^2 \qquad \text{(equation 71)}$$

$$f_{w,u} = \frac{f_{t,d}}{\beta_w \times \gamma_M} = \frac{360}{0.9 \times 1.25} = 320N/mm^2 \qquad \text{(equation 72)}$$

$$\sigma_c \leq f_{w,u} \qquad \text{(equation 73)}$$

$$l = \frac{2213.067}{320} = 6.92mm \qquad \text{(equation 74)}$$

Where

$q_{bridge} = 5.85\ kN/m$
$width, plate\ bridge = 3.21m$
$number\ of\ supports = 2$
$a = 3mm = weld\ width\ thickness$
$l = weld\ length$
$\sigma_c = critical\ stress$
$f_{w,u} = stress\ that\ weld\ can\ bear$
$\beta_w = 0.9$
$\gamma_M = 1.25$
$f_{t,d} = 360\ N/mm^2\ (steel\ S235)$

Appendix J. MATLAB lock gate

```
%% Data

clear all, clc
%{
 Description
D : water depth in extreme cases
dw: water volumetric weight
distance_b: distance between beams
s_n: number of supports
Sd : sum of the distances vector
%}

number_of_beams = 5 ;
D = 10.8 ;                              % m
dw = 10 ;                               % KN/m^3
distance_b = D./(number_of_beams-1);    % m
Sd = zeros(1,number_of_beams);
for s_n = 1:number_of_beams
    Sd(s_n) = Sd(s_n)+(distance_b.*(s_n-1));
end
Sd;
%% Calculations
% Only the coefficients were considered
%{
Description
wp : water pressure
q  : load of the water
F  : Force due to the load of the water
Fs : Support reactions
%}

wp = dw.* D;                           % kN/m^2
q = wp./D;                             % q = (wp./D).* x
F = (1./2).*q;                         % F = (1./2).*q.*l       &     l = x

% Vectors for the matrix
% Support reactions
Fs =  zeros(number_of_beams+2,number_of_beams+2);
for k = 1:number_of_beams
    v = Sd(k);
    for l = 1:number_of_beams
        Fs(k,l) = ((v - Sd(l)).^3)./6;
       if Fs(k,l) < 0
           Fs(k,l) = 0;
       end
    end
end
for m = 1:number_of_beams
    Fs(m,number_of_beams+1) = Sd(m);
    Fs(m,number_of_beams+2) = 1;
end
% Moment equation at the end of the beam
S1 = Sd(number_of_beams);
for n = 1:number_of_beams
    Fs(number_of_beams+1,n) = S1 - Sd(n);
```

```
end
% Support forces
for o = 1:number_of_beams
    Fs(number_of_beams+2,o) = 1;
end
%% Forces
%{
Description
M_sr = Matrix support reactions
F_sr = Final suport reactions
%}

M_sr = zeros(1,number_of_beams+2);
for f = 1:number_of_beams
    M_sr(f) = (1./12).*((Sd(f)).^5);
end
M_sr(number_of_beams+1) = (5./3).*(Sd(number_of_beams)).^3;
M_sr(number_of_beams+2) = (1./2).*(D.*wp);
Fs;
M_sr;
F_sr = inv(Fs)*M_sr';
F_sr = F_sr';
%% Forces on the gates
%{
k : in order to take the next value
L : length gate
%}

%Data
angle = 15;
width_of_chamber = 12.2;                        %m
width = width_of_chamber./2;                    %m
Height_gate = 13.5;                             %m

%Calculations
k = 1;
q_beam = [];
while (k<length(F_sr))&&(F_sr(k)< F_sr(k+1))
    q_beam = F_sr(k+1);
    k = k+1;
end
q_beam = q_beam*1;                                  %kN/m
L = width./(cos(pi./10));                           %m
X_height = sqrt(L.^2 - (width).^2);                 %m
q_moment = q_beam.*(L.^2)./2;                       %kNm
H_force = ((q_moment)./((L.*sin(pi./10))+X_height)); %kN
N_force = H_force.*cos(pi./10);                     %kN
V_force = H_force.*sin(pi./10);                     %kN

%% Graph of the moment
%{
Description
v1 : vector to plot the graph
ma : matrix to plot the moments due to the support reactions
table_moment : table with the moment for each distance
%}
k = 1;
```

```
v1 = [0:0.05:D];
ma = zeros(length(v1),number_of_beams);
[f1,c1] = size(ma);
for f2  = 1:f1
    for f3 = 1:c1
        ma(f2,f3) = (v1(f2)-Sd(f3)).*F_sr(f3);
        if ma(f2,f3) < 0
            ma(f2,f3) = 0;
        end
        end
end
suma = zeros(1,length(v1));
for f4 = 1:length(v1)
    suma(f4) = sum(ma(f4,:))-((F./3).*(v1(f4).^3));

end
suma = - suma ;
table_moment = [suma; v1];
momento = suma;
figure(1),clf(1),hold on
plot(v1,suma)
plot([0 D] ,[0 0] , 'r:')
xlabel('water height (m)')
ylabel('Moment (kNm)')
grid on
hold off

%% Calculation of the thickness of the plate
%{
Description
Fyd = yielding stress
%}

Fyd = 235;                                        % N/mm^2
Length_m = 1e3;                                   % mm
M_plate1 = max(abs(momento));                     % Moment in KN*m
M_plate = M_plate1*10^6;                          % Moment in N*mm
thickness_p = sqrt(M_plate./((1./6).*Length_m.*Fyd)); %mm
Thickness_pm = thickness_p/Length_m;               % m

%% Second order effect
%{
Description
fyd : yielding strength
%}

HEA = 100;
if HEA == 100
 A_profile = 21.2 *10^-4; %m^2
 W_profile = 72.76 *10^-6; %m^3
 I_profile = 349.2 *10^-8; %m^4
 elseif HEA == 120
 A_profile = 25.3 *10^-4;%m^2
 W_profile = 106.3 *10^-6;%m^3
 I_profile = 606.2 *10^-8;%m^4
 elseif HEA == 140
 A_profile = 31.4 *10^-4;%m^2
```

```
 W_profile = 155.4 *10^-6;%m^3
 I_profile = 1033 *10^-8;%m^4
 elseif HEA == 160
 A_profile =38.8 *10^-4;%m^2
 W_profile = 220.1 *10^-6;%m^3
 I_profile = 1673 *10^-8;%m^4
 elseif HEA == 180
 A_profile = 45.3 *10^-4;%m^2
 W_profile = 293.6 *10^-6;%m^3
 I_profile = 2510 *10^-8;%m^4
 elseif HEA == 200
 A_profile = 53.8 *10^-4;%m^2
 W_profile = 388.6 *10^-6;%m^3
 I_profile = 3692 *10^-8;%m^4
 elseif HEA == 220
 A_profile = 64.3 *10^-4;%m^2
 W_profile = 515.2 *10^-6;%m^3
 I_profile = 5410 *10^-8;%m^4
 elseif HEA == 240
 A_profile = 76.8 *10^-4;%m^2
 W_profile = 675.1 *10^-6;%m^3
 I_profile = 7763 *10^-8;%m^4
 elseif HEA == 260
 A_profile =86.8 *10^-4;%m^2
 W_profile =836.4 *10^-6;%m^3
 I_profile = 10450 *10^-8;%m^4
 elseif HEA == 280
 A_profile =97.3 *10^-4;%m^2
 W_profile = 1013 *10^-6;%m^3
 I_profile = 13670 *10^-8;%m^4
 elseif HEA == 300
 A_profile =112.5 *10^-4;%m^2
 W_profile = 1260 *10^-6;%m^3
 I_profile = 18260 *10^-8;%m^4
 elseif HEA == 320
 A_profile =124.4 *10^-4;%m^2
 W_profile = 1479 *10^-6;%m^3
 I_profile = 22930 *10^-8;%m^4
 elseif HEA == 340
 A_profile = 133.5 *10^-4;%m^2
 W_profile = 1678 *10^-6;%m^3
 I_profile = 26790 *10^-8;%m^4
 elseif HEA == 360
 A_profile =142.8 *10^-4;%m^2
 W_profile =1891 *10^-6;%m^3
 I_profile = 33090 *10^-8;%m^4
 elseif HEA == 400
 A_profile =159.0 *10^-4;%m^2
 W_profile =2311 *10^-6;%m^3
 I_profile = 45070 *10^-8;%m^4
end
E = 2.1e8;                                %KN/m^2
fyd = 235000;                              %KN/m^2

%% Calculations stresses
%{
Description
```

```
n_soe : factor of the critical force over the normal force
%}
M_beam = (1./8).*q_beam.*(L).^2;        %KNm
Fc = ((pi.^2).*E.*I_profile)./(L.^2) ; %KN
Fv = N_force  ;                        %KN
n_soe = Fc/Fv;
stength_beam = (N_force./A_profile)+((number_of_beams./number_of_beams-
1).*...
    (M_beam./W_profile));              %KN/m^2
OED = N_force./A_profile;              %KN/m^2
fc = Fc./A_profile;                    %KN/m^2
fsys_1 = (1./fc)+(1./fyd);
fsys_2 = 1./fsys_1;
S_Rs = OED./fsys_2;
Final_1 = S_Rs;

%% Maximal deflections in lock gate

Dmax_beam = distance_b./300;            %mm
Dmax_plate = L./300;                    %mm

%% Deflection of beams in lock gate
%{
Description
n2 : factor of (n_soe/(n_soe-1))
D_beams : deflection beams
D_plates : deflection plates
%}
M_plate2 = M_plate1;                                      % Moment in KN*m
n2 = n_soe./(n_soe-1);
D_beams = n2.*(5./384).*((q_beam.*(L).^4)./(E.*I_profile));        % m
q_plate = (M_plate2.*8)./((distance_b).^2);                        % kN/m^2
I_plate = (1/12).*(Thickness_pm).*((distance_b).^3);               % m^4
D_plates = (1./192).*((q_plate.*(distance_b).^4)./(E.* I_plate));  % m
S_R_deflection = D_beams./Dmax_beam;

%% Volume
%{
Description
volume_b : volume of beams
volume_p : volume of plates
nt : Total number of beams
%}
nt = number_of_beams+1;
volume_b = nt*A_profile*L;                           %m^3
volume_p = L*13.5*Thickness_pm;                      %m^3
volume_colums = 13.5 * A_profile*2;                  %m^3
total_volume= volume_p + volume_b + volume_colums; %m^3
```

Appendix K. MATLAB optimisation lock gate

```
% Optimization of the lock gate
clear all , clc
Angle_vector = zeros(1,25);
Angle = [1:25]
```

```
for k = 1:length(Angle_vector)
    Angle_vector(k) = (k.*pi)./180;
end
Angle_vector

Width = 12.2;                           %m
Width2 = Width./2;                      %m
Height = 13.5;                          %m
q_beam = 257.7536                       % KN/m
E = 2.1e8                               % KN/m^2
L = zeros(1,length(Angle_vector));
q_force = zeros(1,length(Angle_vector));
H_force = zeros(1,length(Angle_vector));
N = zeros(1,length(Angle_vector));
H = zeros(1,length(Angle_vector));
X_force = zeros(1,length(L))
for l = 1:length(Angle_vector)
L(l) = Width2./(cos(Angle_vector(l)));
q_force(l) = (q_beam.*((L(l)).^2))./2;
X_force(l) = sqrt((L(l).^2)-((Width2).^2))
H_force(l) = (q_force(l))./(L(l).*sin(Angle_vector(l))+X_force(l))
N(l) = H_force(l).*cos(Angle_vector(l));
V(l) = H_force(l).*sin(Angle_vector(l));
end
M_beam = zeros(1,length(L));
for m = 1:length(L)
    M_beam(m) = (1./8).*(q_beam).*((L(m)).^2);      %KNm
end
M_beam


 W_profile = [72.76 *10^-6, 106.3 *10^-6, 155.4*10^-6 ,220.1 *10^-
6,293.6 *10^-6 , ...
     388.6 *10^-6,515.2 *10^-6,675.1 *10^-6,836.4 *10^-6,1013 *10^-
6,...
 1260 *10^-6,1479 *10^-6,1678 *10^-6,1891 *10^-6,2311 *10^-6]
 I_profile = [ 349.2 *10^-8,  606.2 *10^-8 ,1033 *10^-8 ,1673 *10^-8 ,
...
     2510 *10^-8,3692 *10^-8,5410 *10^-8,7763 *10^-8,10450 *10^-
8,13670 *10^-8,...
 18260 *10^-8,22930 *10^-8,26790 *10^-8,33090 *10^-8,45070 *10^-8]
A_profile = [21.2 *10^-4, 25.3 *10^-4,31.4 *10^-4,38.8 *10^-4, 45.3
*10^-4,...
     53.8 *10^-4,64.3 *10^-4, 76.8 *10^-4,86.8 *10^-4,97.3 *10^-4,...
     112.5 *10^-4,124.4 *10^-4, 133.5 *10^-4,142.8 *10^-4,159.0 *10^-
4]
EI = E.*I_profile
Fc = zeros(length(EI),length(M_beam));
FV = zeros(length(EI),length(M_beam));
n = zeros(length(EI),length(M_beam));
Min_stress = zeros(length(EI),length(M_beam));
Data = zeros(length(EI),length(M_beam));
```

```
for profile = 1:length(EI)
S(profile) = EI(profile);
for Length_a = 1:length(L)
Fc(profile,Length_a) = ((pi.^2).*S(profile))./((L(Length_a)).^2);
Fv(profile,Length_a) = N(Length_a);
n(profile,Length_a) = Fc(profile,Length_a)./Fv(profile,Length_a);
Min_stress(profile,Length_a) =
((Fv(profile,Length_a)./A_profile(profile))+...
    (n(profile,Length_a)./n(profile,Length_a)-1).*(M_beam(Length_a));
Data(profile,Length_a)= Min_stress(profile,Length_a);
end
end
Data
 x1 = Data(1,:)
 x2 = Data(2,:)
 x3 = Data(3,:)
 x4 = Data(4,:)
 x5 = Data(5,:)
 x6 = Data(6,:)
 x7 = Data(7,:)
 x8 = Data(8,:)
 x9 = Data(9,:)
 x10= Data(10,:)
 x11= Data(11,:)
 x12= Data(12,:)
 x13 = Data(13,:)
 x14 = Data(14,:)
 x15 = Data(15,:)
 figure(1) , clf(1), hold on
 plot(Angle, x1)
 plot(Angle, x2)
 plot(Angle, x3)
 plot(Angle, x4)
 plot(Angle, x5)
 plot(Angle, x6)
 plot(Angle, x7)
 plot(Angle, x8)
 plot(Angle, x9)
 plot(Angle, x10)
 plot(Angle, x11)
 plot(Angle, x12)
 plot(Angle, x13)
 plot(Angle, x14)
 plot(Angle, x15,'k')
 plot([0 25],[235000 235000],'k:')
 legend('HEA 100','HEA 120','HEA 140','HEA 160','HEA 180','HEA
200',...
     'HEA 220','HEA 240','HEA 260','HEA 280','HEA 300','HEA 320','HEA
340',...
     'HEA 360','HEA 400')
 xlabel('angle')
 ylabel('minimum strength (kN/m^2)')
```

```
hold off
```

Appendix L. MATLAB bridge

```
clear,clc
%%Bridge dimensions
lock_width=12.2; %m
gate_width=0.5.*lock_width; %m
alpha=pi/10;
Length_bridge=gate_width/cos(alpha) %m
width_bridge=1.2;   %m
number_of_beams=3;
l=Length_bridge/(number_of_beams-1);     %Distance between beams (m)

%%Mandatory stresses
stress_bridge_length=2+120/(Length_bridge+30); %kN/m^2
stress_bridge_width=2+120/(width_bridge+30)   %kN/m^2

%%Thickness of the bridge plate
q_plate=stress_bridge_width.*1; %kN/m
M_plate=(1/8).*q_plate.*(l.^2); %KNm
fyd=235000; %kN/m^2
thickness_plate=sqrt((6.*M_plate)/(fyd.*l)) %m

%%Forces acting on the beams of the bridge
q_beam=stress_bridge_width.*l %kN/m
M_beam=0.5.*q_beam.*(width_bridge.^2);  %KNm

%%Maximum allowed deflections in the bridge
maximum_deflection_plate=l/300;  %m
maximum_deflection_beams=(0.5.*width_bridge)/300; %m

%%Actual plate and beams deflection
E=2.1e8; %kN/m^2
I_plate=(1/12).*thickness_plate.*(l.^3); %m^4
deflection_plate=(5/384).*((q_plate.*(l^4))/(E.*I_plate)); %m
HEA=100;        %Steel profile
if HEA == 100
 A_profile = 21.2 *10^-4; %m^2
 W_profile = 72.76 *10^-6; %m^3
 I_profile = 349.2 *10^-8; %m^4
 elseif HEA == 120
 A_profile = 25.3 *10^-4;%m^2
 W_profile = 106.3 *10^-6;%m^3
 I_profile = 606.2 *10^-8;%m^4
 elseif HEA == 140
 A_profile = 31.4 *10^-4;%m^2
 W_profile = 155.4 *10^-6;%m^3
 I_profile = 1033 *10^-8;%m^4
 elseif HEA == 160
 A_profile =38.8 *10^-4;%m^2
```

```
 W_profile = 220.1 *10^-6;%m^3
 I_profile = 1673 *10^-8;%m^4
 elseif HEA == 180
 A_profile = 45.3 *10^-4;%m^2
 W_profile = 293.6 *10^-6;%m^3
 I_profile = 2510 *10^-8;%m^4
 elseif HEA == 200
 A_profile = 53.8 *10^-4;%m^2
 W_profile = 388.6 *10^-6;%m^3
 I_profile = 3692 *10^-8;%m^4
 elseif HEA == 220
 A_profile = 64.3 *10^-4;%m^2
 W_profile = 515.2 *10^-6;%m^3
 I_profile = 5410 *10^-8;%m^4
 elseif HEA == 240
 A_profile = 76.8 *10^-4;%m^2
 W_profile = 675.1 *10^-6;%m^3
 I_profile = 7763 *10^-8;%m^4
 elseif HEA == 260
 A_profile =86.8 *10^-4;%m^2
 W_profile =836.4 *10^-6;%m^3
 I_profile = 10450 *10^-8;%m^4
 elseif HEA == 280
 A_profile =97.3 *10^-4;%m^2
 W_profile = 1013 *10^-6;%m^3
 I_profile = 13670 *10^-8;%m^4
 elseif HEA == 300
 A_profile =112.5 *10^-4;%m^2
 W_profile = 1260 *10^-6;%m^3
 I_profile = 18260 *10^-8;%m^4
 elseif HEA == 320
 A_profile =124.4 *10^-4;%m^2
 W_profile = 1479 *10^-6;%m^3
 I_profile = 22930 *10^-8;%m^4
 elseif HEA == 340
 A_profile = 133.5 *10^-4;%m^2
 W_profile = 1678 *10^-6;%m^3
 I_profile = 26790 *10^-8;%m^4
 elseif HEA == 360
 A_profile =142.8 *10^-4;%m^2
 W_profile =1891 *10^-6;%m^3
 I_profile = 33090 *10^-8;%m^4
 elseif HEA == 400
 A_profile =159.0 *10^-4;%m^2
 W_profile =2311 *10^-6;%m^3
 I_profile = 45070 *10^-8;%m^4
end
%I_profile=3.492e-6; %m^4
deflection_beams=(1/8).*((q_beam.*((0.5.*width_bridge).^4))/(E.*I_profile));%
m

SR_deflection_beams=deflection_beams/maximum_deflection_beams

%%Calculation of volume
volume_plates=width_bridge.*Length_bridge.*thickness_plate; %m^3
volume_beams=number_of_beams.*A_profile.*Length_bridge; %m^3
Total_volume=volume_plates+volume_beams %m^3
```

Appendix M. MATLAB diagonal beam

```
clear,clc
%%Data
volume_gate=2.5943; %m^3
volume_bridge=0.1003; %m^3
steel_density=7800; %kg/m^3
length_bridge=6.4139; %m
width_bridge=1.2; %m
stress_bridge=5.8462; %kN/m^2
angle=(2507*pi)./18000;
E=2.1e8; %kN/m^2
lc=14.9; %m
fyd=235000; %kN/m^2
HEA=180;
%%Calculation of total weights (forces)
weight_gate=(volume_gate.*steel_density)./102 %kN
weight_bridge=(volume_bridge.*steel_density)./102 %kN
load_bridge=length_bridge.*width_bridge.*stress_bridge %kN
total_weight_lock_gate=weight_gate+weight_bridge+load_bridge %kN
load_column=total_weight_lock_gate./2 %kN
%%Calculation of normal force on the diagonal
N_diagonal=load_column./(cos(angle))
%%Strength calculations
if HEA == 100
 A_profile = 21.2 *10^-4; %m^2
 W_profile = 72.76 *10^-6; %m^3
 I_profile = 349.2 *10^-8; %m^4
 elseif HEA == 120
 A_profile = 25.3 *10^-4;%m^2
 W_profile = 106.3 *10^-6;%m^3
 I_profile = 606.2 *10^-8;%m^4
 elseif HEA == 140
 A_profile = 31.4 *10^-4;%m^2
 W_profile = 155.4 *10^-6;%m^3
 I_profile = 1033 *10^-8;%m^4
 elseif HEA == 160
 A_profile =38.8 *10^-4;%m^2
 W_profile = 220.1 *10^-6;%m^3
 I_profile = 1673 *10^-8;%m^4
 elseif HEA == 180
 A_profile = 45.3 *10^-4;%m^2
 W_profile = 293.6 *10^-6;%m^3
 I_profile = 2510 *10^-8;%m^4
 elseif HEA == 200
 A_profile = 53.8 *10^-4;%m^2
 W_profile = 388.6 *10^-6;%m^3
 I_profile = 3692 *10^-8;%m^4
 elseif HEA == 220
 A_profile = 64.3 *10^-4;%m^2
 W_profile = 515.2 *10^-6;%m^3
 I_profile = 5410 *10^-8;%m^4
 elseif HEA == 240
 A_profile = 76.8 *10^-4;%m^2
```

```
 W_profile = 675.1 *10^-6;%m^3
 I_profile = 7763 *10^-8;%m^4
 elseif HEA == 260
 A_profile =86.8 *10^-4;%m^2
 W_profile =836.4 *10^-6;%m^3
 I_profile = 10450 *10^-8;%m^4
 elseif HEA == 280
 A_profile =97.3 *10^-4;%m^2
 W_profile = 1013 *10^-6;%m^3
 I_profile = 13670 *10^-8;%m^4
 elseif HEA == 300
 A_profile =112.5 *10^-4;%m^2
 W_profile = 1260 *10^-6;%m^3
 I_profile = 18260 *10^-8;%m^4
 elseif HEA == 320
 A_profile =124.4 *10^-4;%m^2
 W_profile = 1479 *10^-6;%m^3
 I_profile = 22930 *10^-8;%m^4
 elseif HEA == 340
 A_profile = 133.5 *10^-4;%m^2
 W_profile = 1678 *10^-6;%m^3
 I_profile = 26790 *10^-8;%m^4
 elseif HEA == 360
 A_profile =142.8 *10^-4;%m^2
 W_profile =1891 *10^-6;%m^3
 I_profile = 33090 *10^-8;%m^4
 elseif HEA == 400
 A_profile =159.0 *10^-4;%m^2
 W_profile =2311 *10^-6;%m^3
 I_profile = 45070 *10^-8;%m^4
end
stress_diagonal_ED=N_diagonal./A_profile %kN/m^2
fc_diagonal=((pi.^2).*E.*I_profile)./((lc.^2).*A_profile) %kN/m^2
fsys=(fc_diagonal.*fyd)./(fyd+fc_diagonal) %kN/m^2
S_R=stress_diagonal_ED./fsys
```