GREEN-LINKING ROTTERDAM ZUID
DESIGN OF A BRIDGE WITH INTEGRATED PARK CROSSING THE MAAS

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Table of contents

1 Introduction 6
   1.1 Problem statement 6
   1.2 Objectives 7
   1.3 Research question 7
2 Methodology 8
   2.1 Study scope 8
   2.2 Methodology 8
3 Analysis Rotterdam 11
   3.1 Problem statement 11
   3.2 Urban plans 12
   3.3 Visual impact plan 23
4 Analysis site 43
   4.1 Future plans 43
   4.2 Urban context 48
   4.3 Conclusion 50
5 Guidelines and demands 52
6 Structural analysis 53
   6.1 Bridging types 53
   6.2 Moveable systems 64
   6.3 Landings 70
   6.4 Conclusion 73
7 Design study 75
   7.1 Design brief 75
   7.2 Urban context 75
   7.3 Concept 76
   7.4 Design explanation 78
   7.5 Structural simulation and optimisation 101
8 Conclusion & recommendations 112
   8.1 Conclusion 112
   8.2 Recommendations 112
9 Visualisations 113
10 Drawings 115
11 Bibliography 118
1 Introduction

In this chapter an introduction to the design challenge is given. The problem is stated, the objectives are mentioned and the research question is defined.

1.1 PROBLEM STATEMENT

The municipality of Rotterdam has developed an Urban Traffic Plan with a vision for 2030. This document describes the infrastructural challenges that are at hand in the city of Rotterdam.

The Maas offers Rotterdam an unique city profile with a completely own identity. In the meanwhile the river is also a barrier in the middle of the city. Because of the developments on the Kop van Zuid, the Maas is emphatically becoming a part of the down town district. However, the amount and position of the current crossings forces car traffic to the city centre, where they have to fight for space with pedestrians, cyclists and public transport. This takes a large part of the available public space, which decreases the quality of these areas and leaves potentials unexploited. To improve the quality of these areas, the use of cars has to decrease and they will have to move out of the city centre.

These challenges are not only about capacity or continuation of car traffic flow, but also about raising awareness and changing driving behaviour. That’s why providing alternatives for using the car is an important task. The current bicycle network has bottlenecks at several crossroads on the axis Hofplein – Erasmusbrug, where the first Rotterdam bicycle traffic jams are already visible. In addition, there are only a few attractive bicycle paths parallel to the busy car roads.

In the public transport network the current crossings for metro and tram are vulnerable and they threaten to become bottlenecks too: all travellers from Rotterdam North to South have to travel via the city centre. This applies for cyclists as well since the Erasmusbrug is the only ‘bicycle-friendly’ connection.

Fig 1. Bottlenecks in Rotterdam (own work).
The tram network has a bottleneck on the Erasmusbrug and it has issues with the flow of traffic at the landings. The largest bottleneck for subways is at the east-west line between the stations Kralingse Zoom and Beurs and at the north-south line between CS Beurs and Zuidplein. Also, the limited amount of crossing possibilities over the Maas with bicycles or public transport is restricting the access of the inhabitants of Rotterdam South to facilities and employment.

A third city bridge can improve these problems. With a crossing in the east, Rotterdam South will be less isolated and education and employment will be easier accessible. It will also create more space to direct car traffic around the city centre and will provide a new connection for sustainable ways of transport. The design of such a bridge comes with many challenges.

The Nieuwe Maas is of vital importance for the harbour of Rotterdam, since it’s the connection from the harbour to regions and countries land inward. The nautical activity of the Maas creates a challenge. A wide variety of vessels is passing every hour and all vessels have different requirements. They need a certain vertical and/or horizontal clearance to pass the crossing. The Maas is about 400 meters at this point, which is structurally a challenge to span. In addition, the bridge cannot block high ships from passing through. That means an openable part should be integrated within the crossing.

Another challenge is the specific site where the crossing should be designed for. The bridge will have two landings where it connects to the existing infrastructure of the city, one on each side of the river. The infrastructure is completely different at both sides. Especially on the north side the current infrastructure is not suited yet to facilitate the different flows of traffic. On the south side there are plans for a new stadium, which means the current infrastructure might change. It is of major importance that the crossing connects to the structure of the city, because only then it will be used by the people.

This also applies for the design of the crossing, and especially the landings. To be able to reach the proper height, an access is required. This landing has different requirements for the different flows of traffic, for example: a tram can only climb a certain angle and a cyclists doesn’t want to take much effort to cross. This means that it’s certain that these landings will require a lot of space and that it will majorly influence the design.

1.2 OBJECTIVES

The main objective of this Msc thesis is to research the challenges and requirements of a new crossing and to design a feasible solution that solves the challenges at hand. Therefor there will be four sub-objectives:

- Gaining an insight in the infrastructural challenges in Rotterdam
- Gaining an insight in the challenges of a new bridge between Feijenoord and de Esch
- Defining a list of requirements for the new bridge
- Detailed designing of a suitable structure which will be verified with structural calculations

1.3 RESEARCH QUESTION

What structural feasible solution can be found for a bridge with integrated green crossing the Maas between Feijenoord and de Esch?
2 Approach and methodology

In this chapter the approach of the project is given. The scope of the study and the methods used to conduct research are explained.

2.1 STUDY SCOPE

The project will have a main focus on several aspects. The design of such a crossing would in reality take much longer, but choices have to be made to narrow down the possibilities. In this way a research can be created that fits the given timeframe.

Focus on location

The suggested location of the bridge follows from the plans of the municipality. This location is now not suited for a bridge yet. The focus will be on the connection of the bridge to the current infrastructure. The design of the landings, on urban and technical scale, is important here.

Focus on bridge

A crossing can have different meanings, but the decision is made to focus on a bridge. Bridges and tunnels are both an easy way of crossing, but bridges has some advantages:

- Rotterdam is a city of bridges and a new bridge could enhance the cities current image.
- Since slow-traffic will be an important user of the crossing, it should be attractive for them to use. A bridge is then a much nicer experience than a tunnel, where people feel enclosed and there is less social security.
- To not interfere with the nautical activity, a tunnel would be very deep. This requires a lot of space for the ramps. With a tunnel you’re not that flexible with these ramps as with a bridge.
- It is the wish of the municipality to have a new city bridge.

Focus on sustainable ways of transport

A better connection between North and South Rotterdam is needed especially for the more sustainable ways of transport: public transport, cyclists and pedestrians. The public transport should be in the form of a tram.

2.2 METHODOLOGY

Several types of methods will be used to conduct the required research. This research will exist of four parts: three literature analyses followed by a design study. The first analyses focuses on the city of Rotterdam on urban scale. This will provide guidelines for the design of the bridge. The second analysis will focus on the location of the bridge specifically and will provide the boundary conditions of the design study. The third analysis of bridges, openings and landings will provide us with an overview of what is structurally possible. Finally, the design study will be an attempt to find a proper solution that complies with the guidelines and demands.

The analysis of Rotterdam and the bridges is done in cooperation with Merijn de Leur. He is graduating on the same topic, designing a bridge at another location in Rotterdam, so we decided to work together on these parts to save time.
2.2.1 ANALYSIS: ROTTERDAM

Research on Rotterdam was done to get an insight in the problems, challenges and wishes of the municipality. This analysis was split up in several parts, which each will be discussed here.

Rotterdam analysis

In this chapter we aimed to explore the urban requirements by analysing the wish of the municipality for a new crossing over the Maas. We analysed not only the traffic issues, but also the social issues in the city. The vision of Rotterdam for 2030 and the Urban Traffic Plan for 2030 have been used to understand the mindset of the municipality and to extract criteria for the bridge. This resulted in a list of urban guidelines for the design study.

Visual quality plan

In this chapter we aimed to create a visual quality plan to get an insight in the visual requirements of a new bridge in Rotterdam. We focused on analysing the role of architecture in the history of Rotterdam, performing a case study to the current city bridges in Rotterdam and on analysing the role that the quays need to play in the future. This resulted in a list of visual guidelines for the design study.

2.2.2 ANALYSIS: SITE SPECIFIC

Research on the location was done to get an insight in the current morphology of the situation and to define the boundary conditions on site. Several analyses were made to get an insight in the current
urban structure and buildings, infrastructure and nautical activities. Also the future plans for this area were analysed. This resulted in a list of demands and guidelines for the design study.

2.2.3 ANALYSIS: BRIDGES

Research on the different construction types for bridges was done to get an insight in the technical possibilities of crossing the Maas with a bridge. We focused on aesthetical properties, structural principles, technical properties and typical material usage of the different bridge typologies. The same was done for the openable bridging types. Next to the construction systems, additional research was done for the landings.

This analysis was crossed with the guidelines and demands that resulted from the other analyses. In this way a conclusion is drawn for the possible structural systems to use.

2.2.4 RESEARCH: DESIGN STUDY

Research will be conducted to find the best solution that complies guidelines and demands concluded from previous analyses. The study will firstly focus on the urban fitting of the bridge in its location. Then the structural system of the bridge and operable part will be researched. This will then be optimised based on structural performance. Finally, when the design is structurally and aesthetically pleasing, the detailing of the different elements of the bridge will be done.
Analysis Rotterdam

In this chapter an analysis of Rotterdam as a city will be made. This means that both the practical as social problems are stated and that the future plans of the city, that might concern the new crossings, are researched. This will result in demands based on the urban plans. In addition, a visual quality plan is made to determine the visual demands of the new bridges.

3.1 PROBLEM STATEMENT

The city of Rotterdam has to deal with the Nieuwe Maas flowing right through it. This natural barrier poses a problem on different levels which can be subdivided into two main categories. First of all there is a practical, traffic problem. Second, it causes a social division and problem.

Practical

Rotterdam is a city of the cars. This is mainly because of the river. The best used crossings lie in the centre of Rotterdam, leading the traffic straight through the city centre where you don’t want it to be. Other than local traffic, it is desired to have as little traffic as possible in the city centre. The limited amount of crossings also stimulates the use of the car. There is only one tram line crossing the Nieuwe Maas right now, and that’s on the Erasmusbrug, again right in the city centre. Other means of sustainable transport, like the bicycle, are also not attractive. Because the only attractive crossing is again the Erasmusbrug, cyclists will always have to make a detour to reach their destination. In the west there is the Maastunnel which does offer an extra connection for cars, cyclists and pedestrians. The problem here, is that, even though the tunnel takes away the physical barrier, the mental barrier is still there. For cars it works, but for cyclists and pedestrians a 600 m underground walkway is not ideal. The north and south of the city are separated and it feels like it.

Social

Socially, the barrier the Nieuwe Maas forms has led to a difference in development between the north and the south. The lack of crossings makes it hard for people to leave there neighbourhood for i.e. work, educational purposes or social events. This has caused the southern part to stay behind in economic development. While only 38% of the inhabitants of Rotterdam live in the south, the south houses 44% of the unemployed in Rotterdam. There is little variety in the residents. The cheap housing, built originally
for the longshoreman, attracts lower incomes and the underprivileged. The lack of connectivity prevents economic development and the variety of inhabitants of growing.

The two problems are off course very much connected. The practical problems feed the social problems and prevent the situation from improving. It can be seen on de Kop van Zuid that mobility is a large part of the problem. Where the working connections of the Erasmusbrug and the Willemsbrug are, the south thrives in development, whilst we see the western and eastern part of the south stay behind.

3.2 URBAN PLANS

In this paragraph an analysis of the plans for Rotterdam is researched. The plans of Rotterdam for the future are researched. This results in the choice of location and a list of demands that are concluded from this research.

3.2.1 VISION 2030

In 2007, the municipality of Rotterdam developed a vision for 2030, that served as a basis for the Urban Traffic Plan (Gemeente Rotterdam, Stadsvisie Rotterdam, 2007). This spatial development strategy 2030, also called City Vision 2030, gives a look in the future of life in Rotterdam. By means of keywords along with a small explanation, it is told how this life can be. The statements that are most important for the design of a new bridge are picked out and explained.

Recognizable skyline & modern metropole

In 2030 Rotterdam will be a clean, colourful harbour city at the estuary of the Maas. The city, with her recognizable skyline, is known for its business instinct and has an open and international character. More than 600,000 people from more than 150 nationalities are living and working in the city. All these people are in continuous contact with each other and – through their relations with family, colleagues and customers – also with the rest of the world. In the past thirty years Rotterdam underwent a major transformation and has now become an attractive European city.
Residential city with attractive public space

The famous Rotterdam mentality of ‘direct tackling’ has led to the metamorphose that many city quarters have undergone in a period of only 25 years. After years of change Rotterdam has grown to be a real residential town. For every age, taste and wallet there is an appropriate choice for housing that offers quality and a sense of security. Living in the city centre is very popular with starters and seniors, thanks to the attractive and luxurious housing opportunities, with many facilities and public transport nearby. The city quarters around the city centre all have their own character, partly by their (historical) location and function. They offer a quiet, qualitatively good and various living and work environment for all classes of population. The ‘garden quarters’ at the periphery of the city offer a nice living environment, with good basic facilities, in which mainly families feel at home and where children can play on the streets and learn to ride their bicycle. An attractive public space and the areas full with water make these quarters very popular.

High quality public transport & bicycles

Traveling for work, study or free time is simple, because of the high quality public transport with among others an HSL-connection, metros, trams and hydrogen busses. Together with a branched road network and bicycle path structure, this connects the city quarters with each other and with nature and recreation areas around the city. The water terminal at the Leuvehaven connects many different destinations in and out of the city centre by water taxi and busses. Hydrogen taxis, tuktuks and electric vehicles are the other means of transport.

Meeting and recreation at surprisingly green areas

Both citizens as tourists are happy to stay in the city centre. Attractive pedestrian paths can be found everywhere. Walking along the many boulevards and quays offers the citizens and visitors possibilities to meet and relax. There are also sufficient and surprising green areas, clearly visible along the boulevards or almost hidden in small streets and courtyards, but also on top of the high roofs of buildings. These special gardens offer peace, space and possibilities for sports and games in the heart of the dynamic downtown area. Small scale restaurants surrounding cultural institutions and performances of street artists complete the living, though intimate image of the city. The diversity of the population is also clearly recognizable during lunch time, when a diverse public walks along the quays or sits on the benches or in restaurants, enjoying their lunch.

Living on and along water & the Maas

Also the water is never far away: by digging up the historic water routes the recreational function of the city centre is improved. Ponds, canals and rivers give the city an alluring, spacious view. These blue veins also serve as a water storage. The harbour city also offers at a variety of places possibilities to live on and at the water. These ways of living are immense popular.

Conclusion

Rotterdam is aiming for a lively city with attractive public space, green areas and interesting places
along water. All these different areas need a connection with each other and other city districts. With new crossings over the Maas these connections are possible to create.

Looking at the different means of transport, the priority for such a new bridge would be with the sustainable options: public transport, bicycles and pedestrians. It is an option to allow cars to use the crossing too, since there is a demand for a branched car network.

The landings of a new crossing are important public spaces. The quays are attractive areas where pedestrians have the priority, so that people can meet and relax. Water is an important element in the city and it should be experienced.

### 3.2.2 MOBILITY PLAN

In February 2016 the municipality of Rotterdam published the document ‘Urban Traffic Plan Rotterdam 2016-2030+: Smart accessibility for a healthy, economic strong and attractive city’ (Gemeente Rotterdam, Stedelijk Verkeersplan Rotterdam, 2016). This document contains a general vision for mobility in a future Rotterdam and how to achieve this. Several documents were important for the development of this plan, including the pre-mentioned City Vision 2030. A summary of the traffic plan will be described here.

**Problem description**

Mobility itself is not the goal, but the means to contribute to a strong economy, a healthy environment and the spatial quality of Rotterdam. The urban traffic plan shows how, in the long run, an urban network can be created in which different flows of are balanced. This vision responds to the future developments in, for example, economy and housing environment and demand. The plan aims to enhance the opportunities of certain specific areas, improve the quality of living and at the same time contribute to the health of the citizens of Rotterdam.

A transition in mobility has been ongoing in the past couple of years. The usage of cars in the city center has been constant for some years but is now actually decreasing, whilst the use of the bicycle and public transport is increasing. The transition to more sustainable means of transport is ongoing, but is hard to predict as it strongly correlates to economic developments in an area, demographics, developments in price of mobility and technological innovations. The change is best noticeable in the city center and the urban area.

In the urban traffic plan, three main challenges are dealt with. The wanted economic development, the spatial quality and the health of the citizens of Rotterdam. Different traffic scenarios lead to four important results. These results can be determining in the shaping of the accessibility plan in the long run.

**1. Low traffic city center and Coolsingel is possible**

In an inviting city center, meeting is key. The ability to stay, to meet, is what makes a city flourish. Less traffic in the city center and the urban area serves this purpose. Distributing the traffic over the entire network of streets and traffic squares, contributes to the liveability and economic potential. Not only the city center, but also the rest of the urban area profits.

The redesign of the Coolsingel can be the start of this development. By expanding the regional street network, motorists will sooner choose to drive around the city instead of through the city center. This
relieves the city streets like the Coolsingel. Next to this, emphasizing alternate means of transport, especially the bicycle, is an important impulse to decrease the amount of short car rides (3-5 km). The addition of a new crossing possibility over the Nieuwe Maas for car, public transport, cyclists and pedestrians will lead to a more balanced distribution of traffic over the river. Further improving the connection to important bicycle routes between urban areas and the city center will make the use of the bicycle more appealing and will undoubtedly contribute to the decrease of car usage in and around the city center.

2. Breathing space for the city in West and South

A new crossing over the Nieuwe Maas is key in the transformation in the western part of Rotterdam. The Parklane is already a strong element in the West that, thanks to this new connection, can be continued on South. This new connection via the Waalhaven to the Groene Kruisplein, offers a lot of opportunities for spatial and economic development in parts of the South with new residential and working areas, including green connections. The new organization causes a shift of the traffic from the old city center to the West. The air quality, noise nuisance and traffic safety will improve. Also, space for public transport, cyclists and pedestrians will open up, facilitating the transition to sustainable mobility. The western part of the city will get more breathing space for moving, staying and leisure. In the long run, the Maastunnel could become an important part of the public transport network. Important destinations like the Erasmus MC, Hart van Zuid and the western city center will gain in accessibility.
3. Main infrastructure enforces connection Centre and South

Despite the existing metro line there is still a need for public transfer connections in Rotterdam South. The municipality proposes to connect to the strong existing regional networks. An example could be the construction of connecting tramlines over the Willems Bridge between Zuidplein, station Stadion and the Erasmuscampus. This will create a new strong route at Rotterdam South, of which local residents will profit. Because of the better connections the citizens of South will have more and better ways to go around the city. This will increase their chances at a proper reachable job or makes the traveling to school or other educational institutes more easily.

With a new crossing on the eastern side of the city the City Lounge in the centre can be extended more towards the east, in the direction of Blaak, Oude Haven, Willems Bridge and Kralingen. The Kop van Feijenoord and Parkstad have the space to transform into an even more interesting residential area along the river. The development of the eastern crossing will have to be parallel to the development of the Stadionpark. This connection can also contribute to reducing the traffic density on the Van Brienenoord Bridge.

4. A strategy for accessibility that evolves with the city

The long-term vision for accessibility of the city and the region offers promising strategies to form an urban and regional infrastructure network that is flexible and that can adjust to the Rotterdam of the Future (Next City). In the mobility sector the municipality responds to the energy and developments of citizens, partners and stakeholders in the city and city regions. The transition originates from the desired spatial and economic development and can be adapted repeatedly to the current Zeitgeist. That adaption to the Zeitgeist has several starting points:

- Densify urban areas with dwellings
- Transition to Next Economy
- The health of citizens is priority
- Transition to a clean mobility is stimulated
- Technology and information provide effective, safe and sustainable traveling

Conclusion

All measures in this Urban Traffic Plan result together in a city where car traffic has a balanced distribution and where bicycles, public transport and transport over water are given plenty of space. In this way the city will be stronger, healthier, greener and more attractive. It results in an expansion of the City Lounge.
The Urban Traffic Plan provides us with four possible locations for a new bridge in Rotterdam. Two new crossings over the Maas are proposed, and two smaller bridges. These four locations are shown below.

In the next paragraphs each location will be introduced. For each of them a small description will be given, and also the properties that these bridges need to have. Based on this information a choice will be made which bridge will be designed.

A new western crossing over the Nieuwe Maas is planned between the Sluisjesdijk and the Vierhavens, just west of the Maastunnel. This new connection frees the old city centre of the overload of traffic and makes room for development of the south of Rotterdam. Furthermore the new crossing is a missing link in the network of sustainable means of transport (i.e. bicycle and public transport). At the moment there are too few crossing opportunities. The new bridge would cancel out the river as a barrier and at the same time makes for a better destination. The bridge has to deal with different flows of traffic and quite a large span.

For the short term, the municipality chooses for a redesign of the Coolsingel for low traffic, implementation of the Fietsplan, Verkeersveiligheidsplan, Parkeerplan and Koersnota Lucht. In addition, a study has started for a new western crossing. The development of transport over water is stimulated by facilitating a ferry connection between Charlois-Katendrecht and Feijenoord-Kralingen.

For the long term, Rotterdam wants to co-operate with other authorities and parties in the city to tackle the larger infrastructural issues. This concerns for example the new crossings, the functioning of the urban and regional public transport system and the development of car mobility on the Ring of Rotterdam. In short: the ambitions mentioned in the Urban Traffic Plan 2030.

3.2.3 LOCATIONS

The Urban Traffic Plan provides us with four possible locations for a new bridge in Rotterdam. Two new crossings over the Maas are proposed, and two smaller bridges. These four locations are shown below.

In the next paragraphs each location will be introduced. For each of them a small description will be given, and also the properties that these bridges need to have. Based on this information a choice will be made which bridge will be designed.

LOCATION 1. WEST

A new western crossing over the Nieuwe Maas is planned between the Sluisjesdijk and the Vierhavens, just west of the Maastunnel. This new connection frees the old city centre of the overload of traffic and makes room for development of the south of Rotterdam. Furthermore the new crossing is a missing link in the network of sustainable means of transport (i.e. bicycle and public transport). At the moment there are too few crossing opportunities. The new bridge would cancel out the river as a barrier and at the same time makes for a better destination. The bridge has to deal with different flows of traffic and quite a large span.
Traffic

The main function for this bridge is to create a better connection between north and south for public transport. To fulfil the function of relieving the city centre of traffic and to create a better branched network, there might be cars over the new crossing. Next to this, the city of Rotterdam wishes to stimulate pedestrians and the use of the bicycle, so a comfortable bicycle and pedestrian path is needed.

Next to the traffic crossing over the bridge, there is also a shipping lane to take into account. Yachts, barges and possibly even cruise ships will have to be able to pass the bridge.

Measurements

The measurements of the crossing depends on two main factors. First of all the span of the crossing. How much water needs to be crossed? And second, the traffic flows over and under the bridge, influencing the width, height and opening size.

Span: The western crossing will have to span circa 400 meters of water. Depending on the exact chosen location and straightness of the bridge, this can vary ± 50 meters.

Over: Continuing the existing Parklane means that there might be a possibility for cars to cross. The priority is for public transport though. Also a comfortable cycling route is wanted, demanding a two-way cycling path. Finally a safe and pleasant pedestrian crossing is demanded.

Under: The high intensity of shipping over the Nieuwe Maas will influence the height of the bridge and the size of the operable part.

Landings

The new western crossing reaches between the Sluisjesdijk in the Waalhaven and the Schiemond in the Delfshaven. The southern part is mainly industry and in commercial use. There is a parking lot that offers a location for one of the landings of the bridge without any demolishing being needed. In the northern part there are more residential areas. The current infrastructure won’t suffice to accommodate the continuing of the Parklaan as planned.
Surrounding the Maashaven are two different areas. The northern part is already heavily under development and growing fast, while the southern part is staying a bit behind. To expand the neighbourhood and increase the development in the south, a new connection for cyclists and pedestrians is wanted. In the Maashaven, another whole new development is planned. It is planned to have floating housing and services. To accommodate such a development, at least one extra crossing is needed. An extra connection would unify the southern area and raise the social quality of the surrounding neighbourhood and the possible new floating community. Children going to school won’t have to take the long way around anymore, but instead can have a safe route. The Maashaven won’t be a barrier anymore but a unifying element in the neighbourhood.

Traffic

The Maashaven now, mainly forms a barrier for cyclists and pedestrians. This will be the main focus of the bridge. Furthermore, to be able to get some leisure boating into the Maashaven, a small operable part will be needed.

Measurements

The measurements of the new bridge will mainly be determined by the expected traffic crossing the bridge. There won’t be that much boating.

Span: The span of the new crossing will be between 160m and 275m, depending on the exact location.

Over: As mentioned before, the bridge will be focussed on accommodating pedestrians and cyclists. A safe and comfortable crossing is wanted. To create a social connection between the northern and the southern part, a spacious physical connection is needed.

Under: The Maashaven is planned to not be used as an industrial port anymore. This means no large barges will enter. Only a few leisure vessels will have to be accommodated, meaning that a small operable part is desirable.
Landings

The northern part is mostly residential. Even on the quay of the Maashaven the residential buildings have taken over. In the southern part, residential area is also dominant, but now, on the quay of the Maashaven, industry still prevails. The planning is that this part will also become residential and form one big neighbourhood.

LOCATION 3. NEW KONINGINNEBRUG

The municipality of Rotterdam has plans to make a new connection for public transport between North and South. The Willemsbrug will be transformed to facilitate not only cars, cyclists and pedestrians as it does now, but to also facilitate public transport. This public transport connection will be in the form of a tram. The Willemsbrug only reaches up to the Noordereiland, which means that there is still a connection missing in the extension of the Willemsbrug between the Noordereiland and Feijenoord. It will also play a major role in making the infrastructure, other than public transport, more logical for this part of the city.

Traffic

The new bridge will take over the function of the old Koninginnebrug. This means that cars, cyclists and pedestrians need a place on the bridge. In the vision of the municipality, this crossing will serve mainly local traffic. This means that it should be a pleasant crossing for slow traffic, cyclists and pedestrians, since they have the priority. As described before, the new bridge will also play an important role in the public transport network. It will have to facilitate a tram connection.

Measurements

Span: The new bridge will have to cross the Koningshaven, which at this point has a width of about 140 meters. Because there is a limited space, the bridge will most certainly cross on a small angle, making the span about 145 meters.

Over: It will facilitate a spacious path for cyclists and pedestrians. Both the old Koninginnebrug and the Willemsbrug have a double lane for cars in both directions. This is probably needed for the new bridge as well, to prevent traffic congestion. At last the tram needs tracks in both directions.

Under: The Koningshaven is barely used for transport over water. The old Koninginnebrug is so low
that even for small vessels the bridge is required to open. This means that if the Koninginnebrug stays operational, for example as a pedestrian bridge, the new bridge will require the same properties. The only vessels that pass here are large bulge vessels that cannot pass the Willemsbrug. In that case the bridges require to open to let the vessels pass.

**Landings**

The position of the landings are quite fixed at this location. The plans for both the Noordereiland and Feijenoord are determined and lots of urban development is happening at the moment. The bridge will have to connect to the Willemsbrug and the Oranjeboomstraat.

**LOCATION 4. EAST**

As mentioned in the Urban Traffic Plan, a new crossing is wanted in the east of Rotterdam, between the neighbourhoods Kralingen-De Esch and Feijenoord. This will connect different urban economic environments, like the Erasmus University Campus with the Stadionpark. With this new connection, Rotterdam South will be less isolated from the rest and education and jobs will be better reachable. The bridge can be used to guide the traffic around the city centre, and to reduce the traffic load on the Van Brienenoordbrug. It will also play a major role in establishing a better connection of South to the urban public transport network.

**Traffic**

The new eastern bridge will have a very important role in the public transport network. It will have to facilitate a tram connection. Because the municipality is trying to move the cars out of the city centre and to reduce the traffic load on the Van Brienenoordbrug, this crossing is can also play an important role for car traffic. Besides that, pedestrians and cyclist should have wide paths. They are, together with public transport, seen as the vital infrastructure of the city.

**Measurements**

Span: The span will depend on the exact position of the bridge. If it is placed in the exact extension of Kralingse Zoom, the span will be about 600 meters. Placed more perpendicular over the Maas, the span is about 500 meters. The final option is situated more to the east and uses the Van Brienenoordeilands as a support. The span is then reduced to about 375 meters.
Over: The bridge’s will probably facilitate all types of traffic. Research should be conducted to determine the need for car traffic, but a lane in both directions for them might be needed. A tram track should be implemented as well. Finally, it will also facilitate a spacious path for both cyclists and pedestrians.

Under: At this location, the Maas is used primarily by bulge vessels that travel from and to the harbour. It is required that these ships can pass easily underneath the bridge, without needing the bridge to open. For higher ships, it is required that there is an opening in the bridge to let these vessels pass. The vertical clearance and the width of the opening can be compared to that of the Erasmusbrug.

Landings

On the south landing, the position of the bridge, and so the position of the landings, are depending on the plans for the new stadium. This stadium will either be placed west of Cor Kieboomplein or more to the east, near Van Brienenoordeiland. When the bridge will be placed at the west location, the landing can end at an area that now serves for parking. The east location is a bit more complicated, since it’s build full with shops, offices and storages. It will require some demolishing and urban planning to design this landing. The Van Brienenoordeiland can be used as an landing, reducing the span of the bridge and making a connection possible to this unique piece of nature in the city. The north landing has many possibilities since this area is mostly unbuilt, but attention should be given to the unique piece of nature that is there.

CHOICE OF LOCATION

The scale of the bridges required for the four different locations differ a lot, in both measurements and significance. The New Koninginneweg and the Maashavenbrug are relatively smaller projects than the new crossings over the Maas. For this projects we will be focussing on location 1 and 4, the East and West crossing of the Maas. These bridges are of greater importance for the city’s development. It can be a solution for the problems mentioned, both social and infrastructural problems. Besides that they are structurally more challenging to design.

3.2.4 CONCLUSION

From the both the vision of Rotterdam for 2030 and the new mobility plan, conclusions can be drawn regarding the new connections. The most important points are summarised here:

- The new crossings will have to be focussed on sustainable means of transport, meaning plenty of space for pedestrians, cyclists and public transport. Cars can be allowed as a guest.
- The new crossings need to be easily accessible to the public.
- Attractive public spaces are wanted with interesting quays.
- On the quays, pedestrians will have priority in a space for staying and relaxing. Visitors of the quays should be able to experience the water.

These four points should definitely be taken into account when designing a new crossing.
3.3 VISUAL IMPACT PLAN

Next to the spatial planning of a city, which is usually mostly based on functional qualities, the visual impact plan is made to describe the wanted visual quality in a city. In such a plan, architectural and urban demands are stated. A link can be made between a new urban development and existing characteristics or qualities of an area.

For the design of a new bridge, insight in these plans and demands is very important to be able to make the new connection fit into the city and most of all into the future city.

To get a feeling of what role architecture plays within Rotterdam, a small description of architecture in Rotterdam of the last 50 years will be made. This results a description of today’s assignments. Secondly the demands from Welstand for the bridge areas are described. Thirdly the roles that the quays play in the city is researched. Then the current crossings over the Maas are researched, by looking at their characteristics and their role in the city. Finally, the research is combined to set up a list of visual guidelines for the new bridges.

3.3.1 ROTTERDAM AS A CITY OF ARCHITECTURE

Halfway in the 19th century, Rotterdam was made a world harbour with the construction of the Nieuwe Waterweg. In a short period of time Rotterdam grew from a provincial city to an international orientated harbour city. Villages and polders in the surroundings of the city disappeared by the construction of harbours, train tracks and storage facilities. The city itself was also drastically changed, with elevated railtracks right through the city and grand streets like the Coolsingel, where a new town hall symbolized the new big city. The commercial buildings in the harbour, with their rational, sometimes even bold concrete structures, brought an attitude of experiment and progress into the architecture of Rotterdam. From that time on Rotterdam houses the tallest office and residential building of the Netherlands.
Challenged by the turbulent growth of the harbour, architects in Rotterdam were not scared for unusual designs or radical changes. Many examples can be found, some less prominent than others. These rapid changes gave Rotterdam a specific architecture climate, an ‘own’ feeling, a feeling of diversity, modernity and international orientated. With this tradition of walking the unknown path, Rotterdam is more than other cities a real city of architecture.

What is also important for the character of the city and the architecture of Rotterdam is the bombardment of 1940, which destroyed a large part of the city centre and the enclosing districts. The ‘Wederopbouw’ (reconstruction) of the city asked again for an attitude of renewal and experiment, that brought us many valuable buildings, of which some has been listed as cultural heritage. After the harbours were restored, the city centre resurrected as a business centre with the Lijnbaan, the first car-free shopping street. The city was developed into a city where in the centre people would work or go out, but where not many people would live. Housing was located in the new districts, which were located outside the city. Only in the seventies the city realised that the presence of inhabitants is vital for a lively city centre. From that moment on housing in the centre has been an important theme.

Striking new residential buildings had to draw more inhabitants to the relative ‘empty’ city centre of Rotterdam. This development started about 25 years after the Wederopbouw with the renewal of the city. Originally it was the plan to improve existing old districts, but this gradually expanded to renovation of the old harbour areas nearby the centre. The river and shores of the Maas were found as the heart and soul of the city. The city got a new orientation, that reminded them of the big silos, storages and giant ships of the harbour. These images of the past generated an unstoppable desire for high-rise buildings.
When looking at the recent constructions in Rotterdam, you get the impression that it’s an interesting collection of individual buildings, but not that it’s a coherent urban ensemble. Both are not by definition opposites: the challenge is to work on a city with unique architecture, but with more attention for the experience of the city and the relation of the building with the direct environment and public space.

Rotterdam does not only exist of a past-war city centre, old harbour areas and past-war districts. The other half of the city is formed by the districts from around 1900 and from the twenties and thirties, with closed building blocks, streets with trees and canals, build when the harbours didn’t move towards the sea yet. Because of the typical entrances of the houses, these districts have the atmosphere of ‘typical Rotterdam’. Part of these districts are the districts that are known to have great social problems. In these pre-war parts the buildings and streets are refurbished, after which they turn into beloved areas and contribute to an attractive city. Also here attention for integration, coherence and the relation with the environment is of vital importance.

The architectural history of Rotterdam shows a series of different ideologies. In this way a city developed, with tattered villages here and there at the edge of the city and individual metropolitan blocks which are inspired by the world harbour. Only in recent times the idea has risen to create interrelationships within the urban environment (Gemeente Rotterdam, Architectuur en Rotterdam, 2010).

**Today’s assignment**

Rotterdam is a dynamic city with a special and unique collection of buildings. The city is traditionally a city of architecture that is open for renewal. This tradition will have to receive a new impulse. The renewal is in shifting from a focus on outstanding buildings to a more coherent city and architecture with expressive power. The urban environment is at least equally important as a remarkable building on
its own. Streetlife is more important as skyline. Rotterdam should be an attractive city where people and companies want to settle, making the city economically strong.

Architecture can make the city more attractive, which contributes to the wellbeing of the users of the city. It can give Rotterdam a positive image. This power of architecture can be enhanced by focusing on the coherence in the urban planning and on the liveliness of the city.

For every new building assignment there are three important criteria:

- cultural and historical layering: mixing of (transformed) existing and new buildings is of importance for the identity of the environment.
- urban context and coherence: by focusing on architecture that fits, the right programme (especially on ground floor) and a good roof landscape.
- orientation to the future: special attention to sustainability (ecologic), flexibility and transformation of existing buildings.

3.3.2 WELSTAND

It might also be interesting to know which requirements ‘Welstand’ has on the proposed areas. This is the commission that assesses, among other things, if new building plans fit the appearance of the street. The areas of the landings of the east bridge are allocated as ‘river areas’, while the west bridge’s south landing is now allocated as harbour/business area. It is assumed that in a future scenario this is changed into an housing area, so we assume that this will also be allocated as a ‘river area’ (Gemeente Rotterdam, Welstandsnota Rotterdam, 2012).

River areas

River areas are located at the shores of the Maas or at parts of (former) harbours. In the past thirty years many of these areas has lost their (original) function and came available for new development. In the past years many of these river areas have been redeveloped and have become a part of the urban area. Because these developments have occurred on both north and south side of the Maas, the river has become more and more a part of the city centre.

The buildings in these areas are mainly formed as large housing and/or work buildings with public facilities within. The beautiful views on the river and the own character of these areas is regarded as an important quality for living. The new buildings and public space are aware of the Maas and the harbour basins, which are seen as the most important outdoor areas in Rotterdam.

The high-rise buildings along the Maas influence each other and large parts of the river landscape. In addition, they form an important part of the skyline of Rotterdam. This means that the buildings at a river area are part of Fig 16. Highrise along the Maas (4).
an ensemble on different scales. From small to large this is about: the building as part of its direct environment, the building as part of the river banks as coherent area and the building as part of the skyline of Rotterdam.

A river area located at former harbour area reacts on the harbour basins. There are always new development that (partly) keep the old structure and existing buildings. That means that the harbours, with their sequence of water-quay-building, have remained intact and/or are taken as a starting point and that often some old warehouses still exist. Buildings and public space are usually designed in relation with each other and with the river or harbour basin. Almost always there is a clear relation between the inner space (the interior of the area) and the large outdoor space. From the inside of the area there is a view on the metropolitan high-rise landscape located along the water.

River areas are characterized by a high density and stony outdoor area: the quay. The more inside situated public space is often green. The quay now functions as a walking area. The continuity of the quay plays an important part in the visual connection of the different elements.

The buildings at the river areas are on average between 5 and 10 layers high, with here and there an higher building. There are mainly large building blocks or towers that are standing loose within the public space. The aim was to have public functions at ground floor, with living or working above.

**DWL terrain**

An example of such a river area is the DWL terrain. With the design of the buildings on the terrain of the former drink water company the present elements were used, like the water tower and the water basins. Towers are emphasising its location in the outer curve of the Maas, making the district part of the urban river landscape. The district itself has a suburban character.

**Characteristics and qualities**

Many river areas are very different in character from each other, which makes it hard to give a general characteristic or corresponding criteria. Buildings at the river areas form the ‘face’ of the city, when seen from the rivers and the harbour basins. Also, the specific location, in the inner or outer curve, at a former harbour or dike, is of great importance. In relation to that situation, the buildings play a large part in the quality of...
the different scales. They influence their direct environment, the bigger picture of the river banks and the general image of the city in total.

For the functioning and the quality of the different scales, sightlines and depth-working of high-rise buildings along the river are of great importance. The buildings are designed in many different ways. The alternation between view and blocked view, between fore- and background, between river and shores, give the river areas their strong visual layering. The continuity in these areas is created by the public space, the individuality by the robust buildings, with all their own identity.

The architectural unity consists of a block or ensemble, but each other can be significantly different. In most cases when the harbour areas get renewed, their (harbour) characteristics remain and are exploited. The new buildings contrast to the existing buildings, but also shows some similarities, for example in measurements and scale. The public space is designed carefully and has a stony character. The design of the buildings are in conjunction with this, with great attention for materialization. Similarity and repetition of the use of material and colour are used to reinforce the larger scale. In order to do so, many different kind of materials are used, with attention for the detail. The ground floor of the building is of major importance for the transition between building and public space. These spaces are mainly used for public functions. The design of the ground floor therefore gets a lot of attention.

TO SUMMARIZE

Urbanism
- Large live and work buildings
- Often important public functions present
- Buildings react on the Maas: large and small scale simultaneously
- Use of (harbour) characteristics
- Maas or harbour basin as central point
- Sight lines important
- Forming of skyline by visibility from far
- Autonomous volumes, in the meanwhile part of ensemble

Public space
- Carefully designed public space: the quay

Architecture
- Attention for details and materialization
- 5 to 10 floors (70-80m high), sometimes low-rise
3.3.3 QUAYS

The rivers of Rotterdam (the Maas, the Rotte and the Schie) are of high importance for Rotterdam. The experience of the rivers can be emphasised a lot more. Besides that they ask for good connections from, to, along and over the river. At this moment, the Maas forms an important spatial barrier between Rotterdam North and South. A better connection of the shores, by reducing the distance between the current crossings, can greatly enhance the unity of Rotterdam. It offers new possibilities for attractive living and meeting places. It is wanted that the rivers, as part of the urban traffic and transport network, are exploited better, in which mainly local connections can form new links. Moreover traffic over water can be an excellent addition for the urban and regional cycling network, as can be seen in Amsterdam. A better balance in the use of the different modalities of the current crossings offers chances for a spatial quality impulse on the squares and at the landings of these crossings.

The new crossings will have to break down the function as barrier and in the meanwhile improve the river as a destination and place to stay. The reduced amount of car traffic in the city centre will automatically mean less traffic using the crossings and the traffic intersections at the end of the landings. This will help to make the shores more accessible for pedestrians, cyclists and public transport. It should create space for comfortable staying at the shores of the Maas. In this way the river gets a bigger meaning for the city. There should be plenty of green and food industries along the shores (Gemeente Rotterdam, Stedelijk Verkeersplan Rotterdam, 2016).

Fig 20. De boombjes. A good example of a green quay (8).
Demands.
- Experiencing the river
- River as destination and place to stay
- Plenty of green and food industries

Fig 21. Hotel New York. Another good example of a green quay, where the river can be experienced (9).

Fig 22. Holland Amerikakade. A quay that is reserved for pedestrians, but it’s not attractive (10).
3.3.4 CASE STUDIES CURRENT BRIDGES

In this paragraph, the current bridges will be studied to determine the identity of the city bridge in Rotterdam and what this means for the new crossings.

There are currently five important bridges crossing the Nieuwe Maas in Rotterdam, of which four are still in use. One of these, the van Brienenoordbrug, is part of the highway around Rotterdam and the others are real city bridges. These bridges all play a different, but important role in the development and functioning of the city. The proposed new connections will both have their own functions and part in this series of crossings.

Fig 23. Bridge locations (own work).

When sailing land inwards, the new western crossing will be the start of the city of Rotterdam and the series of bridges. The eastern bridge will be the last of the city bridges in the series, in the transition to the highway bridge.

Fig 24. Series of bridges in Rotterdam (own work).
General info

Architect: B. van Berkel
Year of construction: 1993 – 1996
Construction type: Cable-stayed bridge
Operability: Bascule
Material: Steel
Measurements: Total Length 802 meter
Width 33.8 meter
Pylon height 139 meter
Vertical clearance 12.5 meter above NAP

Context

The Erasmusbrug lies centrally in Rotterdam in the extension of the Coolsingel and the Schiedamsedijk. It connects the old city centre of Rotterdam with the Kop van Zuid, on the south side of the Maas.
Why was it built?

Obviously, there is traffic crossing the Erasmusbrug. There are two 1.5 car lanes crossing the bridge, two tram lanes and there is space for pedestrians and cyclists. The most important function though, and the main reason why it was built, was not the connection of traffic, but the symbolic and iconic connection between the centre of Rotterdam and the Kop van Zuid. The Erasmusbrug was to give an impulse to its environment and to boost the development in the area, and it did exactly that. The surrounding area thrived under the icon that the Erasmusbrug is.

Function development

The function of the bridge hasn’t really changed over the years. It was built as an icon and symbol, and it still is. The Erasmusbrug is inseparable from the Rotterdam skyline. The bridge has become one of the most important images of Rotterdam internationally.

Strengths and weaknesses

The biggest strength of the Erasmusbrug is its iconic value and design. It fulfils its task completely as a symbol for Rotterdam as a modern metropole. Another strength of the bridge is its quite ingenious traffic system. There are wide bicycle paths and pedestrian walkways, the needed space for the trams, but a quite narrow two lane street. By narrowing the lanes and having high borders, it is discouraged to use both lanes at high speed, where at low speeds both lanes can easily be used, improving the traffic flow in rush hour but keeping it safe at quieter times.

With one of the biggest strengths, also comes one of its arguable weaknesses. The bridge is designed from an architectural point of view and not from a structural basis. This was cause to some discussion and criticism from structural engineers. The design of the bridge is not the most efficient and this drove up the cost. The design was chosen despite the extra costs, because of the demand for a landmark.

WILLEMSBRUG

Fig 27. Willemsbrug (12).
General info

<table>
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<th>Architect:</th>
<th>C. Veerling</th>
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<tr>
<td>Construction type:</td>
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<td>Width</td>
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<tr>
<td>Pylon height</td>
<td>55 meter</td>
</tr>
<tr>
<td>Vertical clearance</td>
<td>11.5 meter above NAP</td>
</tr>
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Context

The Willemsbrug is the most east crossing in the city centre of the Maas. The red bridge connects the right shore of the Maas with the Noordereiland. The norther ramp is turned 90 degrees relative to the bridge and is made as a viaduct. Underneath this viaduct a nightclub is established. The viaduct ends in a traffic square that enables the people to enter the bridge from both the Maasboulevard and from the city centre, via the Verlengde Willemsbrug. The southern ramp on the Noordereiland is made as a natural ramp that crosses the whole island.

Why was it built?

Until the opening of the Maastunnel the old Willemsbrug was the only fixed connection crossing the Maas. The increasing traffic caused a bottleneck at the landings of the bridge. This problem was somewhat solved with the construction of the Maastunnel in 1941.

There were already plans to replace the old Willemsbrug for a new crossing and a new traffic square on the northern side in the thirties. Also in the Basisplan, the plan that was made for rebuilding the city after the Second World War, a bridge was mentioned with a roundabout at the Oudehaven. During the
fifties the municipality had the idea to replace the Willemsbruggen with a combined train and traffic tunnel. The Dutch most important train operator NS waived this proposal, after which the municipality in 1970 decided to construct a tunnel with six lanes for cars. The new local authorities did not like this idea of unrestrained car traffic. Transit traffic was supposed to use the Van Brienenoord (1965) and the Beneluxtunnel (1967), so that the Willemsbrug was only used by local traffic. The tunnel was therefore replaced by a bridge with only three lanes for car traffic, two additional lanes for busses and wide cycling and pedestrian paths. To save the historical buildings at Oudehaven, it was decided to curl the traffic through the city (Willemsbrug, 2016).

**Function development**

In 1878 a bridge was opened that was named after King Willem III, who had placed the first stone in 1874. Also between 1870 and 1877 the Willemsspoorbrug was constructed over the Nieuwe Maas. Together with the trainbridge ‘De Hef’ and the Koninginnebrug, both crossing the Koningshaven, they connected the centre of Rotterdam via the Noordereiland with the south shore and were called the Maasbruggen. The construction of these bridges was the start of major developments at Rotterdam South. It also made a train connection possible between the line Amsterdam-The Hague-Rotterdam and the line that connected The Netherlands with Antwerpen.

The old Willemsbrug was 326 meters long, divided over two ramps and three large spans. Tram tracks for the horse trams were already constructed in 1884 and in 1904 these tracks were made suitable for electric trams (Willemsbrug Rotterdam, 2014).

In 1975 C. Veerling got the assignment of designing the new Willemsbrug. It was supposed to reach a height of 9,1 meters above the highest known water level, which meant 12,5 meters above NAP. Because of the high building costs, caused by the expensive landings, this was eventually adjusted to 11,5 meters above NAP. From six designs that were developed, the municipality selected the cheapest: a symmetric cable-stayed bridge with A-like pylons, that functioned as a gate. Veerling himself preferred an asymmetric cable-stayed bridge with one pylon, like the later built Erasmusbrug.
The new Willemsbrug was built approximately hundred meters eastward. The two 65 meter high pylons stand 260 meters apart, with a slight curved deck between them. The bridge is 34 meters width. The deck is designed as one slab so that it can have a flexible function. The southern ramp on the Noordereiland is made as a natural ramp and the northern ramp is made as a viaduct. Underneath this viaduct a nightclub is established (Willemsbrug, 2016).

The Willems train bridge was demolished in 1993 and replaced by a tunnel. Nowadays only the landings of the old bridge still exist.

The Willemsbrug is by far the least used crossing of the Maas in Rotterdam. In 2011 only 19,000 cars per day were crossing the bridge. As initiated in the plans of the bridge, it mainly serves local traffic only. This is mainly caused by the turning landings and the illogical route that is needed to get from the main roads over the bridge. It lost its former function as crossing for trams, and now only facilitates two bus lines.

**Strengths and weaknesses**

The Willemsbrug is a very simple but functional bridge. With its sober design it just does where it’s meant for: to bring people from one side of the river to another, while giving ships sufficient space. The most interesting feature of the Willemsbrug is the flexibility that the deck is providing. The deck is designed as a large flat slab. It can facilitate multiple different kinds of traffic because it’s wide enough and has low inclines. Together with its structurally functional look, the red colour and the two gate-like pylons give the bridge its unique character.

Where the structure is very functional, the routing of the landings of the bridge is questionable. The turn on the North side is understandable, since there is no space for a ramp in the same direction as the bridge. And also the fact that the Koninginnebrug is not in the extend of the Willemsbrug is understandable, seeing the history of the bridges at this location. But combined with the extra turning that is needed nowadays after crossing the Koninginnebrug, it is not a convenient route to pass the Maas.

General info

<table>
<thead>
<tr>
<th>Architect:</th>
<th>A.H. van Rood</th>
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<tr>
<td>Year of construction:</td>
<td>1923 – 1929</td>
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<tr>
<td>Construction type:</td>
<td>Truss bridge</td>
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Fig 30. Koninginnebrug (14).
Context

The Koninginnebrug crosses the Koningshaven and connects the Noordereiland with the south of Rotterdam. It is located next to the Hef, the old train bridge. It serves as the extension of the Willemsbrug in the connection of North Rotterdam with South.

Why was it built?

The old Koninginnebrug had the same problems as the old Willemsbrug. Because it was part of the only fixed connection crossing the Maas, the Koninginnebrug was used a lot. This only increased with time. Since the old Koninginnebrug was a swing bridge, it was also an obstruction for ships. The bridge was also not suitable for trams. That’s why it was decided in 1923 to build a new bridge, this time in the form of a double bascule bridge.

Function development

The old Koninginnebrug, that opened in 1870, was a swing bridge connecting the Noordereiland with Rotterdam South. It was positioned at what would now be the extend of the new Willemsbrug. It was built within a series of bridges that would connect the north of Rotterdam with the Noordereiland and the south; the Maasbruggen. The old bridge only had space for two car lanes and a small pedestrian path on both sides. After being in use for 50 years, it was decided that the old bridge should be replaced by a new bridge, with a much larger width.

The new Koninginnebrug was finished in 1929. It was positioned in the extent of the old Willemsbrug.
As mentioned, the bridge is a bascule bridge with two moveable leaves. The massive curved trusses of riveted steel give the bridge its unique appearance. These trusses are part of the roll bascule structure, which is clearly visible. These trusses also help in organising the functions of the bridge, causing they separate the slow and fast traffic from each other.

With this type of opening, the width of the ships that can pass was enlarged. When closed, the Koninginnebrug doesn’t have a high vertical clearance, but that is not needed since most ships will take a different route via the Nieuwe Maas. Only the ships that can’t pass the Willemsbridge take this route.

The deck of the bridge was widened to 30 meters, now facilitating 4 lanes for car traffic, 2 lanes of cycling path and wide pedestrian zones. Since the construction of the North-South line of the metro of Rotterdam finished, there are no more trams on the bridge. Attached to the bridge are 4 bridge operator’s houses. The small round brick houses have notable coper roofs in the shape of a cone. Nowadays these houses have lost their function, but they have a high cultural historic value (Koninginnebrug Rotterdam, 2014).

At the time of construction, the Koninginnebrug and the Hef symbolised the lead that Rotterdam took in both the areas of industry and technology. The Koninginnebrug was at that time the largest bascule bridge in Europe. Together with the Hef it represented the new city of Rotterdam.

**Strengths and weaknesses**

The vertical clearance of the bridge when it’s closed is one of the weaknesses. This is very low and not functional. But with the opening of the double bascule bridge, it has a wide and high clearance. The bridge represented a new era for Rotterdam and is still valued for its industrial and typical Rotterdam look. It is both beautiful and functional. The position of the bridge is in nowadays situation not logical. It would have been better if the bridge was located at the extend of the Willemsbrug.

![Fig 32. View on the Koninginnebrug (15).](image)
General info

Architect: P. Joosting  
Year of construction: 1924 – 1927  
Construction type: Truss bridge  
Operability: Lift  
Material: Steel  
Measurements:  
Total Length: 79 meter  
Width: 11 meter  
Vertical clearance: 8,20 – 46,40 + NAP

Context

Fig 34. Urban context De Hef (own work).
De Hef, or officially the Koningshavenbrug, is an old railway bridge crossing the Koningshaven, connecting the Noordereiland and the south. It was designed by ir. P. Joosting, an engineer from the Dutch railway company, but ever since the construction of the railway tunnel (de Willemsspoortunnel) underneath the Maas, de Hef has been out of use.

Why was it built?

De Hef was constructed to make a railway connection over the Nieuwe Maas. The current bridge however, is not how it was originally constructed. In 1878 the bridge was constructed as a rotational bridge. This design formed a big hindrance for the shipping lane. The narrow passage caused multiple ships to jam. After, in 1918, a ship even crashed into one of the pillars, the decision was made to replace the rotational part with a lift, limiting the vertical clearance to 46.40 metres above NAP, but widening the passage.

Function development

As mentioned before, de Hef started off as a railway connection over the Maas, but has become obsolete after the construction of the Willemsspoortunnel in 1993. After this, the Hef was nominated for demolition, but after extensive protests, this plan was waived. The old railway bridge is now included in the list of monuments to be a memorial to where the trains used to leave the centre of Rotterdam. In the southern pillar, a nesting place for peregrine falcons has been placed.

Strengths and weaknesses

Obviously, the original Koningshavenbrug had its flaws in clearance. However, this has been solved with the new lift system. The bridge has a strong and industrial appearance. The inhabitants of Rotterdam have, as shows by the protests against demolition, are very fond of the bridge. Even though it’s not used anymore it belongs in the image of Rotterdam.

VAN BRIENENOORDBRUG

![Image of Van Brienenoordbrug](image-url)
General info
Architect: W.J. van der Eb
Year of construction: 1961 – 1965
1986 – 1989
Construction type: Arch bridge
Material: Steel
Operability: Bascule
Measurements:
Total Length 1320 meter
Width 2 x 28 meter
Vertical clearance 25 meter above NAP

Context

The van Brienenoordbrug is the largest spanning traffic bridge in the Netherlands. The bridge is part of the A16 highway on the east side of Rotterdam and facilitates over 250.000 cars crossing the Nieuwe Maas each day.

Why was it built?
The bridge was built as part of the expansion of the national road network. The plan for the bridge was already made in the early thirties. The budget, made available for this plan, was then however used for the construction of the Maastunnel. It was after the war that the plan was picked up again. The bridge completed the ring of Rotterdam. It facilitates traffic on the east side of Rotterdam and keeps the traffic away from the city centre.

Function development
The van Brienenoordbrug consists out of two parts. The first arch was opened in 1965, but it quickly became apparent that the capacity of the bridge was inadequate. In 1986 the construction of an almost identical arch started. In 1989 the second arch was placed and doubled the capacity. With six car lanes in two ways, and a wide bicycle path, the bridge became the largest traffic bridge in the Netherlands. Even now the bridge’s capacity is not quite adequate for its demand.

Strengths and weaknesses
For its time, the design of van der Eb was revolutionarily slender and transparent. With the use of the
diagonal cables and the proportions off the arch, the large span of 300 metres was made possible and a stiff and dimensionally stable whole was created.

CONCLUSION CURRENT BRIDGES
The current bridges in Rotterdam played a major role in the development of the city, especially of the Southern part. Nowadays they are still of vital importance, since next to the city bridges, the Maastunnel is the only other crossings of the Maas.

The current bridges in Rotterdam were built to represent the time of that period and the possibilities of technology at that time. In this way they all got their own identity and character. All bridges are also very recognizable by their colour. With their identities the bridges are an iconic part of the skyline of Rotterdam, even though only the Erasmusbrug is really designed to be an icon. The other bridges are designed from a functional point of view.

The Van Brienenoord, a highway bridge, is a very functional designed arch bridge with large dimensions. The two large city bridges, Erasmusbrug and Willemsbrug, are slender designed cable-stated bridges.

3.3.5 CONCLUSION

The research provides us with strategic guidelines for the design of the new crossings:

- The bridge and quays should be part of an attractive and lively public space. This public space needs to create coherency within the urban planning of the city.
- The quays should be attractive for pedestrians and cyclists. There should be space for comfortable staying and relaxing at the shores of the Maas.
- This also means there should be plenty of green on the quays.
- At urban scale, the bridge should be an autonomic volume as part of a greater ensemble.
- The bridge should have its own identity and character, which represents and is coherent with the current time.
- With its identity it should find connection to the current city bridges (Erasmusbrug & Willemsbrug), not to the highway bridge (Van Brienenoordbrug). That means a slender and elegant design is required.
- The bridge should have a coherent design of the different parts. That means that the large span and operable part of the bridge should be integrated in one design.
4 Analysis site

In this chapter an analysis of the specific site will be made. That means that the future plans for this area are researched first. Secondly, the current flows of traffic and the urban structure of the area are explored. This will result in demands and guidelines, specific for this site.

4.1 FUTURE PLANS

There are two plans for this area that are of major influence for the bridge’s design. This is the plan for Feyenoord City, as described in ‘Gebiedsvisie Stadionpark’ (Gemeente Rotterdam, Gebiedsvisie Stadionpark, 2016) and the plan to create two tide parks at the Eschpolder and the Van Brienenoordeiland, as described in ‘Getijdenpark Brienenoord – De Esch’ (Gemeente Rotterdam, Getijdenpark Brienenoord - De Esch, 2015). A description of these plans relevant to the design of a new crossing will be given.

4.1.1 GEBIEDSVISIE STADIONPARK

In this document, a vision is given for the whole area around the current stadion of Feyenoord, including the position of the new stadium. The Stadionpark is located on a very prominent position within the city of Rotterdam. It's on the crossroad of the Kop van Zuid, IJsselmonde, the city districts at Rotterdam Zuid and the river. Because of this position the area is experienced by many people, not only from the districts surrounding it, but by users of the whole city. For travellers by train this is the only place where the relation between the Maas and Rotterdam can be experienced. With the continuing roads and tram lines, this is an area where many people travel through during the day. This makes it an important entry to Rotterdam.

Feyenoord City

Fig 37. New stadium (18).
The area around the new stadium is called ‘Feyenoord City’. The position of this new stadium is a strategic spot within Rotterdam Zuid. Different flows of transport come together in this area and it’s positioned between the Maas and the districts at Zuid. However, currently this area is not functioning as a traffic node, but more as a barrier. The new developments will form the connection between de Kop van Zuid, the districts at Zuid, the river shores and the Sportstad. It will be a lively spot, with supporting functions as food industry, housing and leisure possibilities. In this way not only the stadium will become an important destination, but also the quays. Continues routing along the river will be possible by a passage around the stadium. This passage will make the stadium of extra added value for the area and the city, since it’s a destination but also a connection. It will be accessible by the public at all times.

**Future public transport**

A new bridge is not planned in this document, since this decision has to be made by another department. But the positioning of new possible connections are taken into account with the developing of this plan. That means that the space needed for this infrastructure is kept open. This basically narrows down the possibilities of a new bridge to land at the south to two places, near the stadium or near van Briennenoordeiland.

**Green**

As can be seen in the next image, green plays a vital part in the new plan. Important for the design of a new bridge is the role of the quays within this green plan. The quay will become one recreational route along the Maas with different atmospheres and

![Fig 38. Proposed bridge locations (18).](image)

![Fig 39. Different (green) environments along the Maas (18).](image)
This plan is part of a bigger plan that’s about all areas along the Maas, where the river is seen as one large tidal park. The goal is to make the river more natural, accessible and attractive in relation to the urban environment, to create a stronger relation between water and land, between nature and city.

### 4.1.2 GETIJDENPARK PRIESENYOORD - DE ESCH

This plan is part of a bigger plan that’s about all areas along the Maas, where the river is seen as one large tidal park. The goal is to make the river more natural, accessible and attractive in relation to the urban environment, to create a stronger relation between water and land, between nature and city.
creation of such parks have many ecological benefits, but also social benefits, because they also have a recreational function.

**Brienenoord – De Esch**

This location forms the transition between the urban area of Rotterdam and the more suburban areas of surrounding districts and villages. Because of this it can form a link in a larger recreational network but it can also be a destination for people that want to get out of the city for a moment. In addition, it can serve a nice walk for people from nearby neighbourhoods. Remarkable are the two hidden nature areas at both sides of the Maas. Both the Van Brienenoordeiland and the polder outside the dykes called De Esch are easily passed without noticing, even though they sum up to a total of 70 hectares of nature in the middle of an urban area. By connecting the Van Brienenoordeiland better and by ‘opening up’ De Esch two beautiful tidal areas can be created. Together they form an attractive green city entrance. The parks will be clearly in the view to the city from de Van Brienenoordbrug: the silhouette of highrise buildings through which the Maas meanders, with large tidal parks at both sides of the water at the foreground. The city shows here its green image.

![Recreational areas along the shores (19).](image)

**Eschpolder**

At this moment, de Eschpolder is divided in two parts by a former dyke. The north is now a wild growing piece of nature, while the south part still has the polder structure with old (monumental) buildings. To
realise a tidal park in the northern part of de Esch, the former dyke needs to be raised to protect the polder from the tides.

**North – South connection**

These areas are not only part of the river shores, but also of the green structure that passes through Rotterdam from North to South. The shores and the green along it are now more a barrier, but will become the link between these green structures.

Fig 43. Tidal park at the Eschpolder (19).

Fig 44. Green North - South connection (19).
To determine the position of the bridge and additional demands and guidelines, the site has been analysed within the current urban context. Important here was to look at the physical boundaries, i.e. where can the bridge be build, but even more which networks are there and which need to be created. That’s why the site is viewed within the scale of the city. The most important characteristic of the site are described below.

4.2.1 MORPHOLOGY

Clearly visible in the morphology of the surrounding is the new stadium (red), with next to it an empty area. This is currently a parking place. This area is in future plans reserved for the landing of a bridge. It is also marked as an urban area between the green tide parks. To place the landing of the bridge here would be logical. Next to this area are some newer housings (orange), which can’t be demolished. On the north side of the river are also a few buildings in the polder, which have monumental value, and they can’t be demolished.

4.2.2 GEOLOGY

A remarkable characteristic of the site are the differences in height over the location. At south there is a partly lowered quay, only accessible for pedestrians and cyclists. In the north there is a dyke that
prevents the polder behind it from flooding, since this polder’s ground level is below the water level of the river.

Fig 46. Height differences at the site (19).

4.2.3 TRAFFIC

As deducted from the analysis of Rotterdam, the new crossings will have to be focussed on sustainable means of transport, meaning plenty of space for pedestrians, cyclists and public transport. Cars can be allowed as a guest. These traffic flows near the site are analysed, but also the nautical activities passing the bridge.

Fig 47. Traffic flows (own work).
The current way to get from Feijenoord to Kralingen is quite a long drive. Despite not being the nearest place to cross, the Erasmusbrug is considered the most comfortable way to cross the Maas for cyclists and cars, for trams it’s the only possible way to cross. The other bridges are not considered comfortable, mainly because of the illogical slopes. For cyclists there is also a small ferry for crossing the Maas. Looking closer to the site on the south side of the river, there is already a proper network for cars, trams and cyclists to connect to. In the north there is a small road (Nesserdijk), which is used by cars as a shortcut to get from the east into the city and reverse. This actually makes it a bit unsafe for cyclist and pedestrians. This requires attention in the design of the bridge. Nearby is a final stop of the tram which can be connected to.

**Nautical activity**

The Nieuwe Maas and its crossings have to deal with a lot of shipping. In the map below, the routes of the different types of shipping are shown and thusly the ships the crossings have to account for. In this map, the leisure boating activities are not shown, as they won’t be determinative and don’t have standard routes.

![Nautical Activity Map](image)

It can be seen that there are two main routes for the barge vessels/inland navigation. The northern route is underneath the Erasmusbrug and the Willemsbrug. This route only has a clearance of 11.10m. For ships that are higher, there is an alternate route south of the Noordereiland. In this route the bridges are operable. The route continues on the north side of the river, where also the operable part of the Van Brienenoordbrug is located. Finally, there is frequent public transport over the water. These so called water busses, will have to be able to pass the bridges without them opening.

**4.3 CONCLUSION**

For the design of a new bridge it is important to keep in mind which urban networks it will connect and which new networks and relations it can create, hereby also keeping in mind the future plans for the area.
- The position of the bridge is most logical east of the new stadium.
- The bridge can form a connection between the two nature areas along the shores.
- The quays should be designed as a park to assure a continues route for pedestrians and cyclists.
5 Guidelines and demands

Urban plans
- The new crossings will have to be focussed on sustainable means of transport, meaning plenty of space for pedestrians, cyclists and public transport. Cars can be allowed as a guest.
- The new crossings need to be easily accessible to the public.
- Attractive public spaces are wanted with interesting quays.
- On the quays, pedestrians will have priority in a space for staying and relaxing. Visitors of the quays should be able to experience the water.

Visual quality plan
- The bridge and quays should be part of an attractive and lively public space. This public space needs to create coherency within the urban planning of the city.
- The quays should be attractive for pedestrians and cyclists. There should be space for comfortable staying and relaxing at the shores of the Maas.
- This also means there should be plenty of green on the quays.
- Sightlines to the city's skyline from the bridge and quays are important.
- At urban scale, the bridge should be an autonomic volume as part of a greater ensemble.
- The bridge should have its own identity and character, which represents and is coherent with the current time.
- With its identity it should find connection to the current city bridges (Erasmusbrug & Willemsbrug), not to the highway bridge (Van Brienenoordbrug). That means a slender and elegant design is required.
- The bridge should have a coherent design of the different parts. That means that the large span and operable part of the bridge should be integrated in one design.

Site specific
- The position of the bridge is most logical east of the new stadium.
- The bridge can form a connection between the two nature areas along the shores.
- The quays should be designed as a park to assure a continues route for pedestrians and cyclists.

Technical demands
- Static span of the bridge should have a clearance of at least 200m wide by 12m vertical (Erasmusbrug normative).
- The moveable bridge should have a width of at least 50m (Erasmusbrug) and an unlimited vertical clearance.
- The bridges crosses about 400 to 430m.
6 Structural analysis

In this chapter research on the different construction types for bridges will be done to get an insight in the technical possibilities of crossing the Maas with a bridge. The focus is hereby on the aesthetical properties, structural principles, technical properties and typical material usage of the different bridge typologies. The same will be done for the openable bridging types. Additional research will be done for the landings.

6.1 BRIDGING TYPES

6.1.1 BEAM BRIDGE

Fig 50. Beam bridge (own work).

The beam bridge is the simplest, most common of bridges and probably the first bridging system ever used. It is simply made up of two beams that span across a gap with a deck on top of them. The primitive beam bridges can be found all around us, even in nature, when a log falls across a river.

Structural principle

Fig 51. Compression (red) and tension (blue) in beam bridge (own work).

A beam bridge carries its vertical loading by bending. The bending moment in the beam results in compression in the top and tension in the bottom of the beam. The supports of the beam will be subjected to compression, carrying the loads to the foundation.

Measurements

The span of a simple beam bridge is very limited. A simple system will only span up to about 100 metres. There are systems to improve the spanning capability like a steel plate box girder system. This will greatly improve the spanning capability to about 300 metres. But usually, a simple beam bridge will need a lot of supports when making a long crossing.

Material

A beam bridge can be built in different materials. This usually mostly depends on the needed span. Most of the more modern traffic beam bridges are composite of steel, to take the tension, and concrete.

Rio-Niterói Bridge

Officially called the President Costa e Silva Bridge, the Rio-Niterói Bridge is the longest spanning box girder bridge in the world. It crosses Guanabara Bay in the state of Rio de Janeiro in Brazil, connection Rio de Janeiro and Niterói. The bridge is a massive 13,3 kilometres long and 27 metres in width.

Fig 52. Rio-Niterói bridge (20).
6.1.2 TRUSS BRIDGE

A truss bridge actually uses the same principle as a simple beam bridge. It is an improvement to the primitive system by replacing the simple beams with a truss. This increases the height of the system and reduces the occurring bending moments. A truss bridge gains strength and construction height with minimal material use.

**Structural Principle**

As mentioned, the truss bridge uses the principle of gaining construction height, without increasing material usage. The occurring bending moments in the “beam” are minimized, making optimisation in the separate parts possible. In a truss, the bottom chords will have to endure tension, whilst the top chords endure compression. In the web of the truss, the vertical chords will be under compression, and the diagonals in tension.

**Measurements**

The replacement of the beam by the truss, greatly increases its spanning capacity. Truss bridges can span up to 400 metres. Also as mentioned before, the truss does add height to the bridge.

**Material**

A truss bridge is often built with steel, giving it its industrial look. However, different materials are possible, like timber for instance.

**Ikitsuki Bridge**

Connecting Ikitsuki and Hirado in Japan, is the Ikitsuki Bridge. It is the longest continuous truss bridge in the world, spanning 400 metres.
6.1.3 RIGID-FRAME BRIDGE

A rigid-frame bridge uses a construction in which superstructure and substructure have merged together to form one continuous unit, a monolithic structure that forms deck and supports out of one solid piece.

There are three types of rigid frame structures. A single span rigid frame structure has two support points at the abutments, with a single span in between. The design can be optimized in material use by reducing the amount in the middle of the span. This gives the bridge a characteristic arch shape.

A V-shaped rigid frame structure supports the bridge in two points, while it only requires one foundation. With this structure, a multiple span bridge is possible.

The last option is a batter post rigid frame structure, which uses supports that connect to the abutments on an angle. It is used for single span bridges.

**Structural principle**

A rigid frame structure has rigid connections, meaning that it can transfer bending moments, axial forces and shear forces. The forces will be the highest at the supports of the deck, and lowest in the middle of the span.

**Measurements**

The possible span is depending on the properties of the section of the structure and material. The largest build rigid frame bridges, the Grand Canal Bridge at Le Havre, crosses about 275 meters, using two V-shaped frames. The characteristics of the environment are important for the use of this structure. The rigid-frame structures require a certain height for the columns to function efficiently. This makes them especially useful in areas with canyons, mountains or other areas with steep banks.

**Material**

The structures can be made out of (pre-stressed/reinforced) concrete, steel or composite material.

**Grand Duchess Charlotte Bridge**

The Grand Duchess Charlotte Bridge is a car bridge situated in Luxembourg City, Luxembourg and is built between 1962 and 1965. It crosses a total length of 355 meter, with the largest span being 234 meter. The bridges reaches a height of 74 meters above the Alzette valley. It is clearly visible that the bridges uses a monolithic frame. Also the descending size of the section towards the middle of the span is characteristic for this bridge.
The arch based bridge is the second oldest type of bridge. Many ancient and well known stone arches still exist to this day, but this type of bridge is also still an often used structure for new bridges. In general there are three types of arch based bridges.

A deck arch bridge is a structure where the deck is completely above the arch. The area in between the deck and the arch is called spandrel. The spandrel can either be solid or open, and sometimes it contains a number of columns rising from the arc to support the deck.

The through arc bridge has an arch which base is below the deck. The top of the arch rises above it, meaning that the arc passes through the deck. The central part of the deck is suspended from the arch, while the ends of the bridge may be supported by the arc, as with a deck bridge.

The last type is a tied-arch bridge. With this type the arch is positioned completely above the deck and the deck is suspended from it. This deck is used as a tie, and it's capable of taken the horizontal forces that normally would be exerted on the foundation. A tied-arc bridge can also be a through-arc bridge.

**Structural principle**

The geometry of an arch structure is very efficient in transferring loads to its foundation. The principle of the arch based bridge is for all types the same. The arch itself always primarily acts in compression. The load on the deck is transferred to the arch, either by columns with compression forces, or with cables using tensile forces. The arch then transfers this downwards to the foundations. There it exerts a horizontal force outwards, that is taken by its foundations. In case of a tied-arch bridge, the horizontal...
forces are taken by the deck, that works as a tie.

**Measurements**

The arch bridge can be constructed in many different ways, depending on the span. This can range from simple bent steel profiles to massive truss structures forming an arch. The largest build arch bridge is the Chaotianman Bridge in Chongqing, China, and has a span of 552 meters.

An arc bridge can have one arc, in line with the deck or out of line, or two arcs. They can be slanted relative to the plane of the deck.

The arc bridge requires solid foundations to be able to withstand the horizontal forces. By removing the horizontal forces, as the tied-arc bridge does, the foundations of the bridge can be designed much smaller. This makes the bridge suitable for soft soils of riverbanks and makes it possible to prefabricate the bridge.

An arch based structure with a suspended deck also allows the construction depth of this deck to be reduced to a minimum, even at long spans.

**Material**

An arch based bridge can be made in construction materials like stone, wood, concrete, steel and composite.

**De Oversteek**

De Oversteek is a city bridge located in Nijmegen, The Netherlands, that is built between 2011 and 2013. It's a tied-arch bridge using a single arc to span 285 meter, which makes it the largest single-arc bridge in Europe. The arch is 60 meters high and the bridge has a vertical clearance of 14,5 meters. This bridge is good example of a large span, though a very slender design.

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Fig 62. De Oversteek in Nijmegen (23).
6.1.5 CANTILEVER BRIDGE

As the name suggests, a cantilever bridge uses a cantilevering construction, only supported on one side. Originally the bridges where made using a simple beam, but this limits the possible span. Making use of a truss in the cantilever makes way larger spans possible that can easily be constructed as there is no falsework needed. The steel truss cantilever bridge was a major breakthrough making huge spans possible.

**Structural principle**

In the image below, the structural principle of the cantilever bridge is illustrated in real life. A cantilever bridge generally consists of three spans. Two outer spans, anchored to the shore and cantilevering over the obstacle to be crossed, and the central span, resting on the cantilevered arms extending from the outer spans. The centre part carries its loads like a simple beam or truss, with compression in the upper chords and tension in the bottom chords. The cantilevers however, carry the loads with tension in the upper chords and with compression in the bottom chords. The towers are loaded with compression, straight to the foundation.

Fig 63. Cantilever bridge (own work).

Fig 64. Compression (red) and tension (blue) in cantilever bridge (own work).

Fig 65. Real life representation of cantilever bridge (24).
Measurements

The cantilever bridge can span over 500m. This usually does come with quite a large construction.

Material

The larger spanning cantilever bridges will typically be built in steel trusses. However, the first cantilever bridges, with smaller spans, were made out of wood or stone.

Forth Bridge

The Forth Bridge is a railway bridge in the east of Scotland, near Edinburgh. It has a total length of 2467m and the towers rise 110m above the water. It has a massive vertical clearance of 46m. The bridge consists of three cantilever towers with two spans of 520 metres. It was the longest single cantilever bridge span in the world until 1917. Constructed from 1882 until 1890, it was the first major steel structure in Britain.
6.1.6 CABLE-STAYED BRIDGE

The cable-stayed bridge is nowadays a very common and popular type. It uses one or more pylons, from which the deck is suspended with cables. These cables run directly from the deck to the tower, creating a fan-like pattern or a series of parallel lines.

**Structural principle**

The cable-stayed bridge works if the forces in the pylon of the bridge are in balance. The load on the deck itself is mainly vertical. Due to the connection of the cables directly from deck to pylon, a horizontal component is created. The pylon needs to be stiff enough in order to take this horizontal force, or the horizontal force needs to be taken in a different way. The span of the bridge determines the amount of horizontal forces in the structure. A larger distance between the pylon and the point where the cable connects to the deck, the smaller the angle of the cable will be. The smaller the angle of the cable, the larger the horizontal component will be. The pylons of a cable-stayed bridge will mainly sustain compression forces. The deck girders sustain both compression and bending forces.

**Measurements**

The size of the pylon is depending on the size of the horizontal forces. As mentioned, the angle of the cables determines the horizontal component. To reduce this force, the angle that the cables make has to be maximized. This can be done by making a higher pylon. The structure of the cable-stayed bridge will work as long as the pylon is able to handle the pressure and will not buckle under the loads. If the design is in balance, the pylon can be designed mainly on compression forces and can turn out quite slender.

The largest span cable-stayed bridge that has been built is the Russky bridge in Vladivostok, Russia, which has a central span of 1104 meters. It uses two pylons of 320,9 meters for this.
The points where the cables connect to the deck can be in line with the deck, but also out of line. It is also possible to have two series of cables, each connecting to one side of the deck.

The advantage of the cable-stayed bridge is the vertical clearance underneath the bridges deck. There is no support structure needed underneath it.

**Material**

A cable-stayed bridge has several components that can have different materials. The pylons are usually made from steel or concrete. Steel cables are needed to carry the tensile forces. The deck can be made of steel, concrete or a composite material like FRP. Because of the presence of bending forces in the deck, special attention needs to be given to this when concrete is used.

**Millau Bridge**

One of the most impressive cable-stayed bridges is the Millau Bridge in France, which was built between 2001 and 2004. The bridge has a total length of 2460 meters, with the longest span being 342 meters. It crosses the valley with a vertical clearance of 204 meters. It is seen as one of the greatest engineering achievements of all time.
6.1.7 SUSPENSION BRIDGE

The suspension bridge is one of the oldest of engineering forms. In primitive times they were constructed using vines for cables and mounting the roadway directly on the cables. Over the centuries, this concept, and most of all the materials, were improved. Nowadays, the suspension bridge provides an economical solution to creating long spans when it is difficult to found piers.

**Structural principle**

The main structural principal of the suspension bridge is fundamentally simple. Typically, two towers (or pylons) support two parallel cables between them and from the tower to the anchorage. From the two main cables, multiple vertical cables are hung, which support the deck. The load on the deck is all transferred via the cables in tension towards the towers, which carry them by vertical compression to the foundation, and to the anchorages, which resist the inward pull of the cables. The suspension bridge can be seen as an upside-down arch bridge, only in tension instead of compression. Because the deck is hung in the air, the deck might move excessively if care is not taken. The deck will need to be heavy or stiff to prevent this.

**Measurements**

The suspension bridge has the largest possible span of all the bridging types. The longest span in the world is on the name of the Akashi Kaikyo Bridge, which spans a massive 1991 metres. This does come with 282.8m high pylons.

**Material**

Typically, the large-span suspension bridges are made out of steel. The prefabrication leads to high quality work at minimum cost. But as mentioned before, the original principle of the suspension bridge has been used for over centuries and was originally built with natural products like vines, wood and bamboo. Furthermore the towers of the suspension bridge can be made out of concrete, since they are loaded in compression.

**Golden Gate Bridge**

Probably the most famous and well-known suspension bridge in the world is the Golden Gate Bridge
in San Fransisco, California. As the name says, the bridge spans the golden gate strait between the San Fransisco Bay and the Pacific Ocean. It has been declared one of the Wonders of the modern world by the American Society of Civil Engineers. When it opened in 1937 it was the longest spanning suspension bridge in the world with a main span of 1280 metres.

Fig 74. Golden Gate bridge (28).
6.2 MOVEABLE SYSTEMS

6.2.1 BASCULE BRIDGE

The bascule bridge is a moveable bridge using a balancing principle. The word “bascule” is actually French for seesaw. Bascule bridges have been used for ages, but it was not until the development of steam power (1850s) that long and heavy spans could be moved. The bridge pivots “on a horizontal axis at a right angle on its longitudinal centreline”. The span of a bascule bridge is also called a leaf.

A bascule bridge has different variations. The simplest, most common, being the single leaf bascule bridge, where the leaf pivots on one side of the span and can rest on the other side. Then there is the double leaf bascule, where there are two leaves with two pivot points and interlocking in the centre. Finally, there is also a variation in the pivoting system. In the rolling bascule, instead of heaving one axis as a pivot point, the structure “rolls”.

Structural principle

A bascule bridge only consists of a single moving element which pivots about a horizontal axis near its centre of gravity so that the weight on one side of the pivot axis nearly balances the weight on the other side (Koglin, 2003). Usually, the balance is not exact. If the centre of gravity lies more towards the leaf, the bridge is called “span heavy”, and if the centre of gravity lies towards the counterweight, it is called “counterweight heavy”. Keeping the centre of gravity as close to the pivot point as possible makes it easier to open and close the bridge, reducing opening time and energy usage.

Measurements

Because the leaf is only supported on one side, the span is limited when taking into account the opening time, the opening power and energy usage. The Erasmusbrug has the biggest bascule part in Western Europe with a span of 89 metres. The longest bascule in the world is of the Frederick Douglas Memorial and is 118 metres.

Material

The most important part of the material is that it has to be strong enough to make the cantilevering leaf and withstand the weight of the counterweight. Most of the current bascules are made of steel, but the older ones can also be made of wood.
**Broadway Bridge**

The Broadway Bridge was for a long time the longest spanning bascule bridge in the world. The bridge uses a Rall Bascule design, combining the rolling lift with a longitudinal motion. The double leaves span 85 metres.

![Fig 77. Broadway bridge (29).](image)

### 6.2.2 Swing Bridge

A swing bridge pivots in a horizontal plane about a vertical axis, on a bearing mounted on a central pier called the pivot pier. Its ends are supported on the rest piers. Usually, the pivot pier is in the middle of the span, but a swing bridge can also be asymmetrical. Swing bridges have been around for about 200 years. They were most commonly made in a trussed or cantilever form. Most of the existing swing bridges are railway bridges.

#### Structural Principle

In a swing bridge, just like with the bascule, the centre of gravity is attempted to be brought above the pivot pier. Again, to minimise the energy usage and opening time. Furthermore it's simply a cantilevering beam, truss or cable-stayed deck, rotating around the pivot pier.

#### Measurements

The longest swing bridge span is 340 metres, by the El Ferdan Railway Bridge across the Suez Canal. This is a double swing bridge, meaning that one part spans 170 metres. The swing span has the longest span of all the movable bridges.

#### Material

The earlier swing bridges, as most of the bridges, were made of wood, most commonly in a trussed...
form. In the more modern swing bridges, the timber has again been replaced by steel.

**Puente de la Mujer**

The Puente de la Mujer, or Woman’s Bridge, is a cantilever spar cable-stayed pedestrians bridge, constructed in 2001, designed by Santiago Calatrava. The footbridge lies for Dock 3 of the Puerto Madero commercial district of Buenos Aires, Argentina. The rotating deck spans 102.5 metres.

![Puente de la Mujer](image)

**6.2.3 VERTICAL LIFT BRIDGE**

A vertical lift bridge is quite straightforward. Part of the deck of the bridge is lifted up to clear passage for ships, or part of the deck can be vertically submerged for the ships to pass over it. This last option however, is not very common. Rotterdam has its own vertical lift bridge de Hef, an old railway bridge. Generally, a lift system is cheaper for longer moveable spans than swing or bascule.

![Vertical lift principle](image)

![Submersible system](image)
bridges. In a vertical lift system, the counterweight only needs to be the weight of the deck, whereas the counterweight of a bascule or swing bridge, usually have to weigh several times the weight of the span being lifted. This makes for the fact that vertical lift bridges are perfectly suited for a railway crossing, since heavier materials can be used in the deck.

**Structural principle**

The structural principle of the vertical lift system is pretty basic. With counterweights, with similar mass as the deck, connected to the moveable deck in towers on both sides, the deck can be lifted or submerged with little energy usage. The deck will have to be stiff throughout the spans, since it’s only lifted on the outer extremities. Other than a counterweight lift bridges that use towers, there are also some who use hydraulic jacks, located below the deck. This variant on the traditional vertical lift is called a table bridge.

**Measurements**

The longest spanning vertical lift system built has a span of 170 metres. It can be imagined that a larger span would be possible however. As long as the span can be made and the weight isn’t too high to fit into the counterweight, the span can get as long as you like. The vertical lift does have the disadvantage that, when it’s opened, there is still a vertical clearance limit. When the submergible principle is used, this problem is solved.

**Material**

As with most of the moveable bridges, steel is again the most common material for a vertical lift bridge. The towers could be made of different materials, like concrete, since they are loaded in compression. For smaller bridges, timber is also an option.

**Arthur Kill Bridge**

The Arthur Kill Railroad Bridge is the longest spanning vertical lift bridge in the world. It is a railroad-only bridge connecting Elizabethport, New Jersey and the Holand Hook Marine Terminal on Staten Island, New York. The moveable part of the bridge is a 170-metres truss span, allowing a channel of 150 metres. It clears 9,4 metres when closed and up to 41 metres when lifted. The bridge is completely made out of steel.
6.2.4 RETRACTABLE BRIDGE

With a retractable bridge, as can be expected of the name, the moveable part of the bridge can be rolled or slid backwards to open a gap for nautical traffic. The system dates back to medieval times. Today however, the retractable bridge is uncommon due to the large needed space to open the bridge. Unlike the vertical lift bridge, where the deck moves into unused space, the retractable bridge moves the deck into used space, decreasing the line-up space when the bridge is opened. There are examples of a variant on the retractable bridge where a folding mechanism is used. This solves the spatial problem.

Structural principle

In most of the retractable bridging systems, a cantilevering deck is retracted on one or two sides of the bridge. This causes large bending moments at the supports. There are also examples of floating retractable bridges, like the Hood Canal Bridge in Washington state. Here the cantilevering deck is supported by a floating device that gets retracted with the bridge. This diminishes the occurring bending moment at the support. With the folding type, pulling cables are needed to initiate the folding and pull the different parts of the deck.

Measurements

Because of the needed space and the occurring bending moments, the span of a retractable bridge is quite limited and small. Using a floating system increases the possible span size, but still has the spatial limitations. The folding system eliminates the spatial problem, but will need an extra construction to accommodate the system and hold the cantilever. The floating retractable bridge has the longest span possibilities, up to about 200 metres. The folding and traditional retractable systems are all smaller.

Material

Light materials are preferable, minimising the bending moments in the support. Most of the systems are made with cantilevering steel beams. A composite deck, combining steel beams with concrete can also be used.

Hood Canal Bridge

The Hood Canal Bridge crosses the Hood Canal, connecting the Olympic and Kitsap peninsulas in the state of Washington, U.S.. At 2.398 metres long, it is the third longest floating bridge in the world. Its retractable draw span is 180 metres long and also has a floating system. Because of the length of the bridge, the tide swings of 5 metres to which the bridge is exposed, can be managed. With smaller bridges, the difference in angles caused by the tide swing can cause problems.
6.2.5 DRAW BRIDGE

The drawbridge is the oldest, most straight forward type of movable bridge. The bridge associated with the entrance of a medieval castle. The bridges can still be found in more modern designs. Also in the old city centre of Rotterdam many can be found.

**Structural principle**

A drawbridge has a deck, hinged on one side, resting on the other. It usually hangs from cables which either can be retracted, or are connected to a movable stiff beam, using the bascule principle.

**Measurements**

Drawbridges are very limited in span. They are usually used crossing narrow obstacles, like a moat or city canal, where a large span isn’t needed.

**Material**

The historic drawbridges of medieval times were mostly made of wood. This developed into the use of more steel, first in the cables, then in the deck as well.

**Kolenhavenbrug**

The Kolenhavenbrug lies in the bend of the Rhine-Schie canal in Delft. It crosses the entrance of the Kolenhaven. It replaced an old bridge to make way for a new bus lane. It is based on the concept of the old Dutch lifting bridge. The opening works with a stiff top part, pivoting about one axis, connected to the deck.
6.3 LANDINGS

The slope that connects a bridge to its surroundings is called a landing. The incline of these landings has certain limits, depending on which traffic uses it. Two ways of transport have been investigated, since these have specific demands: trams and cyclists.

6.3.1 CYCLISTS

Research shows that several theories have been developed over the years. In 1946 ir. L. Roos published the first guidelines for the design of bicycle slopes. He advised to set a relation between the height and the length of the slope, with length of slope = 1/10* height difference. Till now this is still used as a rule of thumb. He also suggested to place horizontal plateaus in long slopes, so that cyclists can gain speed for the next part of the slope. Finally, he mentioned that slopes for cyclists should have a maximum of 8% for short slopes, and 6% for long slopes.

In 1984 ir. A.J.M. van Laarhoven published new findings on this subject. He suggested that a slope should be much steeper at the start than at the end. The idea behind this is that cyclists will increase their speed while approaching the slope, so they will gain height fast. Besides that, a decreasing slope percentage will cause a constant speed and effort. He also advises a maximum slope of 1,25% for slopes with a height larger than 4 meters.

The theory of Van Laarhoven formed the basis for the regulations made by CROW (Centrum voor

Fig 90. Desired slope percentage to elevation height (34).
Regelgeving en Onderzoek in de Grond-, Water- en Wegenbouw en de Verkeerstechniek), which were used in the ‘Guidelines for bicycle traffic’ in 1993 and 2006.

Finally, research of C. ter Braack shows that there is a relation between the maximum incline of the slope and its length. His research suggests that the ideal slope is approximately 2%. People prefer a slope with a low incline, even though it means that they have to take a longer distance.

Ter Braack also has a few other points of attention when designing slopes for cyclists. So is the social security for people important in choosing which slope (bridge) they take. It is of importance that a bridge is as ‘open’ as possible, so that a cyclist can see what is ahead of him. This will also make it visible for theclist to see what distance he still has to go, and so he can focus on the end. Also, the road should be wide enough, so that cyclists can easily pass each other (Het Fietsberaad, 2009).

**Conclusion**

Taking into account all research that has been done through the years, we can conclude that the ideal maximum slope for cyclists is about 2%. In general, people prefer a longer slope over a steeper slope. For safety and comfort reasons, it is important to have a clear oversight of the whole slope. The use of wide bicycle paths will increase the security even more.

![Graph showing the ideal maximum slope for cyclists](image)

Fig 91. For slopes with height > 5 meters, a maximum incline of 2% is supported by most theories (own work).
6.3.2 TRAMS

No clear data could be found for the maximum slope of trams for bridges. Therefore we looked into the slope in tunnels. The manual for tunnel construction (Hellingen tram- en metrolijnen, 2015) shows a maximum slope for trams in tunnels to be 4.5%, but a slope of 3.3% is wished for. This is also of course depending on the type of tram that is used.

<table>
<thead>
<tr>
<th>Table 40.2 - Maximale helling tram</th>
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</thead>
<tbody>
<tr>
<td>Locatie</td>
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</tr>
<tr>
<td>tunnel</td>
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<tr>
<td>maximale</td>
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Fig 92. Maximum slope trams in tunnels (35).

To verify this number, we can take a look at a current crossing. The maximum slope of the Erasmusbrug is about 3.6%. Since there is a tram track on this bridge, we can use this number as a reference. It means that the trams in Rotterdam can at least climb a slope of 3.6%. Knowing this we can set a maximum slope for the tram of 4%

Another important aspect to keep in mind is to have line-up space for the trams in front of the openable part of the bridge. When the bridge is open, the trams may not block the other infrastructure. This line-up space can be on the bridge itself, on the landings or at the surroundings. At the Erasmusbrug this is solved with line-up space on the bridge on one side and at the other side with a small space at the landings and more space at the surroundings, at the Wilhelminaplein station.

Fig 93. Line-up space Erasmusbrug (own work).

Conclusion

We can assume a maximum slope of 4% for trams. There should be enough line-up space in front of the openings to prevent a block of the other traffic flows.
6.4 CONCLUSION

With the analyses of the different types of bridges and moveable systems, an assessment can be made to check if the typologies are suitable according to both the technical and visual demands of the new crossings. These checks are shown in two different tables below. Out of the analysis of the landings, conclusions regarding the incline of the slope can be drawn.

BRIDGING TYPES

Cross-checking the bridging types with the visual guidelines and technical demands, it can be found that the cable-stayed and the suspension bridge will be most suitable. The arch-bridge could be suitable, but special care needs to be taken to ensure a slender design.

<table>
<thead>
<tr>
<th>Bridging types</th>
<th>Technical demands</th>
<th>Visual guidelines</th>
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<td>![Bridge 7]</td>
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As for the moveable systems, the bascule bridge seems like the way to go. The swing bridge is the only other option in terms of technical demands, however, this would be quite a hard system to design.

<table>
<thead>
<tr>
<th>Moveable types</th>
<th>Technical demands</th>
<th>Visual guidelines</th>
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<tbody>
<tr>
<td><img src="image1" alt="Bascule Bridge" /></td>
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<tr>
<td><img src="image2" alt="Swing Bridge" /></td>
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<td>+</td>
</tr>
<tr>
<td><img src="image3" alt="Cyclist Slope" /></td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><img src="image4" alt="Tram Slope" /></td>
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<td><img src="image6" alt="Other System" /></td>
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<tr>
<td><img src="image7" alt="Other System" /></td>
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</tbody>
</table>

Regarding the landings, there are two important demands to the slope. Cyclists and trams will be determinative to the desired maximum slope. Both are mentioned as the two traffic flows might be separated in the design. The maximum slopes are:

- Cyclists: 2% (ideal)
- Tram: 4%
Design study

In this chapter the design process and the final design of the bridge will be described. This begins with a recap of the design brief, followed by an explanation of the chosen location and concept. Finally the bridge is explained in detail.

7.1 DESIGN BRIEF

The points mentioned here are the most important demands among the those mentioned before. This is where the final design should be tested on.

- A new connection is to be made between Kralingen and Feijenoord, west of the van Brienenoordbrug.
- The bridge should accommodate trams, cyclists, pedestrians and cars, thereby promoting the use of sustainable means of transport.
- The design should find connection to the current city bridges, with a slender and elegant design.
- The bridge should have a coherent design of the different parts.
- The new crossing should comply with the ‘green’ ambition of the future plans.
- A static free span of 200m with a vertical clearance of 12m is needed.
- A moveable part of 50m with an unlimited vertical clearance is needed.

7.2 URBAN CONTEXT

After the site specific analyses, three possible positions for the bridge were determined. Option 1 is a connection west of the new stadium, crossing from the Nesserdijk directly to Laan op Zuid. Option 2 is located east of the new stadium. Option 3 is a connection west of Van Brienenoordeiland, from Nesserdijk to the large roundabout of Stadionweg.

Fig 94. Possible locations (own work).
Option 1

This option is located almost directly in the extend of the Kralingse Zoom. This makes the northern landing very pleasant. However, the southern landing is difficult because of the train. The bridge can either land at the shore, but the connection to the rest of the city is then very inconvenient or directly to Laan op Zuid, but this requires a steep inclination of the landing. Therefore option 1 was ruled out.

Option 2

This option connects the Nesserdijk with Stadionweg. The new stadium will need a connection to the public transport network and this option can provide that. Also it connects well to the current infrastructure and flows. In addition, there is plenty of space for the bridge to land, since there is empty space between the stadium and the current buildings. It fits well within the future plans for the area, where this part is marked as a small urban area between the park-like quays.

Option 3

This option also connects the Nesserdijk with Stadionweg, but it is located more to the east. Therefore the connection to its surroundings, both North and South of the Maas, is less convenient. However, it does provide an opportunity to really connect the two nature areas found near this location.

Conclusion

The location of the bridge seems most logical and feasible at option 2, east of the new stadium. Therefore this location was chosen for the design of a new bridge.

7.3 CONCEPT

As a start of the design, a concept is formed consisting of several main focal points based on the demands and the first design decisions.

SPLIT DECK

The demands state a different maximum slope percentage for the different flows of traffic. To combine the flows and make the whole bridge accessible for all users, a maximum of 2% should be used for the entire bridge. This proved to result in very long landings, which would not fit. Therefore it was decided to use the two ideal maximum slope percentages for the two different flows: 4% for tram and cars, 2% for cyclists and pedestrians. For the slow traffic this still resulted in a very long slope, so it was decided that this could get up to a maximum of 2.5%.

These different slope percentages result in different lengths for the landings of the two flows. This automatically means that the two flows can’t be combined and that they need to get separated landings. In this way the different flows can each connect to the existing network at the best suitable spot.

The main deck of the bridge will keep this clear distinction between fast and slow traffic, to provide clarity and safety.
PARK INTEGRATION

The bridge will form a green link between the park areas at the south and the nature area at the north of the Maas. Combining this with the slow traffic flow will result in a park. In this way the bridge is not only an infrastructural connection, but also an interesting public space, bringing together people and green.

SUPERSTRUCTURE

The operable part and the large span structure of the bridge should speak the same language in terms of form. This means that they should together define the image of the bridge, forming one ensemble. The design of the superstructure should follow the flow of forces, meaning that the physical logic of the bridge will be the architectural expression.

The bridge should find connection in its design to the current city bridges of Rotterdam. It is part of a series of bridges, starting from the Erasmusbrug to the Van Brienenoordbrug. The typology of a cable-stayed bridge seems to fit most, but looking at the location, next to Van Brienenoordbrug, an elegant arch bridge is a better choice.
7.4 DESIGN EXPLANATION

In this paragraph the design process of the bridge will be described. The design will be explained through the different parts of the bridge.

7.4.1 PLAN AND SITUATION

The design process started with determining the lengths that were needed for the landings to reach the appropriate height to meet the requirements for the nautical activity. Together with the lengths of the free span and operable part, this was tried to fit into the location.

**Position operable part**

The position of the operable part within the bridge is determined to be at the north side of the river, in the inner curve. The bridge is closely located to the Van Brienenoordebrug, which has its opening at the north side too. To ensure a logic and safe route for boats that need to use this passage, the operable part of this design will have the same positioning.

In addition to the relation with the Van Brienenoordebrug, another reason is important to position the operable part at this side of the bridge. The Maas makes a turn here to the North. For large vessels, which will be the main users of the operable part of the bridge, this turn is easier to take by using the inner curve of the river (blue line), because there is more space after and before the bridge to align parallel with the opening.

Fig 96. Positioning operable bridge (own work).
Deck plan

The design consists of a deck that is split in two: the west side for fast traffic and east side for slow traffic. Functionally seeing it was only needed for the landings, but to create clarity in the design, this split is used over the entire bridge. The plan of the two decks are designed as two mirrored arches with a very large radius. They come closer to each other near the middle support, but they stay separated to ensure views on and experience of the water. At the start of the landings, the radius of the arches increase and the two flows go their own way to connect to the existing infrastructure. This gesture is a reaction the context of the site. The fast, urban traffic finds connection to the urban structure, while the slow, green traffic finds connection to the nature and green areas.

Fig 97. Situation plan (own work).

Fig 98. Connection to different context (own work).
Landings

A key point in the design was the proper connection of the different flows, fast and slow traffic, to the existing networks. This turned out to be at different places for the different kind of traffic. The fast traffic is connected in the North to the Nesserdijk, the road along the water. This dyke connects the bridge to the existing infrastructure. By doing so, it will block the east side of the dyke for traffic from the west and vice versa. This road will now only be accessible for local traffic from the east and for cyclists and pedestrians from both sides. At the south, the fast traffic connects at the traffic square nearby.

The slow traffic from the bridge connects to the raised dyke in the Eschpolder. This dyke links the nature area there and provides a way further north into the city. There is also a connection with stairs to the quay. At the south, the slow traffic connects here to the quay, to provide access from here. In this way it will be part of the pedestrian and bicycle routes running along the shores of the Maas. This connection is done by a flat escalator. A ramp was considered, but the space needed for such a connection is not available. With the current solution, a more urban connection is made, which fits with the context.

Park

The bridge forms a new link in the green route running along the shores of the Maas, and also in the overall green structure of Rotterdam. It forms a connection between the two most unique pieces of nature of Rotterdam. To empower this role that the bridge has, green is added to the slow part of the bridge. It is not just a crossing anymore, but it’s a place to meet, to stay and to enjoy an unique experience. The trees and plants are integrated in the bridges structure. In this way the bridge becomes an elevated park over the Maas, clearly displaying the green character of the city.
7.4.2 SUPERSTRUCTURE

Superstructure is here defined as the whole composition of the bridge, both main span and moveable part. It is important for the superstructure to fit in with the current bridges in Rotterdam. Since the largest two bridges are cable-stayed bridges, the design process started with a few sketches of different cable-stayed bridge and a possible matching structure for the operable part.

![Fig 101. Cable-stayed design sketches (own work).](image1)

The attractiveness of these designs was that in both open and closed position, the operable bridge would fit in the total structure of the bridge. But accept for that, these designs showed a lack of own identity. Also, by combining a cable-stayed structure with the operable part in this way, there is a problem with the structural feasibility, since it’s not possible to place back cables at the pylon. In addition, this typology was not visually fitting with the concept of the park. Therefore a cable stayed-bridge got ruled out as suitable typology.

**Cable-stayed arch bridge**

An arch bridge seemed the most suitable option for the bridge, with the notation that the bridge should still find a connection with the current city bridges, and not with the near located Van Brienenoordbrug. Therefore a proposal was in the combination of two typologies: an arch and cable-stayed bridge. This typology can be described as an arch with straight legs and a small radius at the top. The cables of the bridge connect at the top of the structure, at the small arch. The top of the arch is not located in the centre of the span, but more to one side. This creates a more cable-stayed cable arrangement. The operable bridge is a tail bascule bridge. The counterweight part of this bridge is made visual and thereby creates a smaller mirrored image of the superstructure.

![Fig 102. Cable-stayed arch design sketch (own work).](image2)

After trying many variants it was decided that this typology was not suitable. This type of structure feels ‘forced’ and this was proven during the first structural calculations. It is not an optimal solution to cross such a distance. An arch bridge would be much more efficient. Therefore the choice was made to design an elegant arch bridge.
Arch bridge

The basic setup and design of the arch bridge is based on the context of the location. The bascule cellar serves as a centre point of the bridge, from where four arches evolve in two directions. Two smaller arches for the moveable part, in the direction of the green and nature area, and two larger arches for the static part, in the direction of the urban area. The arches are asymmetrical, meaning that the top of the arch leans towards the centre point of the bridge. This was initially an architectural idea, but later turned out to be structurally more efficient as well.

To emphasize this difference in context, the two parts of the bridge have different endings. The arches of the moveable part end on two relatively small abutments, guiding the decks to create a smooth transition to the more quiet green area. However, the two arches of the static part come together in one larger abutment, fitting the urban scale of this area.

By making a double arch that comes together in a single point between the two decks, the superstructure interacts with the split deck configuration. At the abutment it emphasizes the split in decks by landing in between them. At the other end of the arch it lands in the deck, embracing it and holding it together.
7.4.3 ARCHES

The arch design is mainly based on the forces and stresses occurring in the structure. The decision to end the arches in one point has implications for the entire design of the arches.

**Tied-arch bridge**

The bridge will be built on soft ground, that is not capable of taking horizontal forces. This means the arch needs to function as a tied-arch bridge.

![Tied-arch bridge principle (own work).](image1)

The principle of a tied arch bridge is an arch that primarily acts in compression. The load on the deck is transferred to the arch with cables using tensile forces. The arch then transfers this downwards to the foundations. There it exerts a horizontal force outwards, that is taken by the main girder of the deck, that works as a tie. This only works when the main girder of the bridge connects to the end of the arches (fig 102.2). When moving one end of the arch inwards, away from the main girder, a connection needs to be made to transfer the horizontal forces from the arch to the girder (102.1). This also applies when the deck uses a box girder system.

![Arch-tie connection (own work).](image2)

![Connection deck to arches (own work).](image3)
Cable layout

The structure uses a set of cables to transfer the loads on the deck to the arch. In the most basic form of an arch bridge, the arches and main girders are in line. Between these two elements the cables are evenly divided over the deck, in a plane perpendicular to the direction of the span (y-direction). In this case that means they are completely vertical. This principle causes a problem when applied to the design of a three point supported arch bridge. The cables near the single support are now on an angle, which creates a limited free height for trams and trucks to pass the bridge. Therefore, the cables need to be attached higher on the arch, guaranteeing a free height of at least 4.5 meters.

![Changing of cable layout diagram](image)

Asymmetric arch

Looking at the elevation of the arch, the cables are now exerting forces on an angle. This effects the functioning of the arch. A symmetric arch is based on the principle of a load that is transferred to the arch vertically. Now that the forces are acting on an angle, the shape of the arch is not optimal anymore. To make it optimal again, the top of the arch needs to shift to the right, creating an asymmetric arch.

![Changing of cable layout, elevation](image)
With this shape and cable layout, the structure fits well in the storyline of the current city bridges. It forms the transition between city and highway bridge, between cable-stayed and arch.

**Arch section**

The design of the arch is based on the structural behaviour and occurring forces in the arch, together with an architectural expression.

In a standard arch bridge the compressive forces are lowest at the top of the catenary arch and they increase towards the supports. This can often be seen in the design of the section of the arches, which increase towards the end. The same behaviour of the compressive forces occur in this asymmetric design. However, by the shift of the top of the arch, the position from where the arches need to increase in thickness is also shifted. This can be seen from the occurring compression forces in the arch.

The section of the arches also have a large aesthetical impact, on both the slenderness and elegance of the design. Therefore an architectural expression was developed that corresponds with the overall concept of the bridge: the arches are thick at the middle point, from which they gradually get thinner towards the end. This applies only to the height of the arch.

However, this does contradict with the forces in the arches, which are higher at the thin part. Therefore the width of the arch is also gradually changing over the arch, but in the opposite direction. At the centre point it is made smaller, not to interfere too much in the traffic lanes, creating unused areas on the bridge. From here it widens towards the single support, where it reaches its widest section and where it is joined with the second arch. This wide ending of the arches also provides stability to both. In this way the section of the arches is large enough to be able to transfer all the occurring forces towards the abutments.

Also the shape of the section has a large impact on the slenderness of the design. A diamond like shape is chosen to create a section that is both slender, elegant and that creates an interesting play with light and shadow. This diamond shape
has one side that follows the direction of the cables over the arch (fig 114, red side). This causes a rotation of this side, which leads to the change from high and small to low and wide.

Details

![Diagram of cable anchorage at arches (own work).](image)

Fig 115. Cable anchorage at arches (own work).

![Diagram of cable anchorage at arches (own work).](image)

Fig 116. Cable anchorage at arches (own work).
The other rotating side, where the cables are connected, will be coloured. Some colour tests were done to decide on the colour. My choice has fallen on a darkish green look, like the colours of the flag of Rotterdam. Rotterdam now has many coloured bridges, and this green has not been used yet. It also fits well with the green of the park.

Fig 117. Colour tests (own work).
Bracing

The arches are connected with three bracings. These are diamond shaped, just like the crossbeams in the deck. They connect to the arches over the whole profile of the arch, as seen below. The bracings will be connected to the arch by welding. Their colour is the same as the arches.

Fig 118. Bracing between the arches (own work).
7.4.4 DECK

Use

As mentioned before, the deck is split in a part for fast travel and a part for slow traveling. The west side of the bridge provides a fast crossing of the river for trams, cars and cyclists. The structural elements, the arches and cables, are used to divide the deck in two parts, so that the cyclists have their own safe lane at the outer side of the bridge, while the faster traffic is on the middle part.

The faster part is flexible in use. My suggestion now is that at this faster part, the trams have priority, while cars are guests. The deck is designed quite small, but in a way that tram and car still fit together next to each other. That means that during busy periods the deck can be used as a two lane street with low speed levels. In addition, when the bridge opens, there is room for both cars and trams to wait on the bridge. In the future it's possible to change this layout.

The east side of the bridge is designed as a park for pedestrians and cyclists. Again, the cables split the deck in two parts: a bicycle path on the outer side, the park on the inside. The park is designed with a grid of four lanes. These are filled in differently with either an open box with soil, in which plants and
trees grow, or with a path to walk. A maximum of two lanes is filled with a box, to keep enough space for pedestrians to walk.

**Structure**

The two decks are designed as a steel box girder deck, connected by cross beams. The steel box girder is capable of taking up moments and torsion, caused by forces that occur in the deck because of the asymmetric structure and loading. The steel box girders also provide enough stiffness for the deck.

![Bending moments in deck](image1.jpg)

![Cross section of deck](image2.jpg)

The cross section of the deck has a triangular shape. This comes from the occurring bending moments in the deck. Besides this structural function, it also enhances the experience of the water when passing the bridge. With the triangular shape, the sightlines underneath the deck, towards the water, are widened.

![Cross section of deck](image3.jpg)

**Crossbeams**

The crossbeams ensure that the decks works as one. They are designed with a diamond section, referring to the section of the arches. They are welded to the decks over a large area, providing a fixed connection between deck and crossbeam. The shape of the crossbeams and decks makes that the bottom of the bridge is also aesthetically pleasing.

![Visualisation of bottom deck](image4.jpg)
Fig 125. Cable anchorage in deck (own work).

Fig 126. Cable anchorage in deck (own work).

Fig 127. Balustrade detail (own work).
7.4.5 GREEN INTEGRATION

The slow part of the bridge is designed as a park with integrated green. With advise of Joris Voeten (Urban Rooftops) the choice of tree, the integration of the green and the water supply system of the bridge was designed.

Tree choice

Green can mean a lot, but in this case it means trees and a variation of plants. The conditions for trees on a bridge in Rotterdam are not optimal. The used tree must comply with a couple of demands. First of all, the wind can be strong on a bridge above the Maas. Therefore the tree needs to be able to resist such forces. Also, to reduce the effect of the wind, the tree must have a half open crown. Secondly, from a structural point of view the trees may not be higher than 5 meters. This is approximately the same height that is used for the calculations of the effects of the wind on the bridges structure. In this way the trees are not factor in these calculations.

The choice was made for a Chinese Elm. This elm from eastern Asia is known for its long and narrow leaves and its attractive bark. It tolerates urban conditions and is resistant to Dutch Elm disease.

Water supply system

The boxes of the trees are designed in such a way that an active irrigation system is not needed. Instead a Permavoid system is used. This is a geocellular interlocking system designed for shallow ground water storage or infiltration. It consists of plastic rafts that are laid on the bottom of the tree boxes. These rafts use passive capillary irrigation to bring the collected water to the growing medium (soil).

An inert porous medium is used to transport water and oxygen to the roots of the tree by capillary action. The Permavoid units are designed with hollow structural columns, that are filled with an absorbent rockwool. This wool draws up the water that’s being stored within the unit. The Permavoid raft is covered with a wicking geotextile that supplies water on demand across the units to irrigate the soil. The trees and plants that are planted in the growing medium now always have access to all required minerals and water (Polypipe, 2016).

Beneficial of this system is the very small height of the units, only 85 mm. The elms only need about 1 meter of soil to grow properly. That means that the Permavoid system is easily integrated in the structure.
Design

The boxes are cut out in the deck of the bridge. Because of the limited height of the deck, trees can only be placed at the three most outer lanes. In the image below it is placed in the two middle lanes. At the bottom of the box the Permavoid system is placed, to provide irrigation for the roots of the tree. The plants have smaller roots and cannot reach that far to the bottom. Therefore a second set of Permavoid systems are placed higher along the sides, to provide irrigation closer to the plants roots.

Water needed for the plants and trees is collected on the deck and guided to the tree boxes. With the use of the Permavoid system, a continues wet soil is guaranteed. The height of the boxes is namely used as a temporary storage of the water, as seen in figure 129. In case of too much water, the water overflows into the drainage piping. It is then either transferred to the next, slightly lowered positioned, tree box (cascading system), or its brought down.

Detail

Fig 130. Detail of green integration (own work).
A very important demand for the overall design of the bridge is that the operable part and the large span structure of the bridge speak the same language in terms of form. This means that they should together define the image of the bridge, forming one ensemble. This came forth from the analysis of precedents in the earlier phase of the graduation project.

**Tail bridge**

In the first sketches this resulted in a shape that was a smaller and upside-down version of the super structure. The small leg sticking up then functions as the counterweight of the bascule bridge. This is called a tail bridge.

The principle of such a bascule bridge is simple. To create a bridge that opens easily, the centre of gravity of the tail and the centre of gravity of the deck need to be in line with the pivot point of the bridge. A good example of such a bridge is the Rijnhavenbrug in Rotterdam. The principle of this bridge is shown on the right. In this bridge the support of the pivot point is visible. My idea was to have it hidden within the structure, so that the visual emphasize is on the structure itself.

After some research I concluded that this idea is not a realistic option. In order to have the centre of gravity of the tail, the pivot point and the centre of gravity of the deck in line, the tail would have to be very flat, which does not fit in the overall design. Shaping the tail in different ways didn’t seem to have much effect, since this also changes the position of the pivot point. It was therefore decided to approach the operable bridge structure differently.

**Bascule arch bridge**

It was after this decision that the concept of the overall design, with arches erupting from the bascule cellular, was formed. The inspiration for the moveable part was hereby drawn from the Boulevardbrug in Willebroek, Belgium. This is a bascule bridge of 60m, that uses an arch to span this distance.
**Bascule principle**

The prior conducted research showed that the principle of a bascule bridge works on balance. The structure pivots about a horizontal axis. The deck on one side of this point is balanced with a counterweight on the other side. It is important to keep the centres of gravity of the deck and the counterweight in line with the pivot point. Under this condition the ratio between the moments will stay the same during opening, keeping the bridge constantly in balance.

![Equilibrium diagram](image1)

This balance is easily achieved by positioning the pivot point and the counterweight just near the deck, so that they are in line with the centre of gravity of the deck.

**Structural principle**

The structural principle of the bridge is based on the architectural vision to create a mirror image of the main span. However, structurally this shape is a logic choice too. This will be explained with the moment diagrams below. The bridge in closed position can be considered as a beam resting on two supports, with a cantilever at one side (1). If we want to translate this diagram to a structure where the main part is spanned with an arch, the cantilevered part can be held up by a cable, connected from the counterweight to the arch (2). In operable position there is a different situation. Now the beam is just resting on a single support, cantilevering to both sides (3). If we translate this in a structure, the beam needs a lot of material near the support to take up the moments caused by the cantilevers, or we can use a vertical beam above the support that carries the cantilevers by cables (4). Combining these two structures results in an asymmetric arch, that is leaning towards the pivot point (5). A cable connects the top arch with the counterweight. This is close to the architectural expression that was ought to be found.

![Structural principle diagrams](image2)
**Design**

To achieve an uniform design of the whole bridge, the design of the bascule bridge is a continuation of the design of the main arches. The shape of the arches is a mirrored and scaled down version of the main arches.

The decks are, just like the main span, connected with crossbeams, structurally acting as one deck, which is supported by the two arches. The amount of green is decreasing towards the operable bridge. The green is not integrated in the operable bridge itself, since this would ask for a very heavy opening mechanism.

As the shape is a continuation of the main span, so is the operable bridge using the same diamond shaped section concept. Since the height of this shape is already low, the height is not decreasing over the arch. The width however is slightly getting smaller towards the end, to emphasize the end of the overall arch structure. One side of the arch follows the cables again, while the side where the cables...
connect to, is coloured.

The cables of the arch bridge are not cables, but hollow round sections. When closed, the beams work just like cables. However, when the bridge opens, the wind becomes an important factor. When the wind blows against the deck, the cables will slack and be of no use. Therefore elements are needed that can take up compression forces as well. These hollow round sections have the same connections to the deck and the arch as the cables, creating the same image overall.

**Opening mechanism**

The opening mechanism is placed within the middle support of the bridge. It uses a heavy duty hydraulic cylinder for opening and closing. It is important that this cylinder has enough space to cover the path it has while opening the bridge.

To keep the separation of the decks and to fit in the overall design, the operable bridge uses two bascule cellars. That means that the counterweight is not spanned between the two arches, but that there is one for each, hidden within their own cellar. Each counterweight needs to weight about as much as half of the moveable bridge. The weight of the operable bridge was roughly calculated. This results in a large volume for the counterweights that is required.

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**Fig 139.** Longitudinal section bascule cellar (own work).
Fig 140. Cross section bascule cellar (own work).

Fig 141. Bascule bridge opening (own work).
7.4.7 SUPPORTS

Another important aspect of the design is the shape of the abutments of the bridge. These have been designed to fit with the superstructure. They continue the lines introduced by the shape of the changing sections of the arches. Especially the single support is interesting to view closer.

This support is designed to follow the lines of the arches from two sides. In addition to supporting the arches and the deck of the bridge, it also supports the landings. Therefore the cantilevered endings are needed.
Fig 144. Bascule cellar abudment (own work).

Fig 145. Moveable bridge end abudment elevations (own work).
The final structure had to be a result of a design that is architecturally pleasing, but also respects the principles of mechanics at the same time. The optimal outcome of this process is a design were efficiency and aesthetics go hand in hand. Considering this, structural simulations and optimisation was used throughout the entire design process. A parametric model was used to be able to constantly check and verify the consequences of the design decisions that were made.

7.5.1 DESIGN PROCESS

In nowadays architectural world, we are used to have a clear distinction between architecture and engineering. The architect is concerned about the aesthetics and functionality of the bridge, while the engineer is doing the structural calculations. This is also the order within the process: first the architects makes the design, after which the engineer calculates it. This can especially cause frictions in the design process of a bridge, where architecture and engineering are so closely intertwined and connected.

By integrating architecture and engineering at the same time in the design process, a much better integrated result can be achieved. This can be done by using a parametric model. This model gives feedback on all desired themes of fitness functions: aesthetics, functionality and structural feasibility. This feedback is used as a tool to create a better integrated and feasible design.

Such a design starts with an initial geometry, based on first (architectural) sketches and ideas. This idea can come forth from aesthetical wishes, but also functional demands for usage can be the reason, for example the clearance underneath the cables. These ideas are immediately translated to a structural concept, which will serve as the start for the optimisation process. The results of the optimisation process can sometimes lead to an adjustment of the structural concept and sometimes even of the architectural idea. Then the process starts over again, until all demands are met and the final design is created. The benefit of such a design process is that it’s a very fast process. The feedback of the optimisation process
The optimisation process of the bridge started with creating an accurate structural model that would be used for the analysis. This analysis of the structural behaviour was conducted using Karamba for Rhinoceros. For the structural calculations a few boundary conditions had to be defined: the support points, the properties of the materials and the load cases.

Model

To create a good representation of the structural behaviour, the bridge deck is modelled as longitudinal beam with a box section. Using CAD software the moment of inertia and the area of the designed triangular cross section of the deck was calculated. The box section was then adjusted to have approximately the same properties. The crossbeams are also modelled using the same method. The end crossbeams connect the end points of the arch with the deck, creating a tied-arch bridge structure. The connection of the arches at the south support to the crossbeam is modelled with extra beams. This is needed to transfer the horizontal forces from the arch into the deck.

The arches are modelled with a catenary arch. This catenary arch is defined with a variable angle of gravity and length, which determine the (a)symmetric shape of the arch and the height. In addition, the links between the two arches are designed as straight beams.

is instant, meaning it can directly be used to modify the design.

Optimisation process

The structural concept creates the design space and boundary conditions of this process and provides us with a geometry that needs testing. In a shape optimisation this geometry is calculated to minimize one or more fitness function, for example the stresses in the arches or deformation of the deck, or both. An algorithm is then used to adjust the analysed shape using a set of variables, to optimize the results. A typology optimisation can be performed to optimize the material distribution, making sure the material is used efficiently.

7.5.2 MODEL SETUP

The optimisation process of the bridge started with creating an accurate structural model that would be used for the analysis. This analysis of the structural behaviour was conducted using Karamba for Rhinoceros. For the structural calculations a few boundary conditions had to be defined: the support points, the properties of the materials and the load cases.

Model

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The arches are modelled with a catenary arch. This catenary arch is defined with a variable angle of gravity and length, which determine the (a)symmetric shape of the arch and the height. In addition, the links between the two arches are designed as straight beams.
Boundary conditions

The support points are the three points where the two arches come down and the endpoints of the longitudinal beams of the deck. Since there is little space for deformation at the middle support because of the operable bridge, the supports here were defined as hinged bearings. The supports at the other side of the bridge are defined as roller bearings, to allow deformations caused by loads and thermal expansion.

The material that is used for all elements is S355 steel. Because no safety factors are applied to the loads, it was decided (after consultation with Kees van IJsselmuijden (Royal Haskoning)), that the maximum allowed stresses in these elements is 125 n/mm$^2$, resulting in a max utilisation of 35%. The maximum displacement of the fast deck, where the tram is located, is 0.26m (total length deck/800 = 210/800 = 0.26m). The slow deck can have a maximum deflection of 0.35m (210/600 = 0.35m). Both the maximum stresses and maximum deformation should be checked with the all loads applied. The displacement caused by dead load will be diminished by post-tensioning the cables of the bridge after construction.

The amount of cables was fixed at 18, that are connected to the deck at the same position as the cross beams. Early testing proved that the less cables, the less stresses in the structure. Also, the tree boxes need enough space. The division into 18 parts makes sure that this is possible.

Load cases

The dead load of the bridge consists of its own weight and of the weight of the trees. After consultation with Joris Voeten (Roofscapes), it was decided that the weight of the trees can be neglected, but that the density of the sand in the box is normative. The density of wet sand is about 1800 kg/m$^3$. The tree boxes need a depth of 1m, resulting in a q load of 18kn/m$^2$ for every tree box. At this point the position of the trees was not determined yet, so I assumed that over the entire deck the two middle lanes of the park are used for trees (‘worst case scenario’).

The live loads were determined according to the regulations for car bridges described in Eurocode EN 1991-2:2003 as seen in the diagram below. Point loads are left out of the calculation since I was not able to properly apply these in the software that was used. Nevertheless I think that the results with these loads are a proper representation of the structural behaviour of the bridge.

Fig 148. Applied live loads (own work).
Fitness functions

In order to run a shape optimisation, one or more fitness functions are required. In this case three functions are tested: maximum stresses in the arch, sum of deformation in both decks and weight of the total structure. These three functions together define the sustainability and structural feasibility of the structure. The weight is hereby an indicator for the amount of material needed, which is an important factor in the sustainability of a bridge. The optimal result would be a structure with low stresses, deformations and weight. For this optimisation LC1 is used.

Variables

There are multiple variable parameters used in the optimisation process.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position top arch</td>
<td>defines the position of the top of the catenary arch, relatively to the complete span.</td>
</tr>
<tr>
<td>Length arch</td>
<td>defines the length of the catenary curve, thereby defining the height of the structure.</td>
</tr>
<tr>
<td>Position start cables</td>
<td>defines a point on the catenary curve, in relation to the entire length of the curve, where the first cable is connected.</td>
</tr>
<tr>
<td>Position end cables</td>
<td>defines a point on the catenary curve, in relation to the entire length of the curve, where the last cable is connected.</td>
</tr>
<tr>
<td>Position link #</td>
<td>defines the position of the links, in relation to the entire length of the catenary curve.</td>
</tr>
</tbody>
</table>

These loads have been recalculated per meter deck, so it can be applied as line load in longitudinal direction in the model.

This resulted in two load cases that needed testing:

<table>
<thead>
<tr>
<th>Loads</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>LC1</td>
<td>Dead load</td>
</tr>
<tr>
<td>LC2</td>
<td>Dead load + live load</td>
</tr>
</tbody>
</table>

7.5.3 SHAPE OPTIMISATION
Before starting the optimisation process, a boundary check was done to check if the angle of the cables would not interfere with the required height for traffic. This check fixed the variable of the start position of the cables to 0.35.

With these variables the optimisation process was started.
OPTIMISATION RESULTS
The optimisation process provided numerous options to choose from. Important to conclude is that there is no optimal option. The maximum stresses and deformation are inverse related to the total mass. In other words, when the size of the arch decreases (and therefore the mass), the stresses and deformation increase.

The most interesting options are the ones that approach the maximum allowed stresses with low mass, since this will result in an efficient structure. However, most of these low mass options result in higher deformations. These deformations are already near the maximum allowance and will decrease after pretension the cables. Therefore a solution could be chosen with relative high deformations (marked with yellow in graphs).
Fig 153. Maximum stresses vs Total mass (own work).

Fig 154. Maximum stresses vs Total mass (own work).
**Chosen option**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Stresses:</td>
<td>160.8 N/mm²</td>
</tr>
<tr>
<td>Deformation:</td>
<td>0.25 m</td>
</tr>
<tr>
<td></td>
<td>0.36 m</td>
</tr>
<tr>
<td>Mass:</td>
<td>8.91*10⁶ kg</td>
</tr>
</tbody>
</table>

An important aspect in this step was also the aesthetic value of the design. Visually the arch shape of this option was pleasing. This option has, in comparison to the other options, a relatively low arch, which fits well in the idea of the continues structure. However, the position of the links is not satisfying.

When the live load is applied, peak stresses are visible at the start of the arch and at the connection of the arch with the links. This shows that the positioning of the links is structurally also not satisfying. This is to be fixed in the typology optimisation process.

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**7.5.3 TOPOLOGY OPTIMISATION**

The next step was to apply pretensioning to the cables. After this step the cables can be optimised to have an efficient thickness. Also, this pretensioning will affect the stresses in the arch. Because of the angle of the cables, the arch will be pulled out of shape even more. An optimisation of the links will be done to reduce this effect.

**Fitness functions**

For the topology optimisation only one fitness function is required. For the cables the function that needs testing here is the normal forces in them. For the arches the fitness function are the maximum stresses.

**Variables**

The variable in this optimisation process was the section of the arch. Instead of a fixed section of 3250x3250 mm, the simulation could choose from a list of sections, ranging from 3000x3000mm till 4000x4000mm, all with the same thickness of 80mm.
PRETENSIONING CABLES
The cables of the arch should be purely loaded in tension and stay that way. If the tension is lost, the cables will slack and the wind can cause vibrations that will damage the entire bridge. The normal forces in the cables are normative for the dimensioning of the cables. These forces are caused by the loads on the deck (and its own weight) and by the pretensioning of the cables.

The deck deforms under its own weight. To reduce this deformation the cables are pretensioned. As mentioned before, the maximum deformation of the fast deck is 26 cm and for the slow deck 35 cm. The model showed that the required pretensioning is different for both sides of the bridge, which is caused by the asymmetry of the loads. In a real design, all cables would be pretensioned separately. In this model it was only possible to apply a different tensioning for the 2 sets of cables. Therefore the results are not completely accurate, but they give a good indication.

<table>
<thead>
<tr>
<th></th>
<th>Before pretension</th>
<th>After pretension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast deck</td>
<td>Dead load</td>
<td>17.3 cm</td>
</tr>
<tr>
<td></td>
<td>Max. load</td>
<td>25.7 cm</td>
</tr>
<tr>
<td>Slow deck</td>
<td>Dead load</td>
<td>33.2 cm</td>
</tr>
<tr>
<td></td>
<td>Max. load</td>
<td>36.4 cm</td>
</tr>
</tbody>
</table>

By pretensioning the cables, the deflection under dead load is (more than) halved, but more importantly, the deflection under maximum loading is brought well below the maximum allowed deflections.

Cables
After pretension the cables, the normal forces can be extracted to determine the required strength of the cables.
In the earlier optimisations the section of the arch was fixed. Now we can do an optimisation of the section to deal with the high stresses and to find the areas where a larger section is needed. This optimisation shows that additional material is needed at the end points of the arches, especially near the point where the arches come together. Therefore the section of the arches is slightly increased.

The pretensioning of the cables has a negative effect on the arch: it causes higher stresses in the structure. The maximum stresses have increased to 177.8 N/mm². These stresses occur at bases of the arch and at the position of the links. The position of the links was therefore optimised to deal with the changed forces caused by the pretensioning of the cables.

This reduced the maximum stresses occurring in the arches to 148.0 N/mm².

The highest tensile forces occur in the most slanted cable, seen in the image on the left. This force is about 5900 kN. Looking at the VSL SSI 2000 cable stay system (VSL International Ltd., 2013), an admissible load at 50% GUTS (guaranteed ultimate tensile strength) of 5900 kN results in a 200mm thick cable (cable unit 6-43).

Fig 159. VSL SSI200 stay cable system (46).

Fig 160. Maximum stresses in arch before and after position change of links (own work).

This section arch
In the earlier optimisations the section of the arch was fixed. Now we can do an optimisation of the section to deal with the high stresses and to find the areas where a larger section is needed.

Fig 161. Typology optimisation arches (own work).

This optimisation shows that additional material is needed at the end points of the arches, especially near the point where the arches come together. Therefore the section of the arches is slightly increased.
near the support. Also, the arches connect here forming one, which gives them a stronger structural section. On the other side of the arch additional material is also needed. This was already taken into account earlier in the design by increasing the section, creating the continues arch towards the operable bridge. By adapting the section of the arches, the stresses are reduced to 126.0 N/mm², resulting in a feasible design.
8 Conclusion & recommendations

8.1 CONCLUSION

By building a new city bridge between Kralingen and Feijenoord, the infrastructural challenges in Rotterdam can partly be solved. First of all, it will create more space to direct car traffic around the city centre. Moreover, it will provide Rotterdam South with a second connection for public transport to the North. This will create a more stable public transport network within the city. In addition, it will provide cyclists and pedestrians a fast crossing in the east of the city. With a new bridge, Rotterdam South will be less isolated and education and employment will be easier accessible for everyone.

The site has a very unique character, situated between the new planned stadium and two unique nature areas within the city. This context is both a challenge and opportunity for the design of a bridge. A solution was found in a bridge that connects these two nature areas and the quays with a park. This means that half of the bridge is designed as a park, with space for green, pedestrians and cyclists. The other half of the bridge provides a fast connection for public transport, cars and cyclists. In this way the bridge is not only a functional crossing, but also a destination and a unique experience to cross.

The integration of green on such a large span structure has major consequences on the structural design of the bridge. By using a parametric model with feedback about the structural behaviour of the bridge, a feasible design could be designed. Design changes could easily be applied and with the feedback of the model the consequences of these decisions were instantly clear. Especially in the design of a bridge, where the beauty lies in the structural logic of the structure, a parametric model provides the tools to come to a well integrated design.

8.2 RECOMMENDATIONS

Materials research

Quite early in the design process it was chosen to design the bridge with steel and concrete due to a lack of time to do a thorough material research. However, nowadays research to FRP structures could be interesting for a more sustainable design, especially looking at bio-FRP’s.

Green integration

This research touched the technical measurements needed to design a bridge with green. However, it seems further research of the integration of green on a bridge can be interesting, especially for pedestrians/cyclist bridges. For larger span structures the effects on the structure by the wind blowing at the trees could be interesting.

Moveable bridge

Taking this design a step further would be to design a moveable bridge with integrated green, although this seems unlikely, since the force needed to move such a bridge would be immense. However, there might be possibilities of integrating green as counterweight.
9 Visualisations

Fig 162. Overview (own work).

Fig 163. South landing with van Brienenoordbrug on the background (own work).
Fig 164. Bridge seen from quay (own work).
Fig 165. Plan (own work).
Fig 166. Elevation South (own work).

Fig 167. Elevation North (own work).
Fig 168. Elevation East (own work).
11 Bibliography

11.1 TEXT


11.2 FIGURES

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