The structural design of the Rotterdam CS Southern Hall.

Part 1: Concept study

M.Sc. Thesis
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Preface

For the completion of the Delft Civil Engineering study, this thesis has been written. The knowledge gained during the Civil Engineering study had to be applied on a certain technical subject. For this thesis, it has been chosen to make an alternative structural design for the Southern Hall of the new central train station of Rotterdam. The engineering department of the municipality of Rotterdam (IGWR), in cooperation with ARCADIS, created a structural design for the architectural design that has been made by Team CS. For both IGWR and the student it is interesting to create an alternative structural design to evaluate the architectural design and to get an insight in the efficiency of the chosen structure. The chosen technical problem is subjected to many different boundary conditions and parties, what makes the subject politically and technically interesting. In this report, the first part of the thesis, a study will be done to find feasible structural concepts for the Southern Hall.

I want to thank the persons that assisted me writing the thesis. First, I would like to thank all four members of the graduation committee for taking time to read and comment my work to improve the quality of the thesis. Besides that, I would like to thank Ingenieursbureau Gemeentewerken Rotterdam for the facilities, the support and the freedom that I got for writing my thesis. In addition, I would like to thank all the colleagues, especially J. van Gelder and T.A. de Vries, of department Bruggen en Staalbouw for their support, time and effort. A final word of appreciation I want to give to C. Graafland for reading and commenting my work.
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Summary

In this part of the thesis, a study has been done to find a suitable alternative structural concept for the Southern Hall of the new Rotterdam CS. To be able to design a suitable structure, the factors that influence the design have been mapped. First, an introduction to the problem and the problem definition will be given in Chapter 3. Besides that, the different goals of the thesis have been composed and added. After that, the architectural design and the vision of the architect will be described to map the requirements according to aesthetics in Chapter 4. In Chapter 5, these influence factors have been summarized in a program of requirements in which the architectural, technical and functional requirements, the boundary conditions and goals are summarized for the design. This Program of Requirements has been a guideline for the structural design and will be described in Chapter 5. Taking this PoR into account, alternatives have been designed, each with advantages and disadvantages. It came out that it is difficult to create alternative systems within the boundary conditions. These alternatives have been weighed, using an MCA to map the advantages and disadvantages, to make a choice for one alternative. This analysis will be given in Chapter 6 and Appendix 11. It came out that a curved lattice structure is the most suitable structural concept to elaborate. The alternative shape, the chance of a reduction in weight and the alternative structural concept have been the most important motivation for this choice. The curved lattice structure will be elaborated and described in the second report of the thesis.
1. **Introduction**

In this Chapter, the environment and the plans for renovation of Rotterdam CS will be described. After that, the problem and goal definition for the master thesis will be determined.

1.1 **Environment**

Rotterdam CS is located in the centre of Rotterdam between the Groot Handelsgebouw and the Nationale Nederlanden office. The provenierswijk is located at the northern side of CS. At the south side, the stations square, the Weena, the Delftseplein and the Conradstraat are located. This area will be completely renovated. Beneath the new Southern Hall, the RandstadRail subway-station is being built. The subway runs from east to west and is an important factor for the design of the new Southern Hall. Beneath the Weena Street, the main street of the area, the Weena-tunnel is being constructed for motorized vehicles. Beside these facilities, the tram and bus stops are also positioned at the station area. In Appendix 1, an overview picture from spring 2007 is added. This picture shows the status of the focus area of the project in that period.

![Overview environment](image)

**Figure 1-1: Overview environment**

1.2 **From Rotterdam CS to OVTRC**

The current Rotterdam CS is about to undergo a complete renewal. It will become a new traffic-terminal, with an international appearance, which connects all the different types of transportation. The most important factor for this terminal are the pedestrians, their comfort has priority. The total project can be divided in several sub-projects. The most important projects are; the central terminal OVTRC (Openbaar Vervoer Terminal Rotterdam Centraal), the RandstadRail subway station, the southern bicycle storage, the Weenatunnel and a NS-office.
1.2.1 Current situation

The current Rotterdam CS can be divided in 3 zones; the northern side, the centre part and the southern side. An overview of the CS can be found in Appendix 2.

The northern side of Rotterdam CS

Consists of the Northern Hall, the bicycle storage and a temporary station.

- **The Northern Hall**
  - The northern station entrance is located inside the current Northern Hall and provides services for the passengers like ticket sales, travel information and commerce.
  - At the western side of the northern entrance, the NS-office is located.
  - At the northern side of the entrance, space for service and facilities is located.

- **Northern bicycle storage**
  - The bicycle storage is located near the Northern entrance.

- **Temporary station**
  - Near the so-called Provenierstunnel, the temporary station is located.

The central part of Rotterdam CS

Consists of the Provenierstunnel, the passengers-tunnel, the railtracks and the platform canopy.

- **Provenierstunnel**
  - The most western tunnel, called the Provenierstunnel, acts as a connection between the centre and the proveniers area. This tunnel will be used as a temporary passengerstunnel

- **Passengers-tunnel**
  - This tunnel connects the platforms, the northern with the southern entrance and is used by the passengers. It will be closed during construction.

- **Platform canopy**
  - The platforms are partly covered by concrete platform canopies

The southern side of Rotterdam CS

Consists of The Southern Hall, offices, a temporary station, the Weena and the subway station.

- **Southern Hall**
  - At the southern side, the southern entrance and the Southern Hall are located.
  - A basement is located beneath the Southern Hall.
  - At groundlevel, the Hall is surrounded by infrastructural provisions like entrance roads, parking- and storage-space.

- **Offices**
  - At the eastern wing of the Southern Hall, offices are located which will be unoccupied during construction.

- **Temporary station**
  - At the western side of the Southern Hall, near the Provenierstunnel, offices and facilities for the passengers are located for the temporary station.

- **The Weena**
  - The Weena Street is the main street of the area, which runs from west to east.

- **The Kruisplein**
  - The kruisplein is the area between the Nationale Nederlanden-office and the Groot Handelgebouw, located at the southern side of the main entrance.
1.2.2 New situation

The parts of the station mentioned before will change during the project.

The northern side of Rotterdam CS
Consists, in the new situation, of a new Northern Hall and bicycle storage.
- The Northern Hall
  - Beneath the overhang of the new roof construction, above the platforms, all passenger-facilities will be located.
  - The facilities will be expanded.
- Northern bicycle storage
  - The NS-office will be demolished and replaced by bicycle storage.

The central part of Rotterdam CS
Consists of the Provenierstunnel, the passengers-tunnel, the railtracks and the canopy of the railtracks (the canopy above the railtracks).
- Provenierstunnel
  - The Provenierstunnel will be restored as the connection between the centre and the proveniers-area for cyclists.
- Passage
  - The current passengers-tunnel will be replaced by an enlarged new passage.
  - Additional waiting space for the passengers will be realized.
- Canopy of the railtracks
  - A new roof construction will be realized above the platforms and railtracks. At the southern side, it will be connected to the Southern Hall. The canopy of the railtracks will be built up from transparent, bended roofslabs, laminated wooden beams and steal main beams en supports. A part of the canopy will be realized by using steal trusses with stainless steel-roofslabs.

The southern side of Rotterdam CS
Consists of The Southern Hall, offices, the southern bicycle storage and the RandstadRail subway station.
- Southern Hall
  - At the Southern Hall, commercial space and travel information-facilities will be located.
  - The roof structure will be integrated in and connected with the SH.
- Offices
  - At the north-eastern wing of the Southern Hall, offices will be built.
- Subway station
  - At the southern side, a subway station will be built. The metro station will constructed beneath the Southern Hall.
- Bicycle storage
  - The new bicycle storage will be positioned at the south side of the metro. The bicycle storage will be realized underground beneath the Southern Hall.
- The Weena
  - The Weena Street is the main street of the area, which runs from west to east. Beneath this street, the Weena-tunnel will made, to direct traffic underground.
- The tram platforms
  - The tram platforms will be located at the western side of the southern hall.
- The Kruisplein
  - The kruisplein will be renovated to create open space, comfortable for the passengers with the main path oriented towards the Weena.

Team CS, consisting of: Benthem Crouwel Architecten BV, Meyer en van Schooten Architecten BV and West 8 urban design & landscape architecture BV, has made the design for the new Rotterdam CS. IGWR is designing and calculating the roof-construction for the southern entrance hall. Spanning over 80 meters, this part of the new terminal is the most interesting for this thesis project. The design of this part has also been made by the architects and the structural design and calculation will be executed by IGWR. For designing the roof structure, a Program of Requirements has been made. These requirements should be taken into account.
1.3 Problem definition

Team CS has made an architectural design for the Southern Hall of Rotterdam CS. To be able to design the hall according to the wishes of ProRail, a Program of Requirements (PoR) has been made. The architectural design is based on this PoR. The Southern Hall now needs a structural design. To be able to make a design for the Hall, the requirements of the different parties have to be taken into account. Besides the wishes of ProRail, the wishes of the architect and the technical requirements are of great influence for the design. A structural design has to be made, which is suitable for the situation, taking into account the relevant requirements and efficiently spans the ground surface of the Southern Hall.

1.4 Goal definition

An alternate structural design will be made for the Southern Hall, which will be based on the requirements of ProRail and Team CS. These requirements will be gathered in the Program of Requirements. The PoR has to represent the wishes and requirements in such a way that the design, based on this PoR, will be applicable for this situation.

Several structural alternatives will be designed, which are able to realize the wishes of the architect. The alternative, which is the most promising, will be selected from the designs. This selection will be based on the PoR, the wishes of the different parties and other important factors. A more detailed design will be made of the final choice in such a way that the structural behaviour can be determined and calculated.

By calculating the forces acting on the structure, the strength, the stiffness and profiling of the construction will be determined. Based on these calculations, a comparison can and will be made between the chosen alternative and the current design. In the final part of the research an aspect of the façade-structure will globally be detailed in such a way, that the ideas of the architect can be realized.

- The first goal of the research is to compose a Program of Requirements that can be used as a base for the design. 
  This Program of Requirements will contain a set of aesthetical requirements that have to be fulfilled to get a design that fits within the vision of the architects (Team CS). In addition, the functional and technical requirements, boundary conditions and goals for the design will be included.

- The second goal is to create an efficient structural design for the hall that fulfills the requirements given in the Program of Requirements. 
  The goal is to find a shape and a structure, that direct the forces towards the foundation in such a way that a reduction in weight, costs or material use can be found. Several alternatives will be designed and the most promising alternative will be elaborated. To find out if the structure is suitable and efficient for this case, a calculation will be made to determine the forces, structural elements and displacements. This will be the base of a comparison between the two alternatives.
2. The design

To be able to design a structural solution for the given problem, it was necessary to get an insight in the vision of the architects. This vision has been used to create the design, of which the shape the most essential element is. The shape has been designed to emphasize the ideas of the architects. In this Chapter, the vision of the architects will be described. After that, the elements of the shape, which are important for the vision of Team CS, will be described. To complete the description of the design, a detailed description of the roof dimensions is added.

2.1 Vision

To get an insight in the vision behind the design, a meeting was arranged with one of the architects, responsible for the design. The summary of this interview can be found in Appendix 3. The vision of the architect, which is the basis of the architectural design, will now be described. The southern-entrance will be the new main entrance of the OVTRC.

The assignment given to Team CS was to create a design that is internationally representative for Rotterdam and the Netherlands. The architects wanted that the hall will act as a gate towards the centre of Rotterdam and connects the centre with the OVTRC. When the train passengers exit the train station they must feel invited to walk towards the centre.

2.2 Shape

The vision of the architect has resulted in the current design. An impression of the design is given in Appendix 1. The shape of the roof is the most determining factor of the design.

The roof is built up from triangular shapes, is curved at the top edge of the triangular part and has a metallic appearance. The most southern point (A) of the construction is the highest point of the roof construction (30 m above Ground Level (G.L.)). From this point out, the roof-height reduces to all sides (B and C). The roof surface can be divided in four parts with a different inclination. Between the lowest point B (approximately 5 m above G.L.) and point C (approximately 15m above G.L.) a line divides the main roof in two triangles. The inclination of each triangular differs, which results in the given shape. The shape has a few important characteristics that emphasize the goals of the architects; The highest point of the roof design, on the side where the main entrances are located, points towards the centre of the city to emphasize the function of a gate towards the centre.

The main entrance is located at the Southside of the hall to stress the southwards orientation. From the lowest point of the design, a straight “visual line” points towards the canopy of the platforms to visually connect the two parts. The requirements for the design that follow from this vision are gathered in the Program of Requirements (Table 5-1: Requirement A.1.i ).
2.3 Supporting

The main factor for the design of the supports is the subway station, which is being realized at the south side of the Rotterdam CS. It determines the position of the supports and the size of the hall. The station is already under construction and its location is shown in Figure 1-1. Supporting facilities could not be located directly on top of the tunnel. Therefore, the supports had to be located on the northern or southern side of the subway. The choice has been made to locate the supports at the south side to create sufficient floor area, according to the requirements. When this choice was made, the architects wanted the roof structure to support at only a few places to give it a floating appearance and to guarantee as much open space as possible. The two main supports are located at the southern side (Support A & B Figure 2-1). The exact locations are determined by the position and design of the subway station and the bicycle storage. Because the supports will be constructed on the slurry walls of the subway, between the subway tunnel and the bicycle storage, their position is fixed. At the northern side, the hall will be connected to the roof structure of ProRail, which has been designed by ARCADIS. The height of this construction is 15m+ NAP/approximately 16 m above G.L.

2.4 Materials

The architects want the roof-surface to be covered with a material that is representable and is aesthetically pleasing. This requirement was based on the presence of high buildings near the CS. Team CS has chosen for a metallic appearance to guarantee a durable and modern appearance. Their first choice was to use titanium, which is durable and of high quality. The high costs of the material made Team CS choose stainless steel plates. The lower side of the roof structure, in- and outside the façades, will be covered with wood. The choice for this material was made to match with the appearance of the OVTRC. The platform canopy will be built up from steel columns and laminated wooden beams. To create a unity between the two structures, the same appearance was chosen for the Southern Hall. Inside this roof package, light strips are integrated which allow natural light to enter. The total height of the roof structure should be as slim as possible.

2.5 Façades

The main entrance has a triangular shape and is built up from glass panels. Glass has been chosen to create an open appearance between in- and outside and to achieve the floating character. The façade is positioned far beneath the roof-construction to reduce the optical ‘walking distance’ towards the new Kruisplein.

2.6 Dimensions and surfaces

The Southern Hall has a maximum length of 165 meters and an average width of 80 meters. The exact dimensions and surfaces are given in Appendix 5.

The ground-surfaces can be divided in two main parts; the central hall (8600 m$^2$) and several types of buildings (5170 m$^2$). The total ground-surface of the main hall is 13770 m$^2$. 
Figure 2-2: Surfaces Southern[4]
3. Program of requirements

In this Chapter, the requirements for the structural design will be described. The requirements can be divided in Aesthetical, Functional and Technical requirements. Besides that, the goals, boundary conditions and assumptions are described. All these elements have been the basis of the different concepts.

3.1 Aesthetical requirements

<table>
<thead>
<tr>
<th>Nr demand</th>
<th>Name</th>
<th>Description</th>
<th>Source</th>
<th>Demanding party</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.1</td>
<td>Shape</td>
<td>The roof structure has to realize a shape that fits within the vision of Team CS. This vision is divided in the following requirements.</td>
<td></td>
<td>Team CS</td>
</tr>
<tr>
<td>A.1.1</td>
<td>Inclination</td>
<td>The roof structure has to have differences in inclination.</td>
<td></td>
<td>Team CS</td>
</tr>
<tr>
<td>A.1.2</td>
<td>Height</td>
<td>Point B has to remain the lowest point of the roof (maximum 9 m above G.L.).</td>
<td></td>
<td>Team CS</td>
</tr>
<tr>
<td>A.1.3</td>
<td>Height</td>
<td>Point A has to remain the highest point of the roof (minimum 25 m above G.L.)</td>
<td></td>
<td>Team CS</td>
</tr>
<tr>
<td>A.1.4</td>
<td>Highest point</td>
<td>The highest point needs to point towards the centre of Rotterdam</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A.1.5</td>
<td>Supporting</td>
<td>The floating appearance requires as few columns and supports as possible.</td>
<td></td>
<td>Team CS</td>
</tr>
<tr>
<td>A.1.6</td>
<td>Roof material</td>
<td>The material used for the roof has to be representable and esthetically pleasing.</td>
<td></td>
<td>Team CS</td>
</tr>
<tr>
<td>A.2</td>
<td>Roof thickness</td>
<td>The structural height of the roof has to be reduced to a minimum.</td>
<td></td>
<td>Team CS</td>
</tr>
<tr>
<td>A.3</td>
<td>Light</td>
<td>Sufficient facilities for natural light entrance should be designed.</td>
<td></td>
<td>Team CS</td>
</tr>
<tr>
<td>A.4</td>
<td>Façade pos.</td>
<td>The façade has to be positioned under the roof structure.</td>
<td></td>
<td>Team CS</td>
</tr>
<tr>
<td>A.5</td>
<td>Façade material</td>
<td>The direction of the front glass façade has to be more or less equal to the design.</td>
<td></td>
<td>Team CS</td>
</tr>
<tr>
<td>A.6</td>
<td>Façade</td>
<td>The façade has to have an open character and the amount of columns in the façade has to be reduced.</td>
<td></td>
<td>Team CS</td>
</tr>
<tr>
<td>A.7</td>
<td>Façade material</td>
<td>The vertical façade has to be made of glass.</td>
<td></td>
<td>Team CS</td>
</tr>
</tbody>
</table>

Table 3-1: Aesthetical requirements[2]
### 3.2 Functional requirements

<table>
<thead>
<tr>
<th>F.1</th>
<th>Perm. Load</th>
<th>The Southern Hall must be able to resist all loads.</th>
<th>ProRail</th>
</tr>
</thead>
<tbody>
<tr>
<td>F.2</td>
<td>Spec. Load</td>
<td>The Southern Hall must be able to resist loads due to passenger-facilities.</td>
<td>ProRail</td>
</tr>
<tr>
<td>F.3</td>
<td>Façade Load</td>
<td>The Southern Hall must be able to resist the loads acting on the façades.</td>
<td>ProRail</td>
</tr>
<tr>
<td>F.4</td>
<td>Stability</td>
<td>The Southern Hall must be stable in all directions. Stability should be provided by the Southern Hall.</td>
<td>ProRail</td>
</tr>
<tr>
<td>F.5</td>
<td>Hindrance</td>
<td>The Southern Hall must be able to direct all loads to the foundation without hindering the exploitation of passenger traffic.</td>
<td>ProRail</td>
</tr>
<tr>
<td>F.6</td>
<td>Rain</td>
<td>The roof construction and the façade must be able to resist water caused by rain.</td>
<td>ProRail</td>
</tr>
<tr>
<td>F.7</td>
<td>Klimat</td>
<td>The passengers must be protected from weather influences.</td>
<td>ProRail</td>
</tr>
<tr>
<td>F.8</td>
<td>Temperature</td>
<td>There are no requirement for the temperature in the Southern Hall. Inside the hall freezing should be prevented.</td>
<td>Gemeentewerken Rotterdam</td>
</tr>
<tr>
<td>F.9</td>
<td>Durability</td>
<td>The structure must be durable and reliable.</td>
<td>ProRail</td>
</tr>
<tr>
<td>F.10</td>
<td>Roof material</td>
<td>The material used for the roof has to be durable.</td>
<td>Team CS</td>
</tr>
<tr>
<td>F.11</td>
<td>Area</td>
<td>The Southern Hall needs to create a Gross Floor Area of approximately 13.500 m²; 5.000 for offices and services and 8.500 for NS-facilities.</td>
<td>ProRail</td>
</tr>
<tr>
<td>F.12</td>
<td>Columns</td>
<td>As few supports/columns should be used as strictly necessary.</td>
<td>ProRail/architect</td>
</tr>
<tr>
<td>F.13</td>
<td>Ventilation</td>
<td>The Southern Hall must have ventilation facilities.</td>
<td>ProRail</td>
</tr>
<tr>
<td>F.14</td>
<td>Facilities</td>
<td>Screens, information boards, time schedules and installation components will be connected to the structure. The SH has to be able to resist the loads due to these facilities.</td>
<td>ProRail</td>
</tr>
<tr>
<td>F.15</td>
<td>Availability</td>
<td>Public transport has to be able to continue during construction of the SH.</td>
<td>ProRail</td>
</tr>
<tr>
<td>F.16</td>
<td>Rain water</td>
<td>The water caused by rainfall has to be transported to the sewer by a water system.</td>
<td>ProRail</td>
</tr>
<tr>
<td>F.17</td>
<td>Fire resistance</td>
<td>The structure of the Southern Hall has to be fire resistant for at least 120 minutes.</td>
<td>ProRail</td>
</tr>
<tr>
<td>F.18</td>
<td>Cleaning roof</td>
<td>There must be a possibility to clean the roof coverage on the in- and outside.</td>
<td>ProRail</td>
</tr>
<tr>
<td>F.19</td>
<td>Cleaning façade</td>
<td>There must be a possibility to clean the glass façade on the in- and outside.</td>
<td>ProRail</td>
</tr>
</tbody>
</table>

*Table 3-2: Functional requirements*
### 3.3 Technical requirements

#### Loads

<table>
<thead>
<tr>
<th>Nr. req.</th>
<th>Name</th>
<th>Description</th>
<th>Source</th>
<th>Demanding party</th>
</tr>
</thead>
<tbody>
<tr>
<td>T.1</td>
<td>Load factors</td>
<td>Safety class 3&lt;br/&gt;Uf;g;u;normal(pos.) = 0,9&lt;br/&gt;Uf;g;u;normal(neg.) = 1.2&lt;br/&gt;Uf;u; = 1,5</td>
<td>NEN 6702:2001 (art. 5)</td>
<td>Bouwbesluit</td>
</tr>
<tr>
<td>T.2</td>
<td>Load factor</td>
<td>Safety class 3&lt;br/&gt;Uf;g;u;normal(pos.) = 1,0&lt;br/&gt;Uf;g;u;normal(neg.) = 1,0&lt;br/&gt;Uf;u; = 1,0</td>
<td>NEN 6702:2001 (art. 5)</td>
<td>Bouwbesluit</td>
</tr>
<tr>
<td>T.3</td>
<td>Corr. Factor</td>
<td>Yt = 1,0</td>
<td>NEN 6702:2001 (art. 5)</td>
<td>Bouwbesluit</td>
</tr>
<tr>
<td>T.4</td>
<td>Load comb.</td>
<td></td>
<td>NEN 6702:2001 (art. 6, 4)</td>
<td>Bouwbesluit</td>
</tr>
<tr>
<td>T.5</td>
<td>Snow load</td>
<td>Prep= Ci*Psn;rep&lt;br/&gt;Psn;rep = 0,7 kN/m2&lt;br/&gt;Ci</td>
<td>NEN 6702:2001 (art. 8)</td>
<td>Bouwbesluit</td>
</tr>
<tr>
<td>T.6</td>
<td>Wind load</td>
<td>(see attachment...)</td>
<td>TNO Apeldoorn</td>
<td>Bouwbesluit</td>
</tr>
</tbody>
</table>

#### Deflections

<table>
<thead>
<tr>
<th>Nr. req.</th>
<th>Name</th>
<th>Description</th>
<th>Source</th>
<th>Demanding party</th>
</tr>
</thead>
<tbody>
<tr>
<td>T.7</td>
<td>Roof</td>
<td>The additional deflection of the roof construction has to be smaller than 0,004*Lrep</td>
<td>NEN 6702:2001 (art. 10)</td>
<td>Bouwbesluit</td>
</tr>
<tr>
<td>T.8</td>
<td>Hor. Deflection</td>
<td>The horizontal displacement of single stored buildings may not exceed: 1/300 h.</td>
<td>NEN 6702:2001 (art. 10)</td>
<td>Bouwbesluit</td>
</tr>
<tr>
<td>T.9</td>
<td>Vert. Defl.</td>
<td>The vertical deflection of the supports, during the lifetime of the construction, should not exceed 20 mm</td>
<td>ProRail</td>
<td></td>
</tr>
</tbody>
</table>

#### Dimensions

<table>
<thead>
<tr>
<th>Nr. req.</th>
<th>Name</th>
<th>Description</th>
<th>Source</th>
<th>Demanding party</th>
</tr>
</thead>
<tbody>
<tr>
<td>T.10</td>
<td>Height</td>
<td>The near environment of Rotterdam CS is located in the &quot;high rise-area&quot; and has no height-limit.</td>
<td>Bestemmingsplan Gemeente Rotterdam</td>
<td></td>
</tr>
</tbody>
</table>

#### Boundaries

<table>
<thead>
<tr>
<th>Nr. req.</th>
<th>Name</th>
<th>Description</th>
<th>Source</th>
<th>Demanding party</th>
</tr>
</thead>
<tbody>
<tr>
<td>T.11</td>
<td>ARCADIS/ Southern Hall</td>
<td>The structure of the Southern Hall has to be connected to the structure of ProRail/Arcadis.</td>
<td></td>
<td>ProRail</td>
</tr>
<tr>
<td>T.12</td>
<td>ARCADIS/ Southern Hall</td>
<td>The connection between the two parts must be watertight and the insulation has to continue through the connection.</td>
<td></td>
<td>ProRail</td>
</tr>
<tr>
<td>T.13</td>
<td>ARCADIS/ Southern Hall</td>
<td>The ARCADIS structure can resist vertical loads</td>
<td></td>
<td>ProRail</td>
</tr>
<tr>
<td>T.14</td>
<td>ARCADIS/ Southern Hall</td>
<td>The amount of horizontal forces that the ARCADIS structure can resist is limited. Therefore the stability of the Southern Hall cannot be realized by only using the structure of ARCADIS.</td>
<td></td>
<td>ProRail</td>
</tr>
<tr>
<td>T.15</td>
<td>Façade</td>
<td>The roof structure has to be connected to the glass façades</td>
<td></td>
<td>ProRail</td>
</tr>
</tbody>
</table>

*Table 3-3: Technical requirements*
3.4 Goals

- The shape of the structural design should result in the shape that fits within the vision, as described in the aesthetical requirements, of Team CS.
- Spanning the hall has to be realized using as few columns as possible in the open space.
- The alternative design has to have a relevant advantage in comparison to the current design.

3.5 Boundary conditions

- For an overview of the boundary conditions see Appendix 6.
- The Southern Hall has to be connected to the structure of ARCADIS.
- At the west side of the Southern Hall the tram platforms are located. Supports cannot be placed at that position.
- The subway station is located beneath the Southern Hall and its location is fixed.
- At the Southside of the Southern Hall the new bicycle storage will be located. Supports cannot be placed there without additional measures.
- The tram stops will be located at the eastern side of the structure. Its position is shown in Appendix 6.
- The position of the supports is fixed.
4. Alternatives

In this Chapter, the designed concepts will be described for the structural solution for the Southern Hall. First, the possible and suitable structural systems for long spans will be described. After that, the designed concepts will be described.

4.1 Structural systems for long-spans

The structure of the Southern Hall needs to span more than 80 meters. This span can be realized by several structural systems. Each type will be described and its suitability will be treated. The span length is a crucial element in the selection of structural systems. Besides the most economical span ranges also the most important principles of each system will be described. The economical span range is the most commonly used and most efficient span length. Longer spans can be realized, but then the economical efficiency is to be questioned.

Structural systems can be divided in two types of structures; One-Way systems and Two-Way systems.

One way systems are characterized by the single direction in which the loads are diverted towards the foundation. The force distribution and the load paths are relatively clear. The following structural systems can be determined as One-Way systems: trusses, special trusses, arches and cable structures.

Two-Way systems are structural systems, which direct the loads towards the supports in two directions. The load paths of Two-Way systems are less obvious then in One-Way systems. The following structural systems can be determined as Two-Way Systems: space frames, shells, domes, membrane structures.

4.1.1 One-Way systems: Trusses

A commonly used structural system for long-spans is the use of trusses. A truss is an assemblage of linear elements arranged in triangular shapes to form a rigid lattice element. The linear elements are connected in such a way, that only a little bending will occur in each element. Loadings are directed towards the foundation by mainly tensile and compression forces in the linear elements.

Trusses can be made of steel, wood and even concrete (the last is not very common). The shape of the truss-beams can be adapted to the type of loading and functional requirements of the roof structure. Trusses act like beams and are mostly supported by columns. A truss can be designed with fixed, hinged or spring supports and can be schematized as a linear element.

![Figure 4-1: Mechanical schemes truss](image)

Points of attention:

- For using the trusses in the most efficient way, it is important to concentrate the loads on top of the vertical elements of the truss to prevent bending in the elements. This can be achieved by placing girders on the vertical elements.
- Because trusses are relatively weak in the direction perpendicular to the element, provisions have to be taken to prevent movement in this direction and tilting of the truss.

<table>
<thead>
<tr>
<th>Most efficient span-range</th>
<th>(Wood)</th>
<th>10-40 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Most efficient span-range</td>
<td>(Steel)</td>
<td>10-80 m</td>
</tr>
<tr>
<td>Approximate height</td>
<td>(Wood)</td>
<td>L/4-L/10</td>
</tr>
<tr>
<td>Approximate height</td>
<td>(Steel)</td>
<td>L/4-L/15</td>
</tr>
</tbody>
</table>

The design made by IGWR/ARCADIS is built up from normal trusses.
4.1.2 One-Way systems: Special trusses

These specially shaped trusses are often used for long spans (Leiden CS). Triangles are formed in two directions to create “3D”-truss element. These special shapes result in a stiffer and stronger element than normal trusses of the same height, especially perpendicular to the element. They act more or less like normal trusses, but only in two directions. A disadvantage compared to normal trusses is that more material has to be used per meter beam, when the same stiffness is realized, which results in a larger weight of the structural element. The trusses are mostly supported by a vertical truss, columns or walls.

Most efficient span-range (Steel) \[3\] : 20-100+ m
Approximate height (Steel) \[3\] : L/4-L/15

Points of attention:
- The connections of special trusses are more complicated then connections of linear elements.
- The larger weight of the trusses will result in more weight on the ARCADIS/ProRail structure; the bearing capacity has to be sufficient.

4.1.3 One-Way systems: Arches

Arches are a very efficient type of structure for long spans. Especially with evenly distributed loads, the shape of the arch is very effective for distributing the load to the foundation. Arches are often used for train-stations (Amsterdam), sport halls, bridges and storage halls. Arches can be made of laminated wood, steel and concrete.

The principle of the arch is to direct the loads to the foundation by mainly compressive forces. This principle makes it possible to realize large spans with a relatively small element sections. Bending and tensile stresses should be prevented.

Several types of supporting can be chosen, each with its advantages and disadvantages.

The arch with the clamped connection is for example relatively stiff, but sensitive for deflections of the supports.

Most efficient span-range \[3\] : 10-80+ meters.
Approximate height \[3\] : L/3-L/5

Points of attention:
- Large point loads and asymmetric loading should be avoided.
- To create an efficient arch-function of the beam, the total arch-height in the middle of the span has to be large to ensure little bending will occur.
- Large thrusts can occur in the foundation.
- Wind load can result in bending and horizontal deflections in the arch. The arch has to be able to resist these loads.
4.1.4 One-Way systems: Cable structures

Cable structures are capable of spanning great distances. For example bridges with very large spans are commonly realized by using a cable structure. For buildings, cable structures are also applicable. In this type of structure, cables are combined with other elements like beams and columns. The shape of the cable-structure has to be adapted to the type of loading to create an effective system.

Cable structure use tensile forces in the cables to direct the forces to the foundation. By spanning the cables, the tensile forces can be introduced into the cables and stiffness can be given to the structure. These cables are connected to a structural element that can direct the forces to the foundation. The shape and configuration of these cables can differ and be adapted to the type of loading and the structural requirements.

Most efficient span-range[3]: 20-100+ meters.
Approximate height[3]: L/5-L/11
The tower height differs per type.

Points of attention:
- Enough stiffness has to be generated to let the structure function efficiently. Therefore the spanning of the cables is important.
- Upwards wind loads can result in an uplift of the roof, this should be retained.
- Wind loading can result in the phenomenon of resonance. The wind can cause the cables to vibrate. When this vibration is equal to the own-frequency of the cable-structure, the vibration will amplify and result in large movements and great stresses on the structure. Dampers can prevent resonance to occur.
4.1.5 Two-Way systems: Space frames / lattice shells

The space frame is a two-way grid structure and is built-up from, most commonly steel, beams. These linear elements are connected together, forming a network of beams, to direct the loads to the supports in two directions. The space frame acts more or less as a plate and results in a stiff roof structure. Many different types of space frames exist, differing in grids, shapes, curvature and number of layers.

![Space frame images](image)

The space frame is a lightweight structure consisting of many elements. The costs of this structural type can be reduced when a consistent system with repetitive modules is designed. The height of the structure will be determined with this module dimensions. The space frame can be supported by columns or linetype supports (e.g. walls or stiff beams). Supporting by linetype supports results in a relatively stiff structure.

Because the space frame is stiff it will act horizontally more or less as a plate and stability can be realized by using stiff cores or walls.

Most efficient span-range\[^{[3]}\]: 10-50 meters.
Approximate height (column supported)\[^{[3]}\]: \(L/12-L/20\)
Approximate height (wall/linetype-supported)\[^{[3]}\]: \(L/12-L/20\)

![Supporting and mechanical options](image)

Points of attention:
- Large point loads should be evaded.
- Supporting by columns deserves additional attention; forces have to be lead into the space frame by several supporting points per columns.
- Stability can be gained by the shape or the use of cores and walls. The connection between these elements will influence the distribution of forces and can influence the weight of the structure.
- Space frames are supported in the most efficient way, when walls or linetype supports are used.
4.1.6 Two-Way systems: Membrane structures

Membrane constructions are a relatively new type of structure, which is used for car parks, sports halls, porches and pavilions. Membrane structures are often used for buildings/canopies where the requirements for the inside climate are not strict. The covering is usually built up from membrane fabric and many different types of this fabric can be used, depending on climate, functional, durability and strength requirements.

Membrane structures are tensile based structures. The membrane needs to be under constant tensile stress. By putting the membrane under tension, the shape will be fixed and the displacements reduced. To keep the membrane under constant stress, curvature is introduced to the shape. This can be realized by using cables, high and low points, arches and saddles. Tensile structures can be classified in four main types that are commonly used; the cone, the hypar, the saddle and the ridge-valley.

Most efficient span-range[^5,6,7]: 10-60 meters.
Average span of the fabric[^5,6,7]: 10 m

Points of attention:
- The membrane needs to be under constant tensile stress to reduce the displacements and give stability.
- To be able to put the structure under tensile stress it is of great importance to introduce curvature. This can be achieved by differences in heights of the supports, bended beams and curved cables.
- For flat planes, tensile constructions are not suitable, because large forces are needed to keep the membrane under stress.
- The membrane-fabric can span only approximately 10-15 meters.

4.1.7 Two-Way systems: Shells

Shells are capable of spanning large distances. Shells can be made out of concrete, but can also be built up from a latticed structure from steel or wooden elements. Shells are used for several types of buildings. For example: Parkings, auditoria and congress centres. The spans of these structures vary in shape and appearance.

In some cases, it is useful to add stiff ribs to the design, which can carry the main loads and increase strength and stiffness.
The structural behaviour of the shell is closely related to the shape. In shells, most forces will be directed towards the foundation by compression forces; Bending in the shell will result in a large thickness. Therefore, it is important to adapt the shape to the type of loading and the location of the supports, to prevent bending to occur in the shell.

Most efficient span range \[3\] : 20-80 meters
Approximate structural height (rib supported)\[3\] : 500-700 mm
Approximate structural height (thin shell)\[3\] : 100-400 mm

Points of attention:
- The shape has to be adapted to the loading and the support locations.
- The supports and boundary edges are a very important part of the design.
- Point loads should be prevented.
- Where façades are placed beneath the shell, it can be efficient to use it as a supporting structure.
- The execution of lattice shells can be complicated.
- Snow can be gathered at a low point of the structure, which will result in large loads and displacements.

Figure 4-6: Overview structural types
4.2 Alternative 1: Membrane tensile structure.

Goal of the alternative
The goal of this alternative was to create a light-weight design.

Shape
The shape of the structure is different from the shape designed by the architect. The main change to the design of the architect is that this shape has much more curvature than the given design. Besides that, the sight lines towards the ProRail structure cannot be maintained. The height of the arches will increase southwards to create the orientation towards the centre of Rotterdam. This will create the idea of the hall functioning as a gate. The height of the corner points can be maintained as designed, except for the lowest point of the structure, which will be lower than in the architectural design. The highest point of the structure is located at the most southern point and points towards the centre. The open character of the design will be realized by creating large glass façades using arches. The glass façade beneath the structure are also realized by using an arch beneath the membrane.

Roof structure
This membrane structure differs in shape compared to the first alternative. The membrane has to be under tension to keep the construction stiff. To realize tensile stresses in the entire area, curvature has to be introduced to the shape. This will be realized by using arches and cables. Arches are chosen, because a glass façade can be placed beneath the curved beams. In this way, it is possible to separate the inside from the outside climate. The highest point of the structure will remain the highest point. The membrane will be pulled towards the highest point of a column to realize the orientation towards the centre. This high point also adds curvature to the design. Between the arches the membrane will be tightened by cables to create curvature and to prevent large displacements.

The roof structure will be covered by a membrane fabric. An important design aspect is that the fabric can span only 10-15 meters. Therefore the initial shape changes, when this is taken into account. More arches and cables are needed to create enough curvature and reduce the span of the material. The membrane can be made of several types of fabric. The requirements in relation with the climate and the durability will determine the type that has to be used.
The type of the structure can be called a ridge-valley system. The arches will tighten the membrane upwards and the cables will tighten the membrane downwards. Between these two structural elements, the membrane only spans a maximum of 10-15 m.

Supporting
The membrane structure will be supported by a column, cables and arches. A column can be used to create the high point. The membrane will be stretched towards the top of this column to create curvature and to express the architects’ idea. The arches also have to be used to introduce curvature. Besides that, it is possible to distribute the loads in an efficient way (by normal forces) and to create the possibility to place a glass façade beneath the arches.
For supporting the structure, additional piers are needed. The cables, located nearby by the subway tunnel, can be connected to the subway walls. The slurry wall itself will not be able to resist all loads and therefore additional facilities have to be designed. The support will be located near the bicycle storage and deserves additional attention. If the thrust forces cannot be taken by the foundation, columns in combination with a tension cable can be applied.

For the high pylon at the Southside of the structure, two additional supporting blocks have to be designed. These blocks will only have to resist tensile loads. There is only a little space in that area so it might be necessary to make one large foundation block in stead of two small ones.
The membrane can span only to a maximum of 15 meters. Therefore, additional arches and cables had to be added to the initial design. The shape changes because more curve-lines are added. These additional structural elements are placed on the arches and the slurry wall of the subway station.
Stability
Stability will be provided by the structure itself, using cables, the membrane and the given structural elements. It is important that the structure possesses sufficient stiffness. By spanning the membrane, the position of the elements will be fixed. It is important to stress the membrane in such a way, that the bending stresses in the arches will remain small.

Force distribution
The mechanical model is different in both directions. The arches are connected with a rigid connection in the direction perpendicular to the arch. The tension stresses in the membrane fabric will keep the arch in position. In the parallel direction the arch a hinging connection will be applied.

Offices
The offices can be located beneath the structure and will not be connected with the membrane. Therefore, the offices require a structure that is stable and is loaded by only its self weight and the variable loads due to the usage. The climate requirements inside the offices are more strict and can be fulfilled by separately insulate these buildings. The cores of the offices cannot be used for the stability of the roof structure, because they will not be connected. On the east and the west side, two additional parts are made for the offices. The usable floor area is sufficient for the offices.
Connections

The arches will be stabilized by the cables and the membrane under tension. During execution, this equilibrium will be generated. Due to this process and wind loads, differences in stresses between both sides of the arch can occur. Therefore, it is useful to clamp the bottom side of the arches. This will result in additional bending moments on the structure, which have to be limited. To span the membrane an important factor of the design are the edge connections of the membrane. Detailing the structure is very important for its feasibility.

Beneath the arches of the structure, it is possible to design a glass façade. The difficulty here is that membrane structures are relatively flexible and large displacements can occur. The glass façade is relatively stiff and is not capable of resisting large displacements. Therefore, the connection between the glass and the arch deserve additional attention and needs to be able to cope with the displacements.

The structure requires a connection to the ARCADIS part. It is important to check the amount of forces that can be taken by the canopy. Arches, cables and membrane will be connected it and horizontal forces have to be resisted.

Estimated properties\[7,8\]

Roof thickness:
- double layered membrane 200 mm
- steel arch 800 mm

Roof weight:
- Membrane 40 kg/m\(^2\) (2 layers)
- Arch 500 kg/m\(^1\)
- Cables 20 kg/m\(^2\)
- Insulation 20 kg/m\(^2\)
- Roof weight 150 kg/m\(^2\)

Costs
- Membrane € 80 / m\(^2\)
Advantages

- A tensile-membrane structure has a low self weight.
- Sufficient light will enter the hall via the membrane fabric; therefore, no additional facilities have to be designed.
- It is relatively easy to execute a membrane structure, only a few structural elements are needed.
- Aesthetically pleasing.

Disadvantages

- The membrane fabric does not provide thermal and acoustic insulation. Especially acoustic insulation is needed.
- Because of the flexibility of the membrane, large displacements can occur.
- The membrane is a relatively weak material.
- The durability of membrane is limited to a maximum of 40 years.
- Installations cannot be integrated in the roof package. Installations have to be integrated in the floor.
- Water caused by rainfall will be disposed by the shape; a gutter cannot easily be connected to the structure.
- The wind load beneath the canopy will cause large up- and downwards loads large which will result in large displacements and stresses.
- Large tensile forces will have to be resisted by the foundation.
- Large thrust forces will have to be resisted by the foundation.
- When it is raining, a lot of noise can be generated by the fabric. (can be solved by using double layered fabric with insulation)
- The insulation value of one-layered fabric is negligible.(can be solved by using double layered fabric with insulation)

Main difficulties

- The main difficulty of the design is to control the displacements and prevent large displacements. For example beneath the highest point, the wind will create large deflections.
- Stabilizing this structure in southern direction will be a point of attention. The differences in curvature and heights might result in bending moments in the arches. By changing the inclination, stresses and heights of the cables and arches, this and the bending moments in the arches can be controlled.
- The displacement of the arch can influence the connections of the façade. This connection deserves additional attention.
- The integration of the installations into the floor will be difficult. Especially at the subway part of the area complications can occur.
- The stability of the structure has to be guaranteed if the membrane is damaged by external forces.
4.3 Alternative 2: Arch-shaped structure

**Goal of the alternative**
The goal of this alternative is to create a light-weight design using arch and/or shell-action.

**Shape**
The shape of the second alternative also differs from the shape given by the architect. The roof surface is curved. From the top view lines are drawn to several foundation blocks and triangles are formed. These lines are the main spans and can be spanned by arched shaped elements. With the arches, large open spaces can be created. Therefore, it is not necessary to use columns in the free space of the hall. Beneath the arches, the glass façade can be made to create an open design. The front façade can be made beneath the covering, orientated towards the south. To create the highest point pointing toward the centre, it is chosen to end the roof covering at the highest point of the most southern arches. The arches will continue to the foundation on the subway. The design thereby is oriented to the centre. The conoidal shaped connection between the passengers tunnel and the Southern Hall harmonizes both structures. The possible locations for the supports result in the given shape.

**Roof structure:**
The roof is built-up from arches. The area between the arches can be covered by a lattice shell or girders. For a lattice shell, the curvature will influence the roof thickness. If straight girders are used, the appearance of the structure will change. The arches span a maximum of approximately 82 meters and can be designed in laminated wood. This will result in a light structure. The connection to the ARCADIS structure will have a conical shape and will be formed by girders that are placed on the arch and the passengers tunnel-covering. On top of the girders/lattice and the arches, the roof package is placed. The wooden ceiling coverage can also be connected to the wooden girders and beams. The roof coverage can be designed in stainless steel panels, following the wishes of the architect.

**Supporting**
The roof structure is supported by arches. The maximum height of the arch will be around 30 meters on a span of 80 meters. The arches will be retained between two foundation blocks. This will result in large thrust forces acting on the piers. The arches can be supported by the structure for the glass façade. Seven supports are needed to support the structure. All supports will have to resist large horizontal loads and will therefore be costly.
Stability
Stability will be provided by stiffening the roof. If the roof structure can act like a diaphragm, stability can be realized. The different parts of the structure differ in inclination and therefore bending moments will occur if forces are transmitted between these parts. This has to be taken into account. If a thin lattice shell is used, this is a very important point of attention. A thin lattice is not capable of resisting large horizontal loads. The provisions for the stability will therefore result in additional weight.

Offices
The offices can be located beneath the structure and will be connected to the roof structure. The cores will add stability to the structure. The cores will be connected to the girders of the structure, which will transmit the forces to the other arches of the structure. With this design, only 4500 m$^2$ of offices can be realized. An additional built out addition can be made, but this will disturb the design.

Force distribution
The mechanical model of this alternative is shown in Figure 4-17. In the longitudinal direction of the structure, stability will be provided by the cores of the offices. The arches will be connected to the foundation with a hinging joint.

Estimated properties\textsuperscript{[3,8]}

Roof thickness:
- Roof package: 400 mm
- Wooden arch: 800 mm
- Girders (20 m max span): max 800 mm

Roof weight:
- Arches: 500 kg/m
- Girders: 100 kg/m$^2$
- Roof package: 83 kg/m$^2$
Roof weight: 225 kg/m$^2$
Advantages

- If arch action is used correctly a reduction in the structures weight can be realized
- The open and floating character of the structure can be realized.
- If wood is used, the structure has an additional low self-weight.

Disadvantages

- The floor surface will be limited by the shape. Near the support, the construction height is low and therefore the rate between the gross and the usable floor area will be relatively high.
- The transmission of the forces will result in bending forces in the connection between the two triangular parts.
- Large thrust forces will have to be resisted by the foundation.
- The shape is different from the architectural design.
- Only 4500 m² of floor area for the offices can be realized.

Main difficulties

- The main difficulty of this structure is to create the intended arch-action. Because the distribution of the loads will act as shown in Figure 4-18, additional bending moments and torsion will occur in the arch. This has to be taken by the beam and the clamped connection to the foundation. This will result in additional forces and elements dimensions. With this design, it is difficult to create genuine arch action.
  
To adapt the shape of the arches to the force distribution as described in load case 1, it is possible make the arch a bit higher in the middle of the span.

To adapt to the second phenomena it is possible to change the shape of the arch in horizontal direction. By adding weight on the side of the beam that is tilting upwards, it can be prevented.

The arches have to be designed with a variable cross section, which will be difficult and costly. Besides that the beam dimensions will increase and the goal of the design will not be reached.

Stabilizing the structure will result in additional torsion and bending moments in the arches and girders.

It is possible to make a shell like structure of a wooden lattice. This will result in the same problems, but the weight can be reduced even more.
4.4 Alternative 3: Concrete shell

Goal of the alternative
The goal of this alternative is to create a concrete design with fewer connections than the current design, a small roof thickness and a low material/span rate.

Shape
The shape of this alternative is more or less the same arched shape as described in the previous paragraph. For this alternative, the shape has been realized by concrete beams in combination with concrete shells. To be able to realize the large span of the structure it was important to add curvature to the shape of the architect. The shape therefore is different from the design of the architect. At the Southside, the shape, which is shown in Figure 4-20, has been chosen to fulfill the requirements of the architect. If the highest open side of this structure is oriented towards the south, the structure will point towards the centre of Rotterdam. Beneath these edges, a glass façade can be designed to create the open appearance. The bended edges and few supports will stress the floating expression of the hall.

Roof structure
The roof will be built-up from concrete shells. The shape of the shell will be adapted to the loading; an effective shape will transmit the forces to the foundation by mainly normal forces/stresses. At the Southside, a verge is designed. In this part of the shell, bending and tensile stresses will occur. This shell will therefore be relatively thick. The glass façade will be placed at the edges of the structure. This structure can partly support the shell if that is necessary. Beneath the buckles of the shell, ribs can be placed to increase the strength and stiffness of the shell. The roof covering will not be made out of stainless steel; the concrete is durable and can even be painted if necessary. Covering can nevertheless be designed. The two main parts of the shell have to be separated by a dilatation to prevent bending moment to be transmitted between both shells. The most southern part therefore will be thicker than the northern part.
Supporting
The concrete shell will be supported by large concrete supports and if necessary by the façade structure. For the supports, additional piers are needed which will have to resist horizontal and vertical loads. The height of the shell will influence the rate between horizontal and vertical forces. The horizontal loads will be lower, in comparison with the vertical loads, if the construction height is increased.

Stability
Stability can be provided by the shell itself and the clamped supporting of the lowest points of the shell.

Offices
The offices can be located beneath the structure and will not be connected to the shell. Because the offices don’t need to stabilize the structure, stability will be gained by the shape of the structure and therefore it is not necessary. The connection of the cores to the roof shell will influence the shell-action in a negative way and therefore it will not be applied. The cores have to be placed beneath the structure. It is with this shape it is possible to create only 4250 m² of office space, without hindering the passenger-flows.

Force distribution
The main forces will concentrate in the relatively stiff beams. The height of these beams will be larger than the structural height of the shell. If the shapes of the shell parts are correctly designed, mainly normal stresses will occur in the shell. These forces will be directed towards the piers via the beams.
**Estimated properties**

**Roof thickness:**
- Concrete girders: 1500 mm
- Varying shell: 300-500 mm

**Roof weight:**
- Girder: 1380 kg/m
- Shell: 920 kg/m
- Finishing material: 15 kg/m
- Roof weight: 1000 kg/m

**Advantages**
- The concrete can be used as a façade; no additional facilities have to be designed for the sound and the climate on the outside.
- The outside of the concrete can be finished in such a way that its appearance is aesthetically pleasing.
- Concrete is durable.
- The displacements will be relatively small.
- Water caused by rainfall is easily disposed via the shape to the lowest points.
- Relatively small roof thickness.

**Disadvantages**
- The concrete shells will be heavy compared to other structures. This will result in large loading on the piers.
- The usable floor area will be less then in the architectural design.
- Large foundation blocks will be needed to support the shell and resist the thrust forces.
- Supporting blocks will be needed near the construction of ARCADIS. This foundation deserves special attention.
- Light entrance can only take place via the windows on the sides of the structure. These windows are large and the area of the roof is relatively small. Therefore the light entrance probably will be sufficient. Designing facilities for light entrance in the roof structure will disturb the force distribution in the shell in a negative way.
- Connecting large facilities like information boards will disturb the action of the shell and result in additional bending stresses, which should be prevented.
- Bending will occur in the shell what will increase the thickness of the structure.

**Main difficulties**
- To resist the large horizontal forces that will occur in the foundation.
- The connection of the façade to the ARCADIS structure, because of the differences in structural systems, material, displacements and stiffness.
- The interaction between the shells can result in bending moments in the shell and additional thickness.
- The design and execution of the two piers needed at the northern side between the ARCADIS offices.
- To connect the utility services to the structure.
- A concrete shell can be relatively light. In comparison with the steel structure of GW the shell thickness has to be less than approximately 200 mm to be competitive. This will probably not be achievable.
4.5 Alternative 4: Cable stayed roof

**Goal of the alternative**
The goal of this alternative was to create a design to reduce the weight of the structural elements in the roof, decrease the roof thickness and the loads acting on the supporting structures.

**Shape**
The shape of this alternative is the exact shape designed by the architect. This shape is described in chapter 2. Pylons will be added to the design, which will disturb it, but make the structure lighter.

![Figure 4-24: Cable stayed roof](image)

**Roof structure**
The roof structure will be built up from trusses and girders. These trusses and girders span the entire area, but will be connected to the pylons that will carry a part of the weight. The shape of the roof requires planes that can easily be divided in several parts with the same area. Therefore, the architectural shape with flat planes and triangular shapes has been chosen. An important factor of this shape is that the different inclinations of the roof-surfaces have to be taken into account when trying to equally divide the weight of the roof. The different parts of the roof have to be connected to require sufficient stiffness in the structure. Wind bracing elements in the roof can supply stability and stiffness.

**Supporting**
The loads will be directed to the foundation using beams, cables and pylons. The cables connected to the pylons carry some of the loads acting on the trusses, which will reduce the truss height. To prevent large bending moments in the pylon it is important that the resulting horizontal forces of all cables together is reduced to a minimum (preferable 0). Therefore the pylons are placed at the mass centre of each triangle. The locations of the connections of the cables on the roof are determined by the boundary condition that the resulting horizontal forces are more or less zero. The direction of the pylons will be perpendicular to the inclination of the roof.
Stability
Stability will be provided by the cores of the offices, which are located in the Southern Hall. Besides that, the support at the lowest part of the structure (A) can be seen as a fixed point. Therefore, for triangular part 1 of the roof, stability in the x-direction has to be realized by a core or vertical truss. Part 2 can rotate around A and needs stabilizing facilities in both x- and y-direction. The stabilization can be realized at the longest side of the structure. Part 3 can also rotate around point A and needs stabilizing in the y-direction. If part three is horizontally connected to part 2, its rotation is prevented and the structure will be stable. So therefore, the most important stabilizing structure is the structure for part 2. The only way to be able to get mass on the stabilizing core, without disturbing the equal force distribution on the cables is to place a core in the middle line of the triangle. The main beams will be placed on top of the core and the cables and the pylon will move southwards. For part 1 it is more difficult to get sufficient weight on the core. If the core is placed in the middle of the span, it will disturb the passengers traffic towards and from the passengers tunnel. The most suitable option seems to be location C. The same principle as at roof surface 2 will be used. In the drawing, the pylon and cables of part 1 will move a bit northwards to equally divide the forces over the cables.
For part 2, an additional difficulty is present. Because of the inclination of the roof structure, the roof wants to swing westwards. This will result in an additional rotation and additional large horizontal forces that have to be taken by the core (B) and support A. The stability and force distribution of this structure is therefore hard to read and large forces in the cores will be needed to stabilize the structure by cores. To get a more efficient structure, stability has to be gained from the adjacent buildings of ARCADIUS, but it will not be able to take such large forces.
If the cores are only horizontally connected to the roof structure, the force distribution will not be influenced, but it is questionable if the weight will be sufficient.

Figure 4-25: Top view cable stayed structure
Force distribution

The given principle results in the following mechanical scheme. In this scheme, it is possible to see the difficulties of creating an equilibrium and sufficient stiffness. The pylon will only be in equilibrium if the loading core is stiff enough to prevent horizontal displacements.

Offices

The offices can be located beneath the covering and will be connected to the roof structure. The location and stiffness of these cores are very important for the design. The offices on the eastern side of the structure can be attached to the large truss.

Estimated properties

Roof thickness:
- Main trusses: 2500 mm
- Girders: 350 mm
- Trusses: 1000 mm
- Roof package: 400 mm

Roof weight:
- Truss: 350 kg/m
- Girders: 100 kg/m
- Finishing material: 83 kg/m
- Roof weight: 3000 kg/m² (excl. pylons and cables)

Advantages
- The use of this system will reduce the weight of the structure and the loads on the ARCADIS structure.
- The roof thickness can be decreased.
- The shape of the architect can be realized.
- The amount of office space needed can be realized.

Disadvantages
- Large pylons will be placed inside the hall.
- The roof package will be penetrated by large steel elements what will result in thermal bridges.
- The horizontal displacements will be difficult to retain because of the loads on the cores caused by the reduction of the weight.
- The pylons will disturb the design of the architect.
- Flexible structure.
- The connections will be complex due to the interaction between the different parts of the roof.

Main difficulties
- To divide the cables in such a way that the resulting horizontal forces will be more or less 0.
- Stabilizing the structure.
- Connection the roof slabs to each other without disturbing the equilibrium.
- Connecting the cores to the structure without disturbing the distribution of the loads and prevent large tensile forces in the foundation at the same time.
4.6 Alternative 5: Lattice shell in combination with trusses

Goal of the alternative
The goal of this alternative was to design a structure that has a relatively low self weight and a small roof thickness.

Shape
The shape of the roof of this alternative is a hyperbolic parabola, also called a hypar. The hypar is formed by drawing straight lines between the two longest sides of the floor area. By changing the heights of the two corners at the ProRail side, the hyperbolic parabola can differ in shape and curvature. The main change on the design is that the sharp edge, dividing the two main roof surfaces, will become a curved line. Because of this phenomenon, additional space is created above the top of the original line.

Roof structure
For this alternative, a space frame has been used. The basic shape of the space frame is the hypar shape. The shape of the hypar can be adapted to the loading. This shape seems to be more suitable for the load distribution to the foundation. Because of its curved shape, additional normal forces will occur in the lattice shell and the bending will be reduced. By lowering the point at the ProRail structure it is possible to get more curvature in the hypar shape. This will improve the force distribution, characteristic for the hypar and stress the intended design aspects of the architect.

Supporting
The frame will be supported by columns and trusses. On the long edges of the lattice shell, trusses with sufficient height will be designed. Because as few columns as possible should be used, they will be placed at the ends and at the middle of the span of each truss. This additional support in the middle reduces the height and deflection of the trusses. On the long side of the span a large truss will be made to support the space frame for the offices and to realize the open glass-façade. If necessary an additional truss will be added to reduce the span of the lattice. In that case, the truss should be integrated in the space frame to realize the small roof thickness. If this is not possible, the advantage of the roof thickness will not be valid anymore. The reduction in weight of the structure than will become the main goal.
Stability
The stability of the structure will be provided by the lowest fixed corner point and stiff walls/vertical trusses. This can be realised by designing vertical 3D-trusses. The lowest point is fixed, what will result in a rotation around this point by horizontal loading. The vertical trusses should prevent this rotation. To use these stabilizing trusses in an efficient way it is useful to let the trusses vertically support the roof structure. This will prevent large tensile loads in the foundation to occur.

![Image](image1.png)

Force distribution
The load on the roof surface will result in a concentration of the stresses on the edges and corners of the structure. The shape of the roof will make the roof plain act as more or less a shear element. The stresses will concentrate in the trusses at the edge. As show in Figure 4-30 the forces on the columns will act in the drawn direction. It seems that the beam A, located at the ARCADIS side, will tend to move in the direction of the resulting forces. It will be calculated if additional facilities, like a stiff column or core, are needed beneath this beam. This is not desirable, because it is located on the platforms. The necessity of this facility is dependent on the stiffness of the lattice.

![Image](image2.png)

The stiffness of the lattice is of great influence on the force distribution. If the lattice is stiff, it will more or less act as a plate. Redirecting forces to e.g. the stability elements will be relatively easy to make. For this stiffness, a relatively large construction height is needed.

If the lattice will be relatively flexible, it will use relatively little material. If the lattice is flexible, the trusses will be loaded in horizontal direction what will result in displacements and horizontal stiffness is needed. Besides that, it will be more difficult to gain stability by the cores, which will be located along the trusses. Therefore, it seems to be useful to choose a relatively rigid fill between the trusses. For a rigid frame, the construction height will be relatively large and a lot of connections are necessary. The lengths of the linear elements will differ, what will make the execution relatively difficult and the structure relatively high.

Offices
The offices can be located beneath the structure and will be connected to the roof structure. The position of these offices and office area is the same as in the original design (see Figure 4-37).
offices on the eastern side of the structure can be attached to the large truss. More detailed drawings can be found in Appendix 7.

**Connections**
The connections between the cores and the space frame/truss, deserves additional attention. The connection between the frame and the truss will at least need to support vertically. It will have to be calculated if a fixed or hinging connection will be the most efficient. The connection between the trusses will be the most complex at the lowest point of the structure. Possibly 3 trusses will have to be connected there. If this is necessary the same principle can be used as designed at Alternative 7 (see Figure 4-31).

**Figure 4-31: Corner connection lattice structure**

**Estimated properties**

**Roof thickness:**
- Roof package: 600 mm
- Lattice: 2500-3500 mm
- 3D-truss: 3500 mm

**Roof weight:**
- Roof package: 83 kg/m²
- Lattice: 150 kg/m²
- Roof weight: 175 kg/m²
- 3D-truss: 700 kg/m²

**Advantages**
- The shape of the space frame is suitable for a relatively light weight structure.
- The roof structure will be a relatively stiff element. So horizontal bracing elements will not be necessary.
- Connecting the roof façade will be relatively easy, because many connection points will be present.
- Facilities for public services can be located in the roof structure.
- The average height inside the structure will increase.

**Disadvantages**
- Many different element sizes which can result in a difficult execution of the roof.
- Complicated construction and therefore not easy to estimate the forces in the structure.
- Complex connections between space frame and structural elements.
- Connection with the ARCADIS structure deserves additional attention, especially when additional curvature is needed.
- It is likely that columns have to be placed in the free space of the Southern Hall.
- The connection with the core of the offices is hard to make, introducing forces in a space frame is difficult.
- Because many elements are present in the roof structure, installation of the facilities for public services can be relatively difficult.
- Large elements dimension at the corner points.
- Change in the architectural design.
- At the lowest point, the structure will be lower then in the architectural design.
- Many and complex connections.

**Main difficulties**
- To handle the concentrated loads in the corner points.
- To create an executional system.
- To get a system that is easily executable and is built up from easy connections.
- The clearstories are designed as very heavy elements, the space frame might not be able to resist the large point resulting “point loads”. An alternative design has to be made to reduce weight.
4.7 Alternative 6: Cable stayed roof 2

Goal of the alternative
The goal of this alternative was to create a design to reduce the weight of the structural elements in the roof, decrease the roof thickness and the loads acting on the supporting structures.

Shape
The shape of this alternative is the hypar shape. More curvature is added to the design and the buckle in the roof structure will become a curved line. From the ARCADIS structure straight linetype elements will be designed towards the southern end of the structure. The inclination of the trusses will change in the direction perpendicular to the trusses. The shape therefore will be the same as the described hypar type of structure.

Roof structure
The roof will be built up from trusses and girders. The three main trusses are located between the pylons and realize the main span of more then 80 meters. In the other direction smaller trusses will be placed. The largest span these trusses will make is 55 meters. Therefore, the roof thickness will be determined by the height of these trusses. If the trusses are connected in such a way that a clamped connection is realized, the deflections will be reduced. The verge at the Southside can also be realized, without an additional supporting truss. Therefore, the trusses in northern direction will act like beams on four supports. The beams will continue towards the ARCADIS structure.
Supporting

The main trusses will be supported by the six pylons. The pylons direct the forces towards the foundation. The beams that meet at the lowest point of the structure will be connected to the foundation as well to create stiffness and prevent horizontal displacements in its main direction. The trusses in the northern direction will be supported by the main trusses.

Stability

The stability of the structure will be provided by the cores of the office. In the walls of these office buildings, stiff cores can be realized. Depending on the weight of the office facilities and the weight due to the structure, the amount of forces that the core can resist and the stiffness of the core can be determined. If the stiffness of this core is not sufficient, additional stiffness can be gained by another core in the other office building and the ARCADIS structure. The structure will tend to rotate around the fixed lower point. This rotation has to be prevented to guarantee stability. This will be realized by the cores and the use of a stiff roof. The roof will horizontally act like a rigid plate, when wind bracing is applied at the given location above the cores.

Offices

The offices can be located beneath the structure and will be connected to the roof structure. The offices are planned at the wings of the design. The construction of the offices can be connected to the trusses of the roof structure. The construction of the offices will be built up from columns and floors. The structure of the offices has to stabilize itself. The usable floor area for the offices will be 5200 m².

Connections

The pylons will be connected to the piers with a hinged connection. This will reduce the bending forces in the pylon. The trusses will be connected with a fixed connection to reduce the vertical displacements.
Force distribution

The trusses that are connected to the cables will be stiff in comparison with the perpendicular trusses. The displacements of the supported trusses will be relatively small and they will act as a spring support. The perpendicular trusses will be connected with a fixed connection and therefore these beams will act as a single beam spanning over four spring supports. The stiffness of the trusses that span between the supported trusses will determine the main structural height.

The supporting structure is designed in such a way that the pylons will take the compression and bending loads and the cables will direct the tension loads towards the foundation. Because of the little space available at some locations of the pylons, distance B cannot be large. The height H of the pylon will be minimal 3 times as large as B. Therefore, the bending moment caused by the horizontal component Fh of the force in the cable will have to be resisted by the pylon and the cable. Because H is 3 times as large as B, the forces in the cable attached to the foundation will also be 3 times as large as Fh.

Estimated properties

Roof thickness:
- Trusses 2250 mm
- Girders 350 mm
- Roof package 600 mm

Roof weight:
- Truss 250 kg/m²
- Girders 100 kg/m²
- Finishing material 83 kg/m²
- Roof weight 250 kg/m²

Advantages
- The use of this system will reduce the weight of the beams and the loads on the ARCADIS structure.
- The roof thickness can be decreased; its minimum will be determined by the longest span.
- Most of the wishes of the architect can be fulfilled.

Disadvantages
- Additional piers have to be made.
- The design can be sensitive for wind loading.
- The horizontal displacements will be difficult to retain because of the loads on the cores caused by the reduction of the weight.
- The pylons will disturb the design of the architect.
- The shape of the offices changes.
- The pylons and additional piers will be costly.

Main difficulties
- To transfer the large tensile loads to the foundation.
- To realize sufficient stiffness in the structure.
4.8 Alternative 7: 3D-Trusses

Goal of the alternative
With this alternative it is the goal to use the additional stiffness of the 3D elements in such a way that it will result in a smaller structural height and a decrease in the total weight of the structure.

Shape
The shape of this alternative is the shape as designed by the architects. The buckle in the roof can be maintained and the height of the corner points as well.

Roof structure
The roof structure will be built-up from 3D-trusses. These trusses can be placed in the main span directions and are more stiff then normal trusses with the same height. Between these elements, normal trusses will be designed to realize the smaller spans. The main principle is to make the long span in 3D elements and the shorter spans in normal trusses. If this is optimized, the height of the roof package and the weight of the structure can be decreased.

Supporting
The trusses will be supported by columns. Because as few columns as possible should be used, they trusses are mainly supported at the outside ends. It is likely that an additional support has to be placed in the middle of the main span. This will reduce the deflection of the trusses, which will result in a smaller element and less weight. On the long side of the span a large truss will be made to support the space frame for the offices and to realize the open glass-façade.

Stability
Stability will be provided by cores that can be designed inside the office spaces. These cores have to be connected to the roof of the hall to reduce the horizontal displacements. To create overall stability, wind bracing has to be applied in the roof. These can be placed between the trusses and the girders.
Offices
The offices can be located at the same position as in the initial architectural design. They will be connected to the roof structure to guarantee the stability. The vertical trusses will be located inside the walls of the offices. The spatial trusses that are located at both longest edges will rest on these stiff elements to prevent tensile forces to occur in the foundation beneath the vertical trusses. The structure of the offices will provide their own stability and will be built-up from trusses and columns.

Type of truss
It is chosen to use a square 3D-truss. These are twice as stiff in vertical direction as single trusses. In horizontal direction these trusses are considerably stiffer. For the design, it is important to create much stiffness in vertical direction and therefore the square truss is chosen. Another advantage of this type of truss is that the connection to the single trusses is relatively easy to make. The trusses will be built-up from Square Hollow Sections to make relatively easy connections.

Connections:
A complex connection is the connection of the trusses to the lowest foundation block of the structure (Connection A). Several trusses will have to be connected with each other and the foundation block. The concept of this connection is shown in Figure 4-38. For the simplicity of the connection, it is useful to keep the trusses small in width.
Estimated properties

Roof thickness:

- Trusses 2500 mm
- 3D-trusses 2500-3500 mm
- Girders 400 mm
- Roof package 400 mm

Roof weight:

- 3D-truss 1200 kg/m
- Truss 400 kg/m
- Girders (10 m) 120 kg/m
- Finishing material 83 kg/m
- Roof weight 300 kg/m

Estimation needed Moment of Inertia (I). (deflection max 240 mm at 60 meter span)

Hinged:

\[ \delta = \frac{5}{384} \frac{q l^4}{EI} \]

\[ q_{\text{B.G.T.}} \ (\text{estimated}) = 4 \text{ kN/m}^2 \Rightarrow q = 15 \times 4 = 60 \text{ kN/m}^1. = 60 \text{ N/mm}^1 \]

\[ L = 80000 \text{ mm} \]

\[ E = 200000 \text{ N/mm}^2 \]

\[ \delta_{\text{max}} = 240 \text{ mm} \]

\[ \Rightarrow \frac{1}{I_{\text{max}}} = \frac{5l^4 q}{(E \times 384)} = \frac{5 \times 80000^4 \times 60}{(200000^2 \times 240^4 \times 384)} = 8.89 \times 10^{11} \text{ mm}^4 \]

\[ \Rightarrow \text{Single truss (hollow core section 400 mm)} \Rightarrow 10000 \text{ mm height} \]

\[ \Rightarrow \text{Double truss} \Rightarrow 7300 \text{ mm height} \]

Clamped on both edges:

\[ \delta = \frac{1}{384} \frac{q l^4}{EI} \]

\[ \Rightarrow \frac{1}{I_{\text{max}}} = \frac{l^4 q}{(E \times 384)} = \frac{80000^4 \times 80}{(200000^2 \times 240^4 \times 384)} = 1.77 \times 10^{11} \text{ mm}^4 \]

\[ \Rightarrow \text{Single truss (hollow core section 400 mm)} \Rightarrow 5300 \text{ mm height} \]

\[ \Rightarrow \text{Double truss} \Rightarrow 3760 \text{ mm height} \]

Advantages

- 3D-trusses are stiff compared to normal trusses. This additional stiffness could result in less weight and smaller element heights.
- The shape of the architect can be realized.
- Only a few columns will be used in the open space.
- The designed shape can be maintained.
- The stiffness of the trusses will reduce the facilities needed to prevent tilting and wrenching of the trusses. This will also result in a reduction of the structures’ weight.

Disadvantages

- A 3D-truss has more weight per running meter then a normal truss with the same height.
- The shape of the roof is not very efficient and will result in a large material/span rate.

Main difficulties

- To reduce the spans of the normal trusses in such a matter that the additional weight, caused by the additional material of the spatial trusses, will be compensated by the reduction in weight of the normal trusses.
- To realize the overall reduction in the height of the structure.

The thickness of the roof package as designed by TEAM CS differs over the design. This has to be described.

This design is elaborated in Appendix 8.

4.9 Alternative 8: Trusses

In the comparison between the different designs, it can be insightful to add the structure designed by IGWR to the selection of alternatives. This will show the relation to the concepts. Overview drawing of this alternative are added in Appendix 9.
5. Selection of alternatives

First, a short summary about the goals and the difficulties of the elaborated alternatives will be given. After that, the principle of the Multi-Criteria Analysis will be described. The selection, based on the rating of the alternatives, will then be made.

5.1 Summary of alternatives

Alternative 1: Membrane tensile structure
The membrane structure is an alternative that can result in a lightweight structure. The flexibility and the connections are the most import factors of the design.

Alternative 2: Arch-shaped structure
The arch-shaped structure could result in a lighter structure. The shape of the structure does not allow the structure to use genuine arch action and is not very efficient.

Alternative 3: Concrete shell
The concrete shell could result in a structure with only few connections and an efficient material/ span ratio. The large foundation forces and the verge are the governing factors of this design.

Alternative 4: Cable stayed roof 1
With the cable stayed roof it is possible to create a light weight structure with a small roof thickness. The stability and connections of this design are the most important factors and are hard to realize.

Alternative 5: Lattice shell in combination with trusses
The use of a hyper-shaped lattice shell can reduce the weight and roof thickness of the structure with a design that fits within the vision of the architect. The connections in the corner point and the design of the lattice are the most important factors of the design.

Alternative 6: Cable stayed roof 2
The second cable-stayed roof alternative could also result in a lighter structure with a relatively small roof thickness. The very large tensile forces on the foundation of the structure are the most important factor for the design.

Alternative 7: 3D-Trusses
The alternative based on the use of 3D-trusses can result in a lighter, stiffer structure with a reduced structural height. The connections and locations of the 3D-trusses are the most important factors of the design.

Alternative 8: Trusses
In the comparison between the different designs, it can be insightful to add the structure designed by GW. This will show the relation to the other alternatives.
5.2 Decision factors

To decide which alternative will be elaborated, several elements have to be taken into account. The five main elements that influence the decision are aesthetical value, efficiency, technical value, functional requirements and costs.

Aesthetical value
Another sensitive point for the final results of the MCA is the architectural design. For the architectural design it is chosen to compare the alternatives with the vision of the architects. The alternatives that are of the same shape of the architectural design therefore have a high score. This point of departure results in the fact that architectural value is based on the opinion of the architect about value. This is the reference point of the architectural value-factor.

Efficiency
To be able to compare the alternatives in such a way that the efficiency of the design according to shape and force distribution, the factor efficiency is added to the criteria. This factor shows that the design seems to be efficient or not and can give a critical view on the architectural design. The parties that are interested in this factor are the structural engineer and, to a lesser extend, the architect.

Technical value
The technical value the designs is based on the technical difficulties and technical properties of each design. This factor is added to the MCA to be able to compare the technical difficulties of the designs.

Functional requirements
The main point of interest of this public building is the passenger. The hall actually is constructed for the train passengers and therefore the functional requirements are of great influence on the design. Especially for the principal and the architect it is of great importance. Therefore the MCA stresses the functional requirements.

Costs
The costs of the structures are also an important factor. To estimate these costs is of course very difficult. Based on the insight in cost rates, an estimation is made to what extend the alternatives differ in costs and where savings can be made. These estimations are roughly made but give an insight in the rates between the alternatives.

For example the costs of the connections are based on the amount and difficulties of the connections.

To make a well founded decision, a Multi-Criteria Analysis (MCA) is made. The MCA is a tool to get insight in the suitability of the alternatives. This tool is based on the mentioned factors influencing the suitability and gives an insight in the main differences between alternatives. From this MCA a few conclusion can be made. The main advantages and disadvantages of each of the alternatives are displayed in a surveyable way. The MCA table can be found in Appendix 10. The conclusion for the suitability of the alternatives is given in the next paragraph. The most important points that influence the decision are mentioned.
5.3 Conclusion

In this paragraph, all concepts will be treated and their suitability or unsuitability will be described. The valuation in the MCA is used as a guideline for the decisions.

Concept 1: The membrane structure
The membrane structure seems to be a suitable concept for the given situation. It is a very light weighted, rapidly erectable and aesthetically pleasing structure. Besides these great advantages, several important disadvantages are of influence of the decision.

The first important factor is the architectural appearance. Even though the design is architectural pleasing it does not fit as much in the architectural vision as the original architectural design.

The second important factor involves climate requirements. The requirements for the Southern Hall are not very strict, but some of the properties of the membrane fabric can result in difficulties and/or problems. The heat insulation-value of the fabric is very low, and when very low temperatures occur outside, the inside climate will be very cold and even temperatures below zero might occur. Another difficulty according to the inside-climate is the sound insulation. The fabric is low of mass and therefore its sound-insulation value is very low. Rainfall, for example, might result in a loud clattering on the fabric. Because of the large fabric area this can result in a lot of sound nuisance.

The third of the main factor is the durability of the fabric. For this relatively flexible design, the durability of the fabric will be 40 years or less. During the planned lifetime of the station, the fabric has to be renewed at least once. The large advantages make this alternative very interesting, but the given disadvantages and the relatively low value for IGWR result in the conclusion that this alternative will not be elaborated.

Concept 2: The arched structure
The alternative based on the arch (Concept 2) is also not chosen. The main reason for this decision involves the goal of the alternative. This goal was to create a light structure using arch action.

Because of the boundary conditions for the supports, it is hard to create genuine arch action. Another important factor influencing this decision is that difference between the initial and the arch-based design is relatively large.

Concept 3: The concrete shell
The concrete shell design seems to be relatively efficient. The shape is suitable for efficient force distribution and its shape is aesthetically pleasing. Still this alternative is not chosen based on a few important disadvantages. The first important disadvantage are the foundation difficulties. Especially the foundation near the railtracks (the northern side, will be difficult to realize and the horizontal forces on the foundation block cannot be taken by the ground pressure and piles are needed.

The second important disadvantage is the difference compared to the architectural design. Besides that it is not possible to create as much usable floor area as in the initial design. These points decrease the practical value of the design and therefore this alternative is not chosen.

Concept 4: The cable stayed roof
The alternative based on the cable stayed structure is not chosen to elaborate. The difficulties involving the equal force distribution on the cables and the stability problems are the main factors on this decision. It is an alternative with a design comparable to the architectural design, but the mentioned difficulties are to important on to chose this alternative.
Concept 5: The lattice shell
The alternative of the lattice shell is a very interesting alternative. An important element of the design, the buckle, is changed into a curved line. Even though the design is disturbed, some important advantages, make it an interesting alternative to elaborate. One of the main advantages is the weight of a space frame/lattice. If it is designed well, it is possible to create a very light design. Whether if it is possible for this Hall has to be investigated. A second large advantage is that its shape seems to be efficient for force distribution, but more detailed calculations will have to be made to investigated if this is valid. For the master thesis, this is an interesting alternative and therefore this alternative will be elaborated.

Concept 6: The cable stayed roof 2
The second cable stayed roof seems to be more suitable for this situation. It is more stable than alternative 4. Besides that, the disturbance of the architectural design is relatively small. The main trusses will become lighter and the forces on the ARCADIS structure will be decreased. This advantages are not enough to compensate the difficulties and disadvantages. The main factor of this decision is that the reduction in weight of the trusses, will probably not be sufficient to compensate the higher costs caused by the pylons and the large tensile and compressive forces on the foundation. Therefore, this alternative is not chosen.

Concept 7: The 3D truss
The 3d truss is very suitable for this situation. It fulfills the wishes and all requirements of the architect; the design is identical to the architectural design. Besides that it is very useful for IGWR. Still, this alternative is not chosen. This is because of several reasons. First of all, it is not an innovative structure, the resemblance to the given structural solution is very large. The second argument is that the chance and the consequence of the improvement is relatively small. Therefore, this alternative is not chosen.
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Figure A-1: overview area spring 2007 (picture copyright Aeroview)
Appendix 2  From CS to OVTRC

Figure A-2: Overview CS
Appendix 3  Interview with Architect

Meeting 5 september 16:00  Architect:  Wouter Thijsen
Rotterdam Groot Handelsgebouw  Meyer en van Schooten architekten BV
Amsterdam

- What was the goal of the design, what was the most important demand for the first design?
The main goal of the design was to create an attractive infrastructural terminal with an
international appearance, representable for the Netherlands and Rotterdam.

- What was the idea/vision of Team CS?
Team CS tried to create a design that acts as a gate between the railtracks and the centre of
Rotterdam. The shape is an important factor of the vision of the architects. The highest corner
points towards the centre of Rotterdam. From the lowest point, the sight lines of the roof points
toward the canopy of the railtracks. It is an open design that is supported at only a few
locations and connected to the platformcanopy. Because high-rise buildings are located in the
area, the top side of the roof has to be aesthetically pleasing and durable. Titanium was
chosen.

- What is the main goal of the shape?
The most important goal of the shape is that it points towards the centre of Rotterdam en
visually connects the OVTRC and the centre of Rotterdam.

- What determined the height of the corners of the design?
The level of the lowest point is determined by the lines of sight of the passengers. When
standing outside, the roof-lines point towards the canopy of the railtracks. The height of the
two corners at the ARCADIUS structure is determined by the height of the canopy of the
railtracks. The level of the highest point is determined by the visual demand for the shape to
point toward the centre.

- Which requirements were of great influence on the design?
The design of the subway station determined the location of the supports. The height and the
shape of the ProRail construction influenced the heights and the shape.

- Why was a metallic material chosen for the roof?
Because high-rise buildings are located in the area, the top side of the roof has to be
aesthetically pleasing and durable. Titanium was chosen.

- Did Team CS consider other constructive options then steel trusses, which were feasible?
(Tensile structure, space frame, 3D-trusses, other shape?)
The shape limits the amount of feasible structural types in such a way, that the decision was
made to use trusses.

- What was changed in the design and why?
For the metallic skin of the roof stainless steel was chosen in stead of titanium. The costs of
titanium were too high, so a less expensive material was chosen, with a comparable
appearance and durability. For the lower side of the roof wood was chosen. Because of the
high steel-price, wooden girders were chosen for the canopy of the railtracks in stead of steel
ones. This material is clearly visible and to guarantee unity between the canopy of the
railtracks and the Southern Hall the material is also chosen for the SH.
Appendix 4  Impression OVTRC

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Figure A-23: Structural 3D-overview lattice

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Appendix 8 3D-truss design

To be able to calculate the structure, details and connections are very important to determine. Besides that, several configurations of the trusses will be designed and compared. Then the calculation and optimization of the structure is done.

Appendix 8.1 Configuration

To determine the definite configuration of the 3D-trusses it is important to determine where 3D-trusses are efficient. For this determination, a few principles influence the configuration. For the design of long spans, the deflection of the structure is the governing factor for choosing the elements dimensions. The differences in mechanical behaviour between normal trusses and double trusses can be calculated.

Example:

\[ h_1 = 400 \text{ mm} \quad w_1 = 400 \text{ mm} \quad \text{web thickness} = 4 \text{ mm} \]
\[ h_2 = 2000 \text{ mm} \quad w_2 = 2000 \text{ mm} \quad \text{Assumption: stiff connection between elements.} \]

Area Hollow Core Section
\[ A_s = 4 \times 200 \times 2 + 4 \times 192 \times 2 = 3136 \text{ mm}^2 \]

Moment of Inertia (HCS)
\[ I_{\text{hcs}} = \frac{2}{12} \times 4 \times 400^3 + 2 \times 392 \times 4 \times 198^2 = 166 \times 10^6 \text{ mm}^4 \]

Moment of Inertia (single truss)
\[ I_{\text{tr}} = 2 \times 3136 \times 800^2 = 4.0 \times 10^9 \text{ mm}^4 \]

Moment of Inertia (3D-truss)
\[ I_{\text{3D}} = 2 \times 8.0 \times 10^9 = 8.0 \times 10^9 \text{ mm}^4 \]

The deflection of a beam is influenced by its stiffness. For example: A beam supported with hinging connection, the deflection will be determined by the following formula:

\[ \delta = \frac{5}{384} \frac{ql^4}{EI}. \]

From this formula a few design principles can be determined.

The stiffness, determined by \( E \) (elasticity) and \( I \) (moment of inertia) will be twice as large for the square truss in comparison with the single truss. The deflection therefore will be reduced by a factor 2. If the height of a normal truss is increase by a factor 2, the \( I \)-value will be multiplied with approximately a factor 4. For the double truss, the same principle is valid. In comparison with the single truss the \( I \)-value increases with a factor 8. So if the height of the 3D-truss is only a little bit larger than the height of the normal trusses, it is much stiffer.

If the span of a truss is increased by a factor 1.5, the deflection increases with a factor 5. The span therefore is an important factor on the deflection.

The width of the spatial truss does not considerably influence the stiffness in vertical direction. For horizontal loading and torsion a large width is useful.
Appendix 8.2  Configuration 1:

The main span of the structure is located beneath the buckle of the roof structure. If a beam is designed, beneath this buckle, which is relatively stiff, the maximum span of the trusses in perpendicular direction is decreased for a large area. A 3D-truss (1) will be located beneath this buckle and will be supported by a column in the middle of the span. The span will be halved by this column and the height of this beam can decrease considerably.

The same will be done for the edge at the western side of the structure. A 3D beam (2) will be located here, which will be supported at the middle of the span by a column. Between beams 1 and 2, single trusses will be designed. The design of the architect requires a small roof thickness at the northern side and it might be necessary to use an additional 3D-truss (a) to reduce the span again.

At the east side, a high truss (3) will be designed. The office coverage will be connected to the truss and the ProRail structure. Between beams 1 and 3 single trusses will be designed.

Between both southern supports, another 3D-truss (4) will be located. The loads on this 3D beams will be of such proportions, partly by the verge, that it is useful to locate it right above the supports. The glass façade will be located beneath the structure. This façade is cannot resist large displacements. To reduce large displacements, additional stiffness is required here and a fifth (5) spatial truss will be designed. The connection between the glass façade and the roof structure will result in fewer difficulties. An additional truss might be necessary at location (b), this has to be investigated.

The verge probably needs an additional spatial truss (6), because the overhang is relatively large. The single trusses will be located in the x-direction with a centre to centre distance of approximately 10 meters. This is determined by the most efficient span length of the girders.

Some of the trusses can change in cross-section; For some of the single trusses, a spatial truss can be chosen. By calculating the structure, this can be determined.

Appendix 8.3  The main truss

The main truss located at the eastern side of the structure will be built up from Square Hollow Sections (SHS), cables and steel columns. The length of the truss is 138 m from the ARCADIS structure to the support. A large part of the weight of the offices roof will bear on this truss and a large part of the roof of the Southern Hall as well. For the calculation a basic design is made which will be optimized during the calculations. The centre-to-centre distance of the trusses perpendicular to the truss will be 10,8 m according to the basic grid dimensions of k*1,2 m. Therefore the vertical members of the large truss are also placed with a centre-to-centre distance of 10,8 meter. The girders are placed between the

Figure A-28: Location of 3D-trusses
horizontal trusses. The 3 more or less horizontal elements of the truss will be design as a Square Hollow Sections. The roof trusses will be connected to the main truss at the position of the verticals. The stiffness of the total truss will be realized by using bracing steel cables. This will result in a suitable structural element for the long span. At the locations of the 3D-trusses, also 3D-trusses will be used vertically to be able to create a stiff connection between these two elements.

Appendix 8.4 The 3D-trusses

The dimensions of the 3D-trusses will be described. These dimensions will be used as a basis for the calculation of the entire structure. The beams, of which the truss is built up, will be designed as Square Hollow Sections. The trusses will have to be relatively high. At the highest point the truss will be 3.5-4 meters high. The SHS will then have a height and a width of 350 mm and a web thickness of 19 mm. This 350 mm is chosen, because it will allow easy connections with the trusses.

Properties SHS 350:

- Weight = 194 Kg/m
- \( I_{yy} = 4.336 \times 10^8 \) mm^4
- \( W_{yy} = 2.478 \times 10^6 \) mm^3
- \( A = 24200 \) mm^2
- \( H1 = 350 \) mm
- \( W1 = 350 \) mm
- \( T1 = 19 \) mm

Properties Truss (height 3500 mm):

- Weight = 1000 Kg/m
- \( I_{yy} = 4 \times 24200 \times (1750-175)^2 \) = \( 2.4 \times 10^{11} \) mm^4
- \( W_{yy} = 1.37 \times 10^8 \) mm^3
- \( A = 4 \times 24200 \) = 96800 mm^2
- \( H2 = 3500 \) mm
- \( W2 = 3500 \) mm
- \( T1 = 19 \) mm

Appendix 8.5 The 2D-trusses

For the design of the structure according to the single trusses a few factors are important to treat. The truss is relatively weak in the direction perpendicular to the element. If a truss is axially loaded it can buckle out in this direction, if the length of the truss is relatively large. By supporting it in perpendicular direction, this can be prevented. In Figure A-29 the principle is shown with 1 support. If the amount of supports is increased, the force needed for buckling to occur will increase as well, because the buckling length decreases. This horizontal supporting will be realized by using the wind bracing elements in the roof as described in paragraph 6.4.
The second point of attention is the possibility of tilting of the truss. This can occur if only the top element is horizontally supported. A vertical load on the top side of the truss can result in this phenomenon. Some suitable solutions are shown in Figure A-30. The first option is to horizontally support the lower element by cables, that are attached to the girders. This will prevent large horizontal displacements of the lower element. Another option is to design trusses at some locations in stead of single girders. This is a solution that requires more material, but will make the total structure stiffer. It will be chosen to use the first alternative using cables. If additional additional stiffness is needed, the second alternative will be used at locations that require stiffness. These locations will be determined by the calculation. Both of these phenomena are not likely to occur to the 3D truss.

For the 2D truss, the following dimensions and elements will be chosen as a starting point for the calculation.

For the top and bottom elements I-Beams will be chosen. These elements allow relatively easy connections. This configuration of trusses is aesthetically not very pleasing, but will be left out of sight.

For the start-calculation of the structure HEM 360 will be chosen for the largest trusses (height 3-4 m).

Properties HEM 360:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>250 Kg/m</td>
</tr>
<tr>
<td>$I_{yy}$</td>
<td>$8.487 \cdot 10^8$ mm$^4$</td>
</tr>
<tr>
<td>$W_{yy}$</td>
<td>$4.297 \cdot 10^6$ mm$^3$</td>
</tr>
<tr>
<td>$A$</td>
<td>31880 mm$^2$</td>
</tr>
<tr>
<td>$H$</td>
<td>395 mm</td>
</tr>
<tr>
<td>Width</td>
<td>308 mm</td>
</tr>
<tr>
<td>$T_{fl}$</td>
<td>40 mm</td>
</tr>
<tr>
<td>$T_w$</td>
<td>21 mm</td>
</tr>
</tbody>
</table>

Properties Truss (height 2500 mm):

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>575 Kg/m</td>
</tr>
<tr>
<td>$I_{yy}$</td>
<td>$2 \cdot 31880 \cdot (1250-197.5)^2$ mm$^4$</td>
</tr>
<tr>
<td>$W_{yy}$</td>
<td>$1.83 \cdot 10^7$ mm$^3$</td>
</tr>
<tr>
<td>$A$</td>
<td>$2 \cdot 31880$ mm$^2$</td>
</tr>
<tr>
<td>$H_2$</td>
<td>2500 mm</td>
</tr>
<tr>
<td>$W_2$</td>
<td>2500 mm</td>
</tr>
<tr>
<td>$T_{fl}$</td>
<td>40 mm</td>
</tr>
<tr>
<td>$T_w$</td>
<td>21 mm</td>
</tr>
</tbody>
</table>
Appendix 8.6  The stabilizing facilities/bracing

The stabilizing structure will be built-up by the core beneath the structure. The main core is located beneath the western side of the structure. For it to function well it is important to put much of the weight of the roof on this core. This will be done by placing a truss on top of the core parallel to its direction. This truss will be designed as a 3D-truss, because much forces will occur in this part. Wind bracing will be placed in the roof package to make the structure act as a rigid frame. If additional stiffness is needed it will be investigated which part of the forces can be distributed to the ARCADIS structure.

![Figure A-31: Stabilizing facilities](image)

In Figure A-31 an occurring problem can be determined. The main forces will gather in the central beam. A lot of the vertical forces will be taken by this truss and not by the core. The beam above the core, will therefore by executed as a stiff truss. This will support the middle large truss. It therefore needs more stiffness compared to the middle truss, what can be realized by the smaller span. It will be supported by the core and a column that will be placed at the corner of the eastern offices. For the force distribution it is useful to place the core as close to the middle beam as possible.

Appendix 8.7  Roof thickness

The roof thickness of the structure differs over the length of the structure. Near the ARCADIS structure the roof thickness will be small, at the Southside it will be relatively large. In Figure A-33 a drawing is added with the exact dimensions. This desired roof thickness has to be taken into account and during the calculation, the feasibility will be discussed.

Appendix 8.8  Additional supports

As mentioned in paragraph 6.4 additional supports will be located at the cores position and the corner of the eastern offices. If additional supports are needed will be determined by the calculation.

Appendix 8.9  Connections

The connection of the structure to the façade deserves additional attention. According to the vertical deflections of the beam on top of the façade, connections will be designed. If the deflection can be reduced, the connections will be relatively easy to make.

Appendix 8.10  Façades
The facades will be located beneath the roof structure. The façade structure will be designed as a lightweight structure and will not support the trusses vertically. For the calculation, this façade supporting structure will not be added as a supporting structure. It will influence the design, the wind load will be directed via the façade to the roof structure.

Appendix 8.11 Offices

The eastern offices construction will bear on the main truss and trusses attached to the ARCADIS offices. Between these trusses, girders will be placed to create a roof slab. Between the roof structure and the floor the façade will be located.

Figure A-32: Eastern truss

Figure A-33: Roof thickness
Appendix 9  
Overview IGWR/ARCADIS structure

Figure A-34: Top view IGWR truss structure
Figure A-35: Top view structure
Figure A-36: Southern façade (Section A-A')

Figure A-37: Western façade (Section B-B')

Figure A-38: Eastern truss (Side view C-C')
Appendix 10 The Multi-Criteria Analysis

To make a well-founded decision, a Multi-Criteria Analysis (MCA) will be done. The MCA is a tool to get insight in the suitability of the alternatives. This tool is based on the main factors influencing the suitability and gives an insight in the main differences between alternatives. The main subjects of this MCA are aesthetical value, efficiency, technical value, functional requirements and costs.

Appendix 10.1 Aesthetical value

Another sensitive point for the final results of the MCA is the architectural design. For the architectural design it is chosen to compare the alternatives with the vision of the architects. The alternatives that are of the same shape of the architectural design therefore have a high score. This point of departure results in the fact that architectural value is based on the opinion of the architect about value. This is the reference point of the architectural value-factor.

Appendix 10.2 Efficiency

To be able to compare the alternatives in such a way that the efficiency of the design according to shape and force distribution, the factor efficiency is added to the criteria. This factor shows that the design seems to be efficient or not and can give a critical view on the architectural design. The parties that are interested in this factor are the structural engineer and, to a lesser extend, the architect.

Appendix 10.3 Technical value

The technical value the designs is based on the technical difficulties and technical properties of each design. This factor is added to the MCA to be able to compare the technical difficulties of the designs.

Appendix 10.4 Functional requirements

The main point of interest of this public building is the passenger. The hall actually is constructed for the train passengers and therefore the functional requirements are of great influence on the design. Especially for the principal and the architect it is of great importance. Therefore the MCA stresses the functional requirements.

Appendix 10.5 Costs

The costs of the structures are also an important factor. To estimate these costs is of course very difficult. Based on the insight in cost rates, an estimation is made to what extend the alternatives differ in costs and where savings can be made. These estimations are roughly made but give an insight in the rates between the alternatives.

For example the costs of the connections are based on the amount and difficulties of the connections.

These factors are not all of the same importance. To determine this importance it is useful to determine the most important parties that are of influence on the design and what their main interests are. The passengers for example are not really interested in the technical requirements of the design, but are very interested in the functionality of the design. In the following table, a global interest rating is done. The average value of each factor is calculated to make an estimation of the global interest.
From this table, the functionality of the hall seems to be the most important, because the passenger-traffic is the basis of the design. The functionality of the design is therefore important for all parties. The aesthetical design is also a very important factor. For the architect and the principal it is of great influence. The average weight factors will be used in the MCA-Table.
The discussed influence-factors (red) can be divided into sub-factors (blue) that influence the value of the mentioned influence-factors. The importance of these sub-factors, with regard to the main factors, is rated in the weight factor column.

Each alternative is then rated by giving a value for each sub-factor regarding to the alternative. The higher the value, the better the alternative scores for the sub-factor. It is determined to what extent the alternative “scores” for each sub-factor.

By calculating the average score (multiplied by the value of the main influence factor) the total score for each alternative, regarding to the main factor, can be calculated. By adding up these scores a total score for the design can be determined.

![Table A-2: MCA](image)

The total score of each alternative is sensitive for changes in the valuation of all factors. The difference between alternatives has to be relatively large to be able to tell anything about the suitability of the alternatives. The differences in these scores look relatively small, but the differences are not easily equalized. Therefore some conclusions can be made by this MCA.
Appendix 10.6 Conclusion

The final score of the alternatives have to be interpreted with care. The differences between the alternatives are relatively small. A few alternatives can seem to be less suitable for the given situation. The alternatives based on the cable stayed structure for example do not have a high score (Concept 4 and 6). The technical difficulties and the costs are the most important disadvantages of these alternatives. The costs of the pylons and the difficulties in the foundation make these alternatives less promising and are therefore not chosen.

The alternative based on the arch (Concept 2) also has a relatively low score. The main causes for this low score are the architectural value and the technical difficulties, occurring by trying to reach genuine arch-action. The goal of the alternative was to use genuine arch-action and the design does not really fulfill the goal. Besides that, it differs relatively much from the design and is therefore not chosen.

The alternative based on the concrete shell (Concept 3) also has a relatively low score. This is mainly due to the architectural value, the relatively small useable floor area and the foundation difficulties. This alternative is not chosen to elaborate.

The scores of the other alternatives are comparable. The score of the membrane structure (Concept 1) is lower than the other alternatives. The main factor of this difference is the architectural value. The design is very different from the architectural design. Another important difficulty is the durability of the membrane. It will have to be replaced during the lifetime of the structure. The climate requirements are the third important difficulty. The improvement in weight of the structure is the main advantage of this structure, but does not seem to be sufficient for compensating the disadvantages. The membrane structure will therefore not be chosen.

The alternatives of the lattice and the trusses-structure are more or less the same. The main advantage of the structure of the trusses is the resemblance to the architectural design. The apparently more efficient shape of the lattice compensates this difference. It has to be notified that the insecurity of this efficiency is relatively large and has to be investigated. These three designs seem to be the most suitable for the situation.

To make the final decision for the alternative that will be elaborated, a determination of the value for the thesis will be made. Four elements will influence the value of the thesis. The chance of improvement of the design, the consequence of this potential improvement, the value for Gemeentewerken and the academic value.

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Appendix 11 References

[1] Bestemmingsplan Rotterdam

[2] Interview with W. Thijssen member of the team of architects (Appendix 3).


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## Appendix 12  List of sources

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