STRUCTURAL DESIGN OF AN ICE ARENA ROOF

Design Book

Daria Safonova

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Author: Daria Safonova

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School: HZ University of Applied Sciences

Supervisor(s): J. de Keijzer, G. Scuderi

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Student Information

Student:	Daria Safonova
Student number:	00070192
E-mail:	safo0001@hz.nl / D.Safonova@iv-consult.nl

University Information

University:	HZ University of Applied Sciences
Faculty:	Civil Engineering
University Supervisor:	J.de Keijzer
E-mail:	j.de.keijzer@hz.nl

Graduation Company Information

Company:	Iv-Consult
In-company supervisor:	Jimmy Tat
Supervisor E-mail:	j.c.tat@iv-consult.nl
Project Manager:	Wouter Visser

Client Company Information

Company:	Zwarts & Jansma Architects
In-company mentor:	Bas Symons
Mentor E-mail:	bs@zja.nl
Project Manager:	Rob Torsing
E-mail:	rob@zja.nl

Preface

This bachelor thesis was written as a part of the Bachelor curriculum of Civil Engineering in HZ University of Applied Sciences. The project was carried out in collaboration with two firms: engineering firm Iv-Consult and architect firm Zwarts & Jansma Architects.

This thesis is a reflection of all the personal interests I have in the professional field: architecture and engineering, in particular massive steel structures. I hope that the reader will feel the passion I put in this project and the amount of inspiration I had at each stage of its implementation. This broad topic gave me an opportunity to develop a very multifaceted research. Cooperation with two firms gave me an unforgettable professional experience dealing with two “worlds”: engineering and architecture. Moreover, new skills of parametric design are obtained during this thesis, opened a different view on how the projects in my future career can be approached.

During the thesis duration I got to know various people with different professional specializations. Their support and expertise gave me priceless knowledge which were applied in this thesis. I would like to acknowledge everyone who guided me during this journey.

First of all, I would like to thank Iv-Consult manager Wouter Visser who has very similar views on engineering, who inspired me to create something great and introduced me to Rob Torsing, the director of Zwarts & Jansma. The architect firm gave me a task for the thesis.

I am very lucky with my supervisors for this thesis. The in-company supervisor Jimmy Tat gave very straight-forward comments and opinion on my work, helped me to keep-up with the scope when my inspiration flourished to different directions, but at the same supported the originality of my methods. Large gratitude to my university supervisor, Joachim de Keijzer, for constant support and inspiration. My second university mentor Giuliana Scuderi supervised in the last research phase and provided me with the ideas on research improvements.

Special thanks to Ralph Cloot, the architect from Zwarts & Jansma who introduced me to parametric design and made this challenge possible. And I cannot underestimate support of all the engineering team in Iv-Consult, in particular Graham Jardine, Ralph Kievits and Damy van den Bergen.

Finally, I would like to thank my family and friends. Even being so far I felt your constant support and it motivated me most of all.

Daria Safonova, Papendrecht, August 2019

Abstract

The following report gives a full description of the Bachelor Civil Engineering graduation project. The graduation is done in engineering firm Iv-Consult and the thesis topic is provided by Zwarts & Jansma Architects. Architectural bureau requires a structural solution for the roof of the ice skating rink, which is a part of the sport complex project. The project is on a very concept development and only the dimensions of the building and the main functional requirements are provided. The main idea of the following thesis is to provide the client with the structural design which includes overview of such aspects as architecture, functional requirements and future prospects of the design.

Although, the structural design of the arena roof has to be done, it is not enough to look at the research problem from the structural point of view only. An ice arena has very specific inner-environmental conditions, has to provide safety and comfort of sportsmen and spectators. Moreover, the financial aspect requires solutions which will allow to minimize use of the energy to get correct ice-surface and air conditions. This means that the roof design has to take into account the sustainability aspects and consider the latest developments of the ceiling and cladding design with low-e values.

The minimized material use, together with the smart consideration of the roof future prospects such as constructability, maintainability, and demolition can minimize the life-cycle costs. The roof life-span is 50 years, which means, that the structure has to have the perfect conditions for the entire life-span. In this case, accessibility to the roof surface, water accumulation and cladding type with the same life-span are the aspects which have to be considered as well.

Another sustainability aspect for the structures nowadays is a post life-span demountability and re-use of the structural elements. This have to be considered at the early design stages, by means of the structural system, used material, sizes of the elements, type of connections, etc.

The designed roof is a large-span structure, therefore, not all of the structural systems can be applied. However, there are three general systems, with the use of steel: truss, arch and cable systems. They can be considered in various configurations and give an optimal solution with the above-mentioned functional aspects.

The last but not least, the future ice arena building, is a part of sport venue in the Netherlands. It is a massive construction which will attract attention of the public, possibly including national and international competitions. No need to explain how the visual perception is important. If the structural solution, together with the fulfilled functional and technical requirements, can be also aesthetically appealing, the value of the design will increase significantly.

Four concept studies were developed and the final alternative based on the multi-criteria analysis was chosen. After that, the winning alternative is parametrically developed as a final design of the current thesis project. Grasshopper is used for the geometry development and parametric load, nodes, supports and cross-sections input and linked to the SCIA Engineer. Geometry optimization for the minimized material use is done and final structure is verified for strength, stability and stiffness according Eurocode in SCIA Engineer. Moreover, within Grasshopper Tekla Live-link is used and the final technical drawings with parametric adjustments possibilities are obtained as one of the final products of the project. The conclusion shows that the final design fulfills the consideration of all the requirements for the following research and satisfies the minimum demands of the preliminary structural design.

Table of Contents

1 Introduction

1.1 Background

The following graduation research is done in cooperation with two companies: Iv-Consult and Zwarts&Jansma Architects (ZJA). Iv-Consult is an engineering firm which mainly deals with complex civil and construction engineering projects. ZJA is an architectural bureau, one of the main specialization of which is to design arenas and stadiums. The personal fascination of the large constructions with visible steel structure together with the passion for architecture and structural engineering led to the discussion of the following graduation project during the internship in Iv-Consult and further agreement to implement it.

ZJA offered a project for this graduation. The firm is working on the architectural development of a new sports complex in the Netherlands (see an initial render from architect Figure 1-1). The firm wants to know the structural feasibility of the top sports ice skating arena roof. Architects provided several renderings to give an impression of the sport complex scale.

Figure 1-1 Rendering of Sport Complex by Zwarts&Jansma

1.2 Project Definition

1.2.1 Problem Statement

The task from ZJA is to investigate the structural design possibilities to create an unique design which will contribute to the appearance of overall arena for the roof of the ice arena, part of the large sports complex. According to the initial renderings from the architect, the roof has a saddle shape. It is not a requirement to make a design of the same shape, but it was offered to consider it as a design possibility. Area of Den Haag was suggested to be considered to implement structural calculations. The following sports complex has to have a possibility to be built in multiple locations and environments, therefore structural design has to be really general.

The architects` requirement was to cover completely the ceiling to keep sufficient environmental conditions for the perfect ice surface. Several requirements were suggested by Iv-Consult as well. The overall design has to be an aesthetically appealing structure while carrying its technical requirements. Steel has to be used and highlighted as the main structural material.

Further, the most important information given by the architect is highlighted. More drawings with floor plans for each level provided by the architect bureau is given in Appendix 1.

1.2.2 Data Given

The initial information about the ice skating arena is provided by the architect. The dimensions of the building are given on the layout and cross-section drawings. The summary list of the most important data for this research is given below.

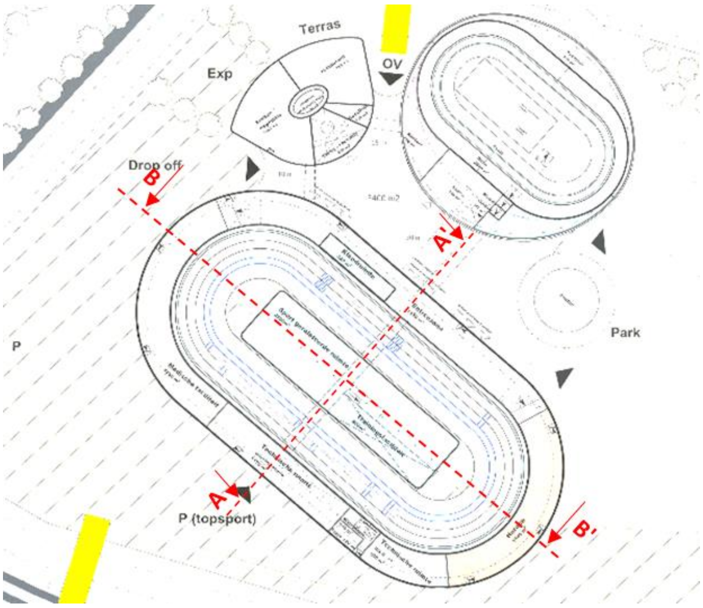


Figure 1-2 Layout Sport Complex

<u>Initial Data:</u>

- ✓ Standard 400 meter ice rink oval with additional lane (5 lanes in total)
- ✓ Absolute minimum height to the ceiling is 10 meters
- ✓ Ceiling has a slight curvature to the outer walls (for better air flow)
- ✓ Height of the façade is about 20 meter according to initial render
- ✓ First possible position of the column is at the end of the tribune
- ✓ Minimum span based on the first possible position of the column is about 103 meters in the transverse direction and 215 meters in the longitudinal direction
- ✓ Capacity: 10.558 seats

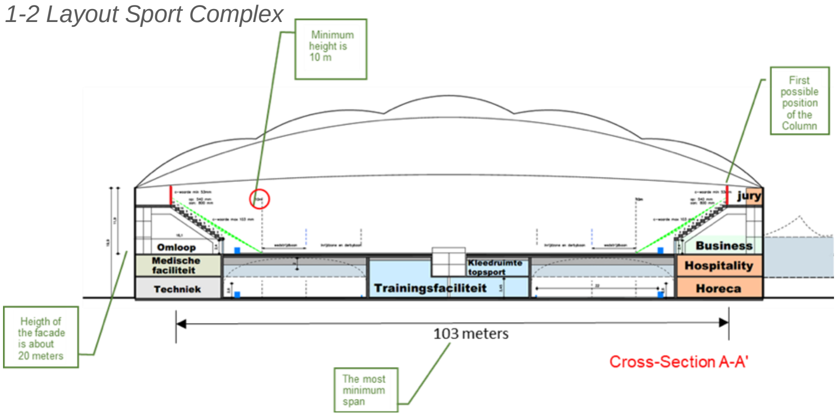


Figure 1-3 Cross-Section A-A' according Figure 1-2

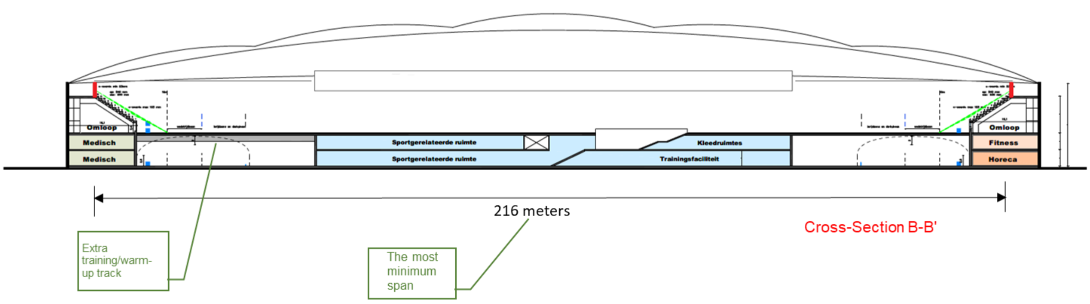


Figure 1-4 Cross-section B-B' according Figure 1-2

1.2.3 Research Scope

The research scope is defined in order to be able to set an objective for the project and stick to the objective through the entire project flow. Project scope is based on the requirements given by the two key-stakeholders of the following graduation research: Iv-Consult and Zwarts & Jansma.

List of Requirements

Architect	Iv - Consult
• Possible roof design and its feasibility	• Steel is the main structural material
• Ice-surface is fully isolated from natural light	• The structural system should be innovative and aesthetically appealing
• No columns in the main span and at the location of the tribunes (to provide a clear sight to total arena inside)	• The preliminary structural design of the roof (LOD 200)
• Roof design should encounter for supporting of the ventilation system, lighting, etc.	• Parametric design application for the final variant development
• Roof design includes insulation	• Preferably, the structural system is clearly recognizable (either visible, or recognizable by shape)
• Ice arena is not considered for the other non-ice skating events to keep conditions of ice in perfect conditions; it is planned to be operational all the year	
• Ceiling should be slightly higher towards the sides of the arena for the air flow	

Scope Definition

The research focuses mainly on the preliminary structural design of the roof structure of the ice arena. Certain attention will be given to the architectural aspects of the design. The inner building of the arena is a boundary condition of the dimensions only but not a part of the design consideration. Multiple possible structural systems will be examined and analyzed whether each of them are worth for further development. Such aspects as aesthetics, costs and construction are the part of the scope mainly for the concept design stage.

1.2.4 Objective

The objective of this graduation project is to provide an architect bureau with an optimal and appealing structural design solution of the ice arena roof. Optimal in this case will be considered a design which covers functional, spatial and technical aspects of the ice arena roof and, thus, fulfills requirements of the project`s key-stakeholders: architect and Iv-Consult.

1.2.5 Research Question

After analyzing the given data, requirements and objective, the following research question is defined:

“What is the optimal structural design solution of the ice arena roof which will fulfill requirements of both the architect firm and engineering firm?”

To answer this question, a further specification of the question is needed. The following secondary questions formulated below will help to answer the main question :

1. What are the functional and technical requirements of the ice arena roof?
2. Which standards and codes will be used for the calculations and what are the requirements?
3. (a) What are the design alternatives for the multiple-criteria analysis?

   (b) What are the main design criteria?

   (c) What are the weight factors of the design criteria for the alternatives assessment?
4. (a) What are the design requirements for the final design?

(b) How the final design look like?

(c) Which material and structural principles are used?

1.3 Research Methodology

Literature Study

The first part of the research is the literature study. The theory collection helps to get required knowledge and information for the project. The following information is included in the literature study:

- Architectural and technical design requirements of an ice arena
- Technical requirements of the large-span steel structures
- Case studies about existing arenas

Concept Design Phase: Alternatives Development and Multi-Criteria Analysis

Based on the literature study several structural systems are defined as potential for the final design. These structural systems are integrated to the current design case in such way that they can fulfill functional and technical demands and have aesthetical value. Several concept design alternatives are developed. Parallel to these concept design phase, interviews are organized with the potential stakeholders and key-stakeholders for these project. The main criteria are defined and sort out to the corresponding importance. Based on that, multi-criteria analysis is performed and the most optimal alternative is determined. In Chapter 3 the methodology of the concept design phase is described I more details and results and conclusion of the phase are given.

Final Design: Parametric Modelling

Based on the method and results of the concept design phase, the final alternative is further parametrically developed. Parametric design allows easy geometry adjustments and optimization of the material use. The following software tools are used for the final structural design development:

- Grasshopper: a parametric design plugin for Rhinoceros 3D, with the use of the following Grasshopper additional plugins:
    - XML Code (allows information transfer to SCIA Engineer)
    - Tekla Live-Link (link with Tekla)
- SCIA Engineer (a FEM software package for structural calculations)

All the geometry input is developed in Grasshopper. Multiple parameters are chosen as variables and are adjustable, which allows automatic geometry variation of the particular elements or overall geometry. After the geometry is developed, XML code is used to transfer model information to SCIA Engineer. Load input, supports and hinges locations are included in the grasshopper input, therefore, the structural calculations can be immediately done after the model is transferred to SCIA. The technical drawings are made in Tekla, using the live-link with Grasshopper. More thorough description of the final design phase methodology is given in Chapter 4.

In this report two chapters with research methodologies description are given (Chapter 3 *Concept Design & Multi-Criteria Analysis* and Chapter 5 *Final Design Methodology*). This allows to describe the two design phases of the project and their methodology in chronological order and make a focus of a reader on each of them separately.

1.4 Report Outline

The report structure repeats the procedure described in section 1.3 above. In this chapter the research setup is introduced. In Chapter 2, the Literature Study is given and the potential structural systems are highlighted. In Chapter 3, several alternatives are developed and the multi-criteria analysis is performed based on the interviews and case studies. The preparation for the winning alternative design is then done in Chapter 4. This chapter also summarizes the requirements of the architect and engineering firms together with Eurocode requirements, which the final design have to satisfy. The design development procedure is described in Chapter 5. The final design results are summarized and discussed in Chapter 6. The last part to the research is to verify whether the final design satisfies project requirements and, therefore, answers the main question, therefore conclusions and recommendations are summarized in Chapter 7. Attachments in the end of the report (see chapter Appendices) give broader information for several parts described in the report and are in chronological order, corresponding to the referencing in the report. Appendix can be considered as a separate document with individual chapter and page numbering.

2 Theoretical Framework

This chapter gives an opportunity to consider the research problem from several aspects. The most required information on the current project topic is introduced. The theoretical background is separated into two parts: functional and technical requirements of the ice arena roof. Technical requirements contain information on what kind of material and its quality and quantity are used to construct the roof, what is the procedure of the calculations has to be followed in order to obtain reliable results. However, in order to discuss technical requirements, functional requirements of the roof have to be primarily considered: what is the function of the ice arena roof, what are the most important concerns related to the indoor/outdoor climate which have to be considered during design, etc.

2.1 Ice Skating and Ice Arena

" For the Dutch, ice skating is far more than a sport. Ice skating is part of the long tradition of competition, fun and games on ice in the Netherlands, providing an exuberant and festive atmosphere whenever skating competition are held in Dutch arenas."

(ZJA Zwarts&Jansma Architects, 2018)

According to Stubert, 2018, an ice rink building can be defined as a shell protection, which has the right circumstances to provide high-quality artificial ice for the ice skaters to enhance their performance. Ice arena remains a challengeable building to design providing a controllable environment not only in winter but also in summer. The comfort of the sportsmen has to be the central function of the ice arena, since their performance heavily depends on it. Within long track speedskating, the ice has to be as even and low resistance as possible, with the temperature around -7°C. Air movement and temperature is not preferred to move with a high velocity. Due to cold and warm air exchange, the ice rink buildings have a humid environment because of the condensation, influencing the structure of the ice arena. Since energy costs are the largest bills for skating buildings, an inaccurate design of the building can increase energy costs. The roof of the ice arena has a significant surface area of the entire building, and has a huge contribution to the life-span of the arena, the comfort of sportsmen and spectators and, the last but not least, an aesthetical perception of the entire arena from indoor and outdoor.

Arena Design Overview

Top sport arena is a long-span structure. According to Romeijn, 2006, the structural system used for a stadium or sports arena must fulfill a set of requirements like: human safety, regulations, spectator satisfaction and the client's objective to generate the highest possible revenue.

The following groups of aspects when designing a long-span arena structure are highlighted:

Safety and Comfort

Safety of the structure is central – arena is designed for a large number of people (10.600 seats). To increase the safety of the large span structure it is important that the design includes also the existence of redundancy - the structure doesn't collapse immediately after a certain structural element fails. The comfort of a stadium is also important. This aspect can be a reason for the public to visit the stadium more than once. The view that the spectators have in the sports area is also important for the aspect of comfort.

Functionality

During designing of the arena structure, the most important is to keep in mind the functional purpose of it and all the aspects based on this purpose. In the case of ice arena, such aspects will be environmental conditions, required installations: such as ventilation and lighting, etc. The shape of the roof can impact the environment within the structure. Therefore, roof structure design should encounter all of these requirements (Romeijn, 2006).

Structural Consideration

The choice of material is determined by its properties. The relatively light weight of steel and wood make these materials ideal for long span structures. When the structure get larger it is advised to save extra weight and material by optimizing the cross section. When designing a large span structure it is important to have a very good overview of loads and which load case will be decisive. This can make the design process easier and shorter. The designer of a large span structure like a stadium has to create this structure in such a way that it can be constructed at the planned location. The method of roof construction plays a very important role in the design of a structure. Some important aspects are fabrication, assembly, transportation, handling, the sequence of construction (Romeijn, 2006).

Financial Consideration

The structure has to be designed within the budget. A free cantilever is a lot more expansive than a structure which is simply supported at both ends (Romeijn, 2006). In case of this research construction budget of the arena is not decisive, but the design has to consider interests of the future contractor at the preliminary design stage.

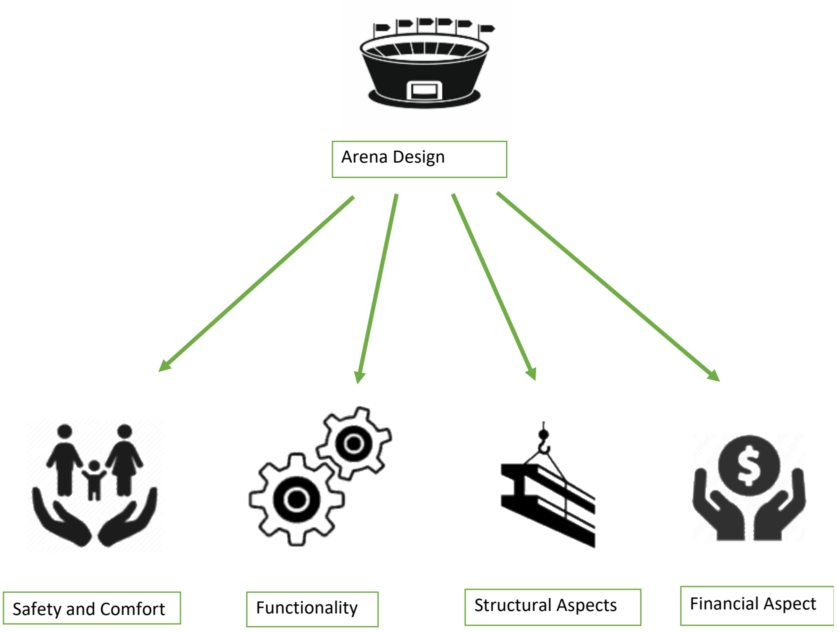


Figure 2-1 Design Aspects of the Ice Arena

2.2 Architectural Design

2.2.1 The Roof from Architectural Point of View

Based on the (Van Rijswijk & Kelleher, 2002) and list of requirements from the Zwarts&Jansma, there were determined the most important features of the ice arena roof to be considered during design:

- High temperature variation in the same indoor environment from -4°C to +24°C, meanwhile these internal climate zones have to be maintained and stay not interfered
- Humidity caused by temperature variation – condensation
- Air tightness is the most important requirement
- Glazing should be avoided to prevent high operating energy costs; fully closed membrane and the casing is preferred
- Roof structure should allow clear spectator`s view on the sport area and spectators seating opposite them, this lead to:

- the absence of columns in the tribune area, sport area
- optimal height of the ceiling.

2.2.2 Basic Building Design Scope

For the ice arena energy efficiency is the main design criteria of the building. According (Burley, 2019), the environmental demands of a skating complex require the design approach which leads towards energy performance and determines the required investments. But the added construction cost with efficient environmental conditions of the ice arena building will quickly return in first years of the exploitation.

The following list of the most essential components for the ice arena roof and ceiling is built up based on (Burley, 2019):

Building Insulation

The roof has to be insulated to a minimum of an R-30. Fiberglass insulation is recommended for this purpose as the most cost effective material in this case. R-value, in this case is a measure of resistance to heat flow through the insulation material (Insulation, 2019).

Vapor Barrier

Vapor barriers must be placed on the outside of the insulation membrane, as opposed to the inside. The preferred material for the barrier have to be with a low permeability rating, such as polyethylene or polypropylene.

Ceiling Emissivity

The major ice floor load is the radiant heat transmitted from the ice arena ceiling into the ice sheet. This can be virtually eliminated with the proper building design. The ceiling must be produced from low-emissivity material (Low-e). The main focus for the low-e materials is to reduce the heat transfer through thermal radiation (Jelle, Kalnaes, & Gao, 2015). To create the low-e ceiling not necessary to use directly the low-e material, low-e paint or coating can be suitable for this purpose.

Moisture & Rust Proof Ceiling

Ceiling used in the rink must be moisture and rust proof. All material used for construction or interior purposes inside the ice arena should be designed for a high moisture application.

Lighting Systems and Dehumidifier Discharge Air

Care should be made to coordinate the light fixture placement and the dehumidifier discharge air at the ceiling.

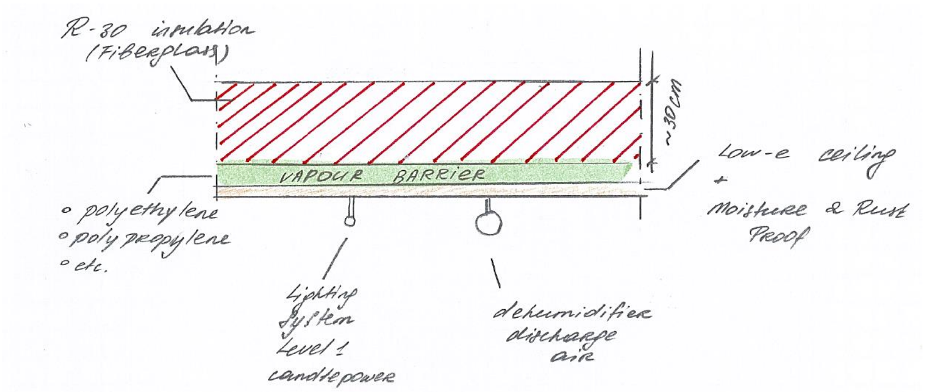


Figure 2-2 Summary Sketch Ceiling Components

2.2.3 Summary of Architectural Design

Below, the summary sketch represents the architectural components and requirements needed to be considered for structural roof design:

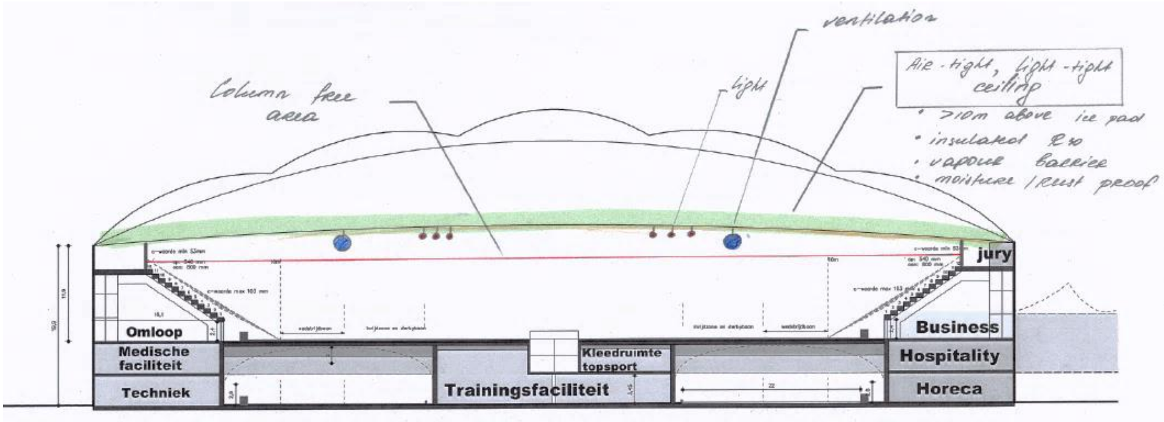


Figure 2-3 Summary architectural design

2.3 Structural Design

To begin with the structural design, the global structural overview of the typical sports arena has to be done. Ice arena has individual environmental conditions which influence the choice of shape and materials of the structure, but at the same time, it still corresponds to general structural principles of long-span building. Figure 2-4 shows an overview of the structural components of the Sport Olympic Arena in London, UK.

The scope of this project covers only the top two components: roof load bearing structure and roof skin as a load input. Further, in this chapter, these two components will be discussed in terms of structural principles, materials, and shape.

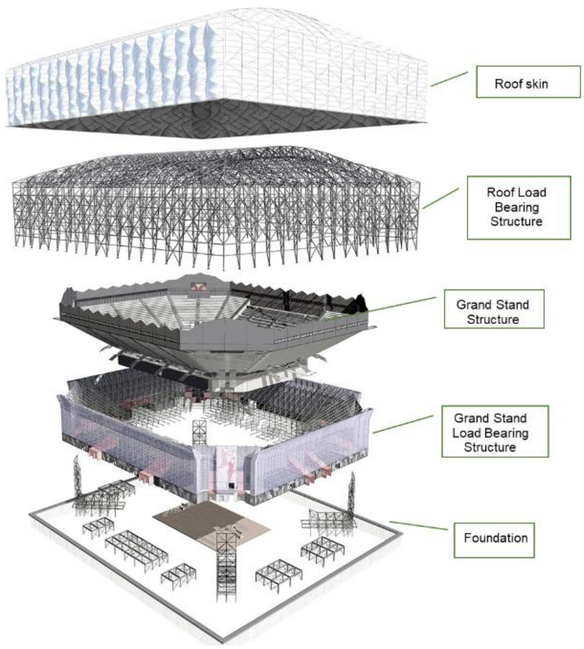


Figure 2-4 Structural Components of the Typical Arena (WilkinsonEyre, 2019)

2.3.1 Roof Load Bearing Structure

Like any other building, ice arenas can be built using various structural systems and construction materials. In the book *Stadium Atlas* (Nixdorf, 2009), the structural systems for the long-span strucutres are given with the maximum allowable span and material use possibilities. An analysis of the list of the systems is done (see Figure 2-5). Since the span for the ice arena is at least 100 m one direction and 215 m in another direction and the main material is steel, some of the systems do not correspond to these conditions. Only systems highlighted with red can be further considered for the ice arena design.

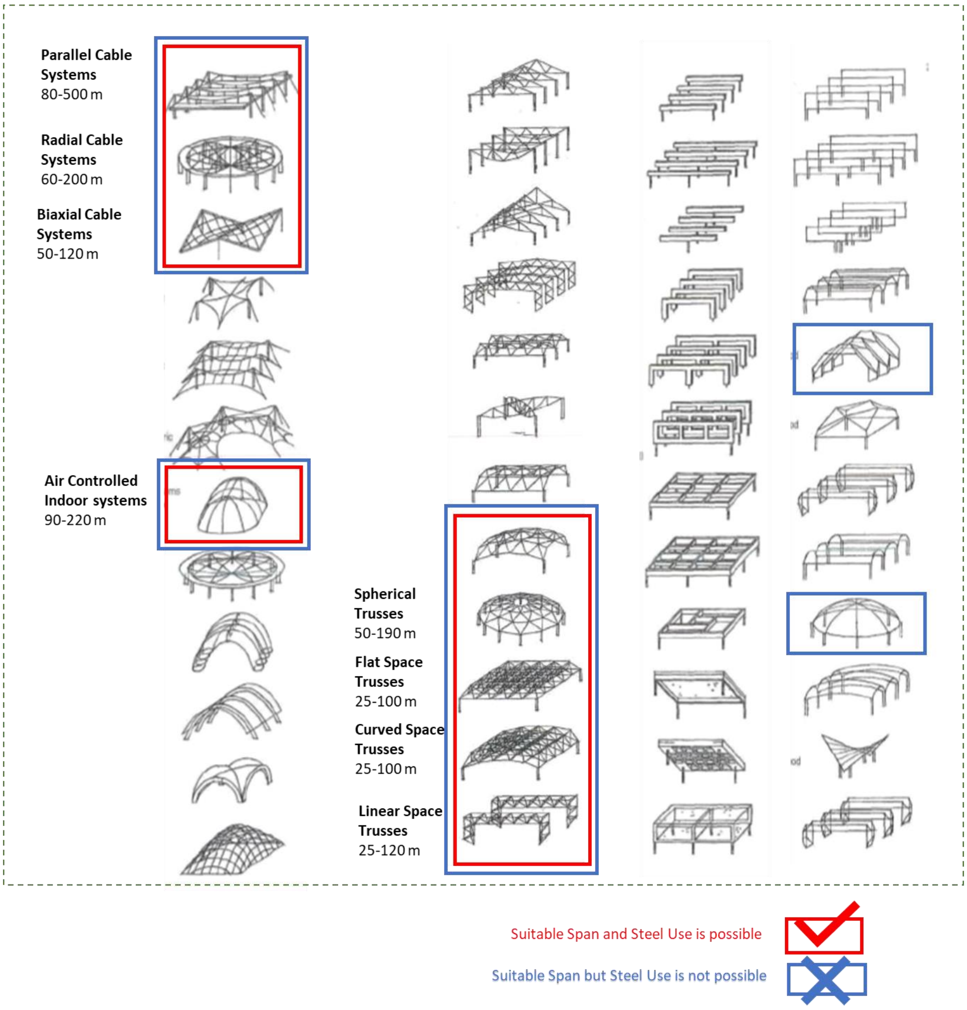


Figure 2-5 Analysis of the span and material possibilities for the arena structural system variants based on (Nixdorf, 2009)

<u>Thus, the **possible structural systems for the load bearing roof structure** are:</u>

- **Truss systems - Tension-Compression System**
- **Cable systems - Tensile System**
- **Arch Systems - Compression System**
- Pneumatic System

The literature study on the structural prinicples of work for each of these systems is done and can be found in Appendix 2. The pneumatic system will not be considered, as this corresponds to more specific design solution.

2.3.2 Building Envelope: Roof Cladding

The steel structure of a single story building generally consists of three main components: load bearing structure, secondary steelwork (e.g. purlins which support roof cladding) and roof panels. The roof panels or cladding is usually called as the building envelope (ArcelorMittal, Design Manuals "Steel Buildings in Europe", 2019). According to Rijswijk, 2002, the main function of an ice rink envelope is air tightness. The envelope structure should be done most efficiently to fulfill this main ice arena roof characteristic. Most used roofing structure is made of several layers:

- Profiled, load-bearing steel sheets
- Thermal insulation(at least 10cm-15 cm rock wool)
- Vapor barrier
- Water insulation (cladding)

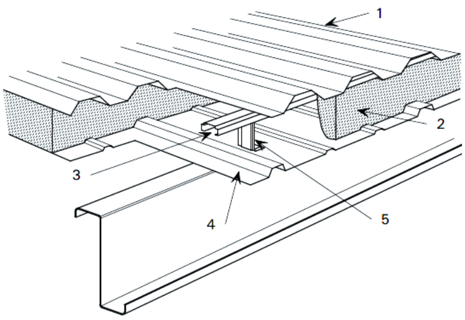


Figure 2-6 Double-Skin System

General systems for roof cladding with insulation are given by (ArcelorMittal, Design Manuals "Steel Buildings in Europe", 2019). Double-skin system is a cladding composition that is fastened to the purlins, followed by a spacing system, insulation and the outer profiled sheeting. “Rail and bracket” solution is used for the spacing system, as it provides greater lateral restraint to the purlins and allows the large depth of insulation. This system is illustrated in Figure 2-6.

Standing seam sheeting has hidden fixings and can be fixed in lengths of up to 30 m. The great advantage of such a system that prevent water penetration through the roof, thus weather tightness and less maintenance is provided. The fastenings are in the form of clips that hold the sheeting down but allow it to move longitudinally (see Figure 2-7). However, a correctly fixed liner tray should provide sufficient restraint. Composite panels made of foam insulation layer can be incorporated within this system and provide good spanning capability.

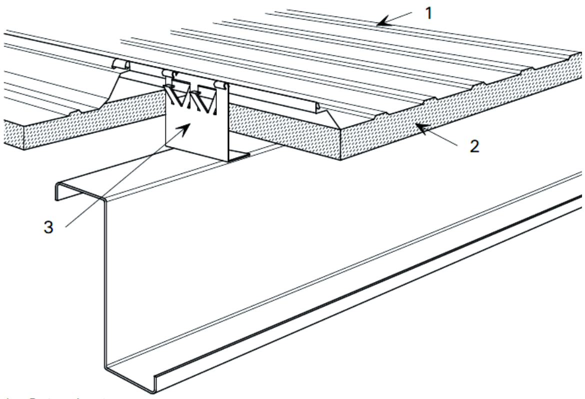


Figure 2-7 Standing Seam Sheeting

In case of tensile structure, tensile membranes are used for the cladding. Types and materials are various, but they all correspond to certain structural behavior and life-span. For the permanent structures, (Schueller, 1996) highlights coated fabrics which provide high-strength, stiffness, and durability. For fabric, polyester based or glass-based material is used covered with one of the following coatings:

- PVC-coated polyester
- Vinyl-coated fiberglass
- PTFE-coated fiberglass
- Silicone-coated fiberglass

When the final structural system is known, cladding choice is considered in more details.

2.3.3 Design Approach

Level of Design

According to the project scope, the designed roof has to relate to preliminary design or LOD200 (Level of Design 200), which specifies certain boundaries of the detailing.

Definition of the LOD200 is:

"LOD200: The Model Element is graphically represented within the Model as a generic system, object, or assembly with approximate quantities, size, shape, location, and orientation. Non-graphic information may also be attached to the Model Element."

(Designingbuildings.co.uk, 2019)

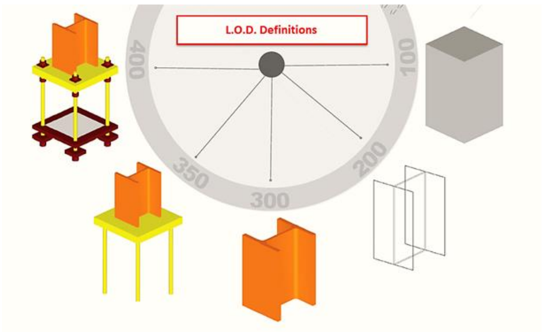


Figure 2-8 Level of Design Definitions (Adams, 2019)

IV-Consult provided with representative drawings for each LOD (see Appendix 3). After analyzing the example drawing, the definition mentioned above was proved. The following general description of LOD200 is summarized:

All specified sections and plate thicknesses are estimated sizes and shapes. The orientations of the sections are not final.

Based on the mentioned information above, the preliminary design of the arena roof will specify the overall geometry, shapes and type of the load bearing structure elements (estimated cross-sections).

Building Code

In order to transform the structural system of the arena roof to the preliminary design, design building codes should be applied. The designed arena is considered to be built in Den Haag, therefore Eurocode with Dutch National Appendix (NEN-EN1900, 2002) is used for this research.

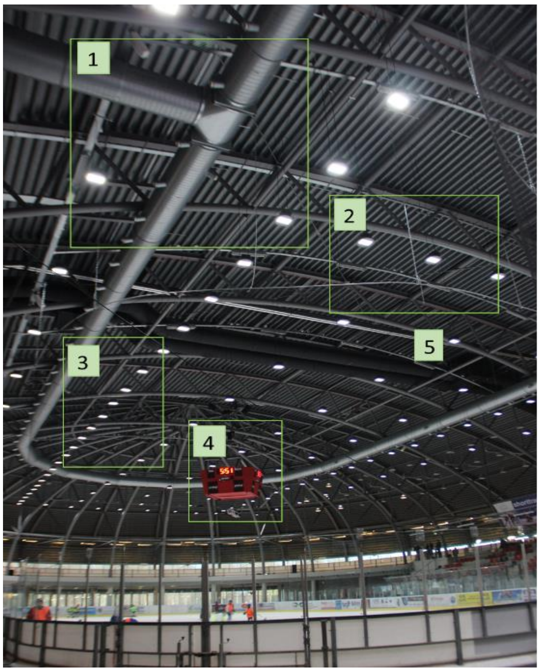
Concept Design Loads

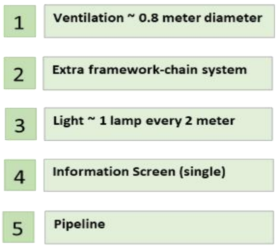
Several concept variants will be evaluated with multi-criteria analysis. In order to be able to give the approximate dimensions of the main load-bearing elements, rough loading estimations have to be done. Only vertical loads will be considered at this point. These include:

- ✓ **Dead Load**
- ✓ **Wind load**
- ✓ **Snow load**

When the final alternative is known, loads will be considered in more details, according the dimensions and shape of the roof.

Dead Load





The dead load includes the self-weight of the roof structure and all the possible elements which will be located below or above the roof. Since no initial loads were provided, an assumption is made on the elements of the ice arena roof in Dordrecht after its visit and analysis of the roof elements. Since the roof structure of the arena is not covered with the ceiling, it enables the full visibility of the components hanging from the roof.

Based on the research made so far and analyzing the roof components of the arena in Dordrecht, the following elements will contribute to the dead load: self-weight of the structure, ceiling and its components, roof skin and its components. Thus the following list of all the **dead load components** is proposed:

Figure 2-9 Analysis of the Dordrecht Ice Arena Ceiling

Table 2-1 Dead Load Components

Load Component	Thickness [m]	Load	Reference	Remark
self-weight member: steel weight	-	-	-	The weight of the element will be determined during calculation, using the iteration method;
steel roof sheeting (70R/800)	-	15 [kg/m^2]	(Sab Profiel, 2018)	Steel as a sheeting material will give the heaviest loading. The chosen profile is used in Amsterdam Arena (Tata Steel, 2019)
insulation roof cladding	0,5	22 [kg/m^3]	(Rockwool, 2019)	Rockwool is assumed at this point as suggested in (Van Rijswijk & Kelleher, 2002)
vapor barrier	0.4 mm	0.3 [kg/m^2]	(Carlisle, 2017)	Based on the type: VapAir Seal MD
electric equipment/light	10 rows – 1 lamp every 2 meters (~700 lamps)	18.8 kg/per one lamp	(Philips, 2019)	Based on Philips Arena Vision Lighting System
steel frame for ceiling fixture	-	0,5 kN/m^2	-	Initial estimation
Ventilation/ dehumidifier	0,8 Ø	200 kg	-	Generally very light (based on initial discussion with architect)
ceiling sheeting (bamboo)	0,02	400 [kg/m^3]	(Engineering ToolBox, 2004)	Bamboo was initially discussed with architect as the material for the ceiling in the ice arena

Table 2-2 Total Dead Load excluding weight of the roof structure

Load Component	Total Load on the Roof [kN]	Total area Arena [m2]	Load [kN/m2]
self-weight member: steel weight	-	23230	-
steel roof sheeting (70R/800)	3418		0,1471
insulation roof cladding	2507		0,1079
vapor barrier	68		0,0029
electric equipment/light	129		0,0056
steel frame for ceiling fixture	11615		0,5000
Ventilation/ dehumidifier	2		0,0001
ceiling sheeting (bamboo)	1823		0,0785
			Total Load [kN/m2]
			0,84

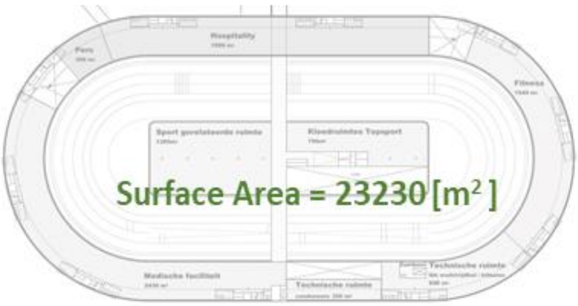


Figure 2-10 Flat Surface Area of the Arena

Based on the load components stated in Table 2-1 and the surface area of the flat roof in Based on the load components stated in Table 2-1 and the surface area of the flat roof in Figure 2-10, the total load of all components excluding the self-weight of structural members, is **0,84 kN/m²** (see Table 2-2)

The following list is an assumption for the concept design only will be reviewed for the final design.

Wind Load

Table 2-3 Wind Load for the Concept Design

Place	Den Haag	
Wind Area	II	
Height	35 [m]	*Assumption (Façade=20 [m])*
Type of the area	Unbuilt area	
Wind Load	**1,43 [kN/m2]**	*Excluding shape factors*

(NEN-EN 1991-1-3, 2011)

Snow Load

$$S_k = 0,7 \left[\frac{kN}{m^2}\right]$$

(NEN-EN 1991-1-4, 2011)

Concept Design Load Summary

- ✓ **Dead Load** — **0,84** $\left[\frac{kN}{m^2}\right]$
- ✓ **Wind load** — **1,5** $\left[\frac{kN}{m^2}\right]$
- ✓ **Snow load** — **0,7** $\left[\frac{kN}{m^2}\right]$

As stated above, these are the concept design loads only, in the Chapter 4, the load input is considered in more details for the final model, according to the design shape.

2.4 Case Studies

In the beginning of the research, a number of structures were reviewed, to get a feeling of large-span structures and get inspiration on design possibilities. The focus was on the structures with similar span and functional requirements. In Appendix 4 all the case studies are presented. There were nine sport arenas analyzed for the structural system only. Three of these arenas are considered as detailed case studies. These are:

1. **Thialf arena:** is the largest ice arena in the Netherlands, was recently renovated and has the most innovative inner facilities for the best ice quality.
2. **Dordrecht Arena:** the visit of this arena was organized and interview with one of the skating coaches was done at the same time.
3. **London Velodrome:** has a saddle shape and cable-net structure, has really interesting structural solution and looks very similar as an initial render (see Figure 1-1).

These three cases are considered in a poster format and can be found in Appendix 4.

2.5 Conclusion

The literature research shows: although, the structural design of the arena roof has to be done, it is not enough to look at the research problem from the structural point of view only. An ice arena has very specific inner-environmental conditions, has to provide safety and comfort of sportsmen and spectators. Moreover, the financial aspect requires solutions which will allow to minimize use of the energy to get correct ice-surface and air conditions. This means that the roof design has to take into account the sustainability aspects and consider the latest developments of the ceiling and cladding design with low-e values.

The minimized material use, together with the smart consideration of the roof future prospects such as constructability, maintainability, and demolition can minimize the life-cycle costs. The roof life-span is 50 years, which means, that the structure has to have the perfect conditions for the entire life-span. In this case, accessibility to the roof surface, water accumulation and cladding type with the same life-span are the aspects which have to be considered as well.

Another sustainability aspect for the structures nowadays is a post life-span demountability and re-use of the structural elements. This have to be considered at the early design stages, by means of the structural system, used material, sizes of the elements, type of connections, etc.

The designed roof is a large-span structure, therefore, not all of the structural systems can be applied. However, there are three general systems, with the use of steel: truss, arch and cable systems. They can be considered in various configurations and give an optimal solution with the above-mentioned functional aspects.

The last but not least, the future ice arena building, is a part of sport venue in the Netherlands. It is a massive construction which will attract attention of the public, possibly including national and international competitions. No need to explain how the visual perception is important. If the structural solution, together with the fulfilled functional and technical requirements, can be also aesthetically appealing, the value of the design will increase significantly.

All of the above mentioned aspects will be considered in the design stage of this research. In the next chapter, the structural systems will be analyzed whether they can fulfill these conditions together with the direct technical application.

3 Concept Design & Multi-Criteria Analysis

In this chapter, the methodology for the concept design developments is given and the conclusions based on the multi-criteria are done. Four structural solutions are conceptually developed and analyzed on the structural feasibility. Multi-criteria analysis results are shown and explain why the best alternative have to be further developed.

3.1 Introduction

From the literature research, there were four main structural systems highlighted as the most suitable for the span of more than 100 meter and steel as the main material. These are the following: truss, arch, and cable systems: cable-net and cable-supported hybrid structures (for the primitive initial application in the arena cross-section see Figure 3-1). These four systems are applied to a concept design study and multi-criteria analysis is implemented to be able to highlight the most potential criteria. The criteria are determined based on the interviews organized with some of the stakeholders of this research/project.

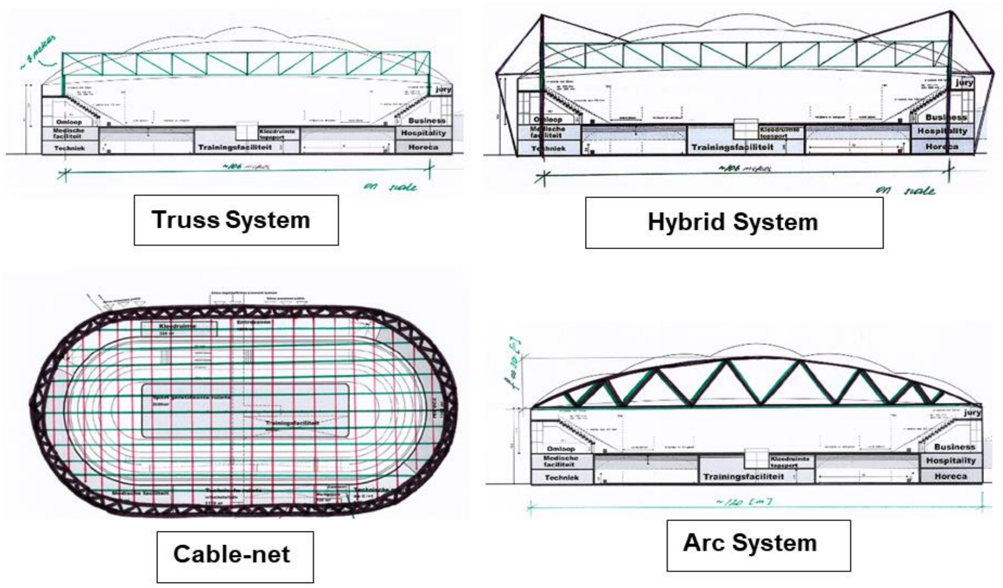


Figure 3-1 Four Structural Systems for Further Development

3.2 Architectural Design Concept

Based on the list of the initial given information and requirements, the ice arena building is considered not only as a structural engineering product but more as a sport venue banner - the reflection of what is going on inside. Moreover, one of the requirements is to underline the structure. However, the cladding and ceiling hide the roof structure from the top and the bottom. The main approach to be able to do so, is either to bring structure outside, show the structure or by making the shape of the roof looking interesting. On the other hand, structural solution has to have also a logical technical meaning, not only the architectural expression.

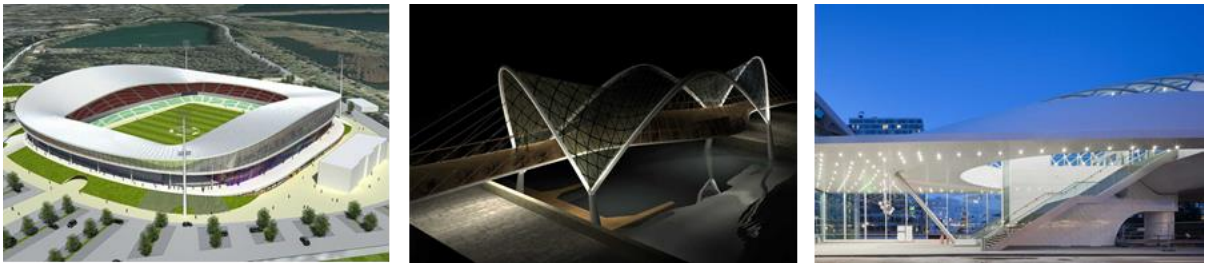


Figure 3-2 Projects (ZJA Zwarts & Jansma Architects, 2019)

The previous projects of the Zwarts&Jansma are analyzed. The main feature of the most of the designs, from my perspective, is very elegant and clear style, have calm shapes and forms which reflect the functional demands of the designed elements. I am inspired by the way they integrate technical and functional meaning into the projects, considering it also from the social, sustainability, urban and environmental aspects.

Structural systems are known, the next step is to understand how to integrate the structural solution within the given conditions. How the structure can be expressed within each of the structural solutions? What is considered as an structural expression even? All of these questions are part of the initial concept design steps.

The proposed solution, in this case, is - if the structural system cannot allow an interesting shape of the roof like saddle-shape in the cable-net, for example, the structure will be brought outside. This will also allow to consider the roof as an individual element, kind of the exterior cap. In Figure 3-3, two approaches are shown which can be followed. Approach 1, the roof covers the ice arena only. Approach 2, the roof is extended to the façade with the outside columns and all-in-all look as an homogeneous structure.

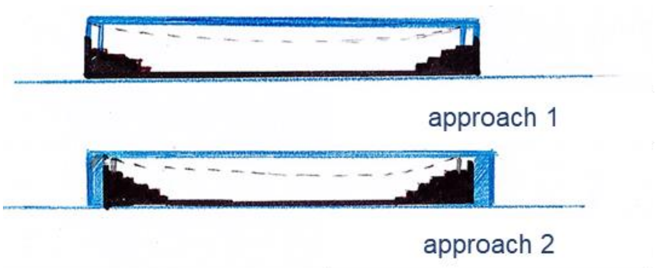
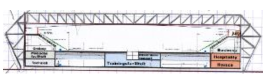
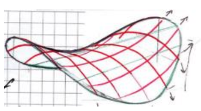
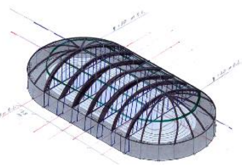


Figure 3-3 Approach for the roof design

Table 3-1 Shape Definition

	Truss System	Cable-Net System	Arch System	Hybrid System
Measure to underline structural design	Bring structure outside[1]	Shape of the roof	Shape of the roof	Bring structure outside[1]/shape of the roof
Visualization				

[1] The main idea is, by means of structural design solution, create a possibility to make a roof structure explicit

Table 3-1 shows the applied approach for the architectural solution within this research. This means: cable-net, arch and, partially, the hybrid structural systems can be an architectural solution by its own. But with the hidden under cladding and ceiling flat truss system, an extra shape study had to be done.

Below, in Figure 3-4 the proposed shape for the truss and cable-supported systems is represented. It is a twisted mobius-like shape which appeared during shape investigations, as an extra branch of this research (can be found in *Appendix 6: Shape Development*) .

To explain in short, portal or braced frames were considered. Both require significant space inside and at this moment it is not known at which location the column will be and can be placed. To avoid future problems of having massive column structure in non-desirable area (e.g. offices, etc.), it was considered to place a truss column structure on the outside of the arena building. Experimenting with the shape of the columns on the outside the mobius-like shape appeared. Columns outer shape gradually changes with each next column, this gives an impression of the twisted shape. The shape proposal is discussed with architect and project manager, and it was allowed to continue further investigations.

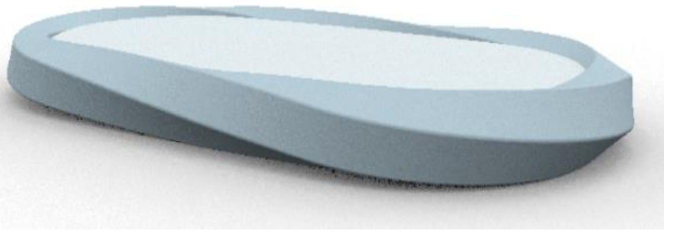


Figure 3-4 Mobius-Like Shape: Arena Shape Proposal

3.3 Design Criteria

The concept design development requires a set of criteria which will help to fulfill research goal and, respectively, the project requirements. The list of design criteria have to be concise but cover as fully as possible all the demands from architect and other stakeholders. These criteria are used for alternative development and in multi-criteria analysis (MCA), where the most potential alternative is determined.

3.3.1 Interviews Summary

During the initial research phase, several interviews were organized. Interviews were beneficial for both: get an insight to the research topic and to be able to create a list of design criteria and the corresponding importance weight. The list and interviewees selection` explanation is given below. All interviews notes and conclusions can be found in *Appendix 5: Interviews.*

Project Key-Stakeholders:

For this particular graduation project, there are two key-stakeholders who can define the main design criteria: architect and project manager of the engineering company. Criteria specified by them include the demands of the future stakeholders, e.g. spectators & users, engineers and contractors, municipality and many others.

Architect

The interview session is organized with the architect, who is responsible for the current project. Since he was also the head architect during the Thialf Arena renovation – the largest skating arena in the Netherlands (currently), therefore has enough background knowledge on the roof system, ceiling, climate control, etc. At the same time, as a key-stakeholder, the architect knows exactly what are the main criteria of the final design from the architect side: aesthetics (architecture), functional requirements and costs.

Project manager (Iv-Consult)

The same as architect, project manager is the person which primarily determines criteria for the design evaluation, therefore, his opinion in this case is also prior. Moreover, the applied experience about the efficiency of the large projects in terms of: costs, construction, project selling targets and many others can be used as an extension of the literature research. During interview, the following criteria were underlined: life-cycle costs, durability, constructability/demountability, sustainability. These are then combined to the criteria which is named in this research as future prospects.

Extra Interviewee:

To expand the view on the research topic and get diverse opinion about the importance of the particular design criteria, these two interviewees are also included.

Structural Engineer

The structural engineer with the background of stadium or arena long-span projects can help to provide practical knowledge and avoid mistakes on early stages. It was a beneficial opportunity to discuss during the interview the concept variants in terms of cost and efficiency, feasibility, difficulty of constructability, etc. The main criteria highlighted were: constructability, maintainability and cost-effectiveness, so part of a future prospects criteria. However, after this interview another criteria appeared: efficiency of the structural solution (explained below).

Skater (Potential User)

The final outcome of this structural design project is Ice Arena. It is built for the sportsmen. Thus, the opinion of the potential user have to be heard and taken into account. Mainly, the functional requirements and overall aesthetics of the building were discussed during the interview. Functional requirements criteria is the main concern for the skater: they need the best quality ice and air conditions for the better performance.

3.3.2 List of Design Criteria

Based on the interviews outcome discussed above, four main criteria can be set-up:

Criteria 1: Architecture (Aesthetics)

The key point of this criteria is to analyze whether the structural system of the roof can contribute to the overall architectural impression and aesthetics of the ice arena design. The ice arena is a part of sport venue, therefore the overall design has to be attractive and memorable, somewhat a sport venue banner which “invites” people to participate in sport activities. Façade and cladding possibilities, LED light inclusion and other presentation features, can contribute to architectural success of this project.

Criteria 2: Functional Requirements

Functional requirements of the ice arena are very specific. The main question to answer with this criteria is: how difficult it will be to fulfill the functional requirements within the considered structural system. Among these requirements are light restraint, cladding and ceiling attachment facilities and dimensions.

Criteria 3: Efficiency

The central idea of this criteria is to analyze the structural system in terms of the efficiency for the given case. The boundaries of the ice arena remain the same but the structural solution is applied with different force distribution and steel amount. Moreover, one feature of this research is parametric design and it is useful to consider what are the parameters which can be considered at the preliminary design stage to improve efficiency of the structural solution.

Criteria 4: Future Prospects

This criteria is covering multiple sub-criteria of the various perspective. The main idea is to analyze what is the future lifetime of this roof: from construction to demolition. Life-cycle costs, durability and sustainability are also briefly considered.

3.4 Structural Design Concept

3.4.1 Introduction

Now the design criteria are known, the concept design of each of the alternative can be developed. The concept design covers both: briefly architectural and more thoroughly structural engineering developments. The elements of the primary structure are estimated for the required stiffnesses and dimensions. This allows to calculate the approximate expected steel weight of the primary structure for each of the structural solutions.

To be able to analyze the alternative with enough evidence, each of the alternative description will include the following analysis segments:

- Goal of the alternative
- Shape
- Roof Structure
- Supporting
- Stability
- Force Distribution
- Connections
- Advantages
- Disadvantages
- Main Difficulties
- Parametric Design Possibilities

Moreover, separately form alternative description, the additional table is done, where the future prospects of the roof design are summarized for each of the alternative (see 3.4.3).

3.4.2 Alternative 1: Truss Portal Frame Structure

Goal of the alternative

The roof structure by the requirement is covered from inside with the ceiling to keep the specific environmental conditions. Also, sufficient cladding is required to block the sunlight inside the arena. As one of the requirements is to highlight the structure, the idea of portal frame is popped up to underline the structural solution from façade part. Moreover, large span of the roof and symmetry of the shape leads to the consideration of such relatively simple structural solution – truss system. This idea allows to consider the roof as a separate element from the superstructure of the arena and play with the overall shape to create an interesting façade.

Shape

The shape of the alternative is the one which is proposed to the architect, since no exact shape was provided. Columns of the portal frame will vary in geometry to create a desired shape of the torus. Since the final design is planned to be done parametrically, calculation process with the shape variation in the columns is planned to be more straightforward.

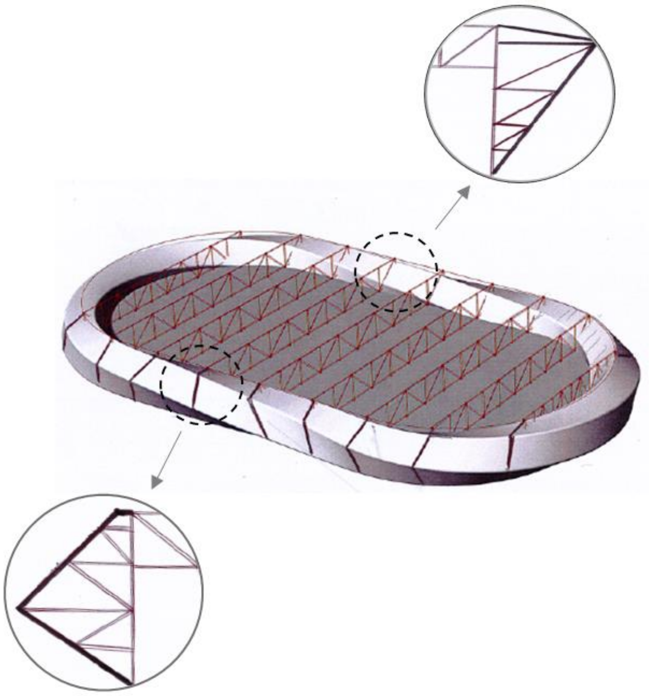


Figure 3-5 Truss Structure: possible integration in the concept shape

Roof Structure

The primary roof structure will be built-up from 3D-trusses to reach a required stiffness with the same height as normal 2D-truss. The possible configuration of the primary trusses can be seen in Figure 3-7 below. With dark orange the primary structure elements are highlighted. With thin grey lines, the secondary elements are represented. Secondary elements will be defined at the later design stage. For now the assumption is Square Hollow (SHS) profiles between primary trusses every 5 meters, however at later stage IPE sections, which are the most common for the roof panels support, will be considered. This can be optimized later with smaller trusses as well. For this stage only the largest span of 114.2m in the rectangular shaded area (see Figure 3-7) is considered to find the required approximate dimensions of the primary truss. Trusses at the circular part are assumed to be of the same property.

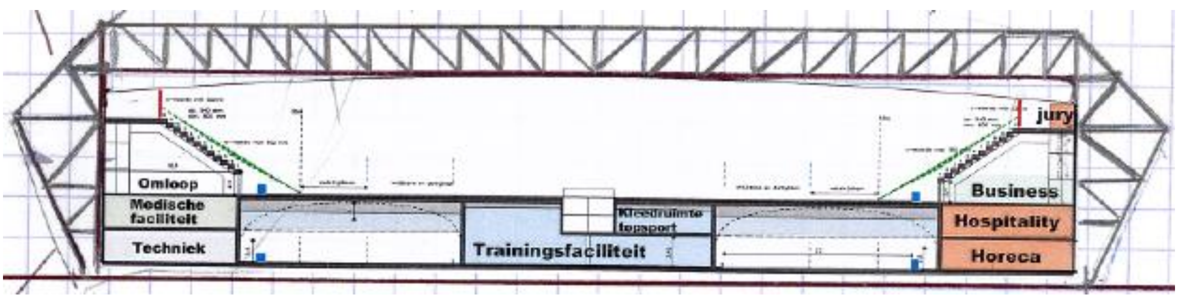


Figure 3-6 Portal Frame Concept Design

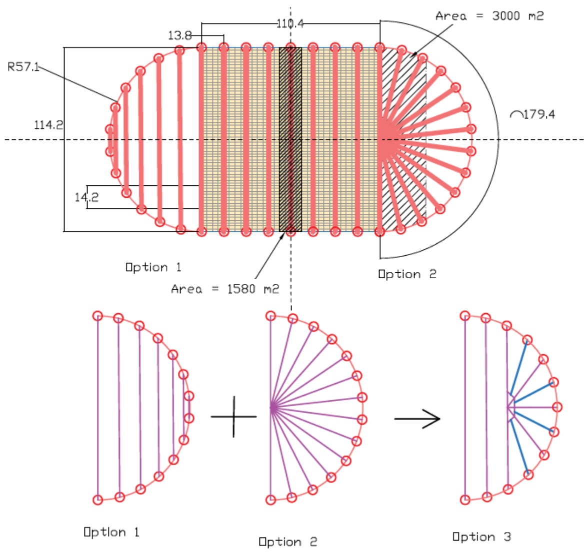


Figure 3-7 Truss System Concept Design Layout

At this stage, columns and truss configuration is an assumption. At the later design stage, with parametric design, column distance and truss heights and width will be parametrized which will allow to optimize the structural design.

Supporting

In the case of portal frame truss and column is a one system, so roof structure is self-supported. Columns further than area of the tribunes (see red line in the Figure 3-7) are not allowed. So additional columns outside this area will not really contribute to the deflection reduction or truss optimization in terms of size or weight.

Stability

The initial idea is to create a portal frame as a primary cross-section, so the roof is a separate structure from the superstructure of the arena building. Since the dimensions of the structure are really large, during further investigations at the preliminary stage, it will be studied if the portal frame system is feasible. Otherwise, in-plane stability of the portal frame truss structure will be provided by the cores inside the superstructure and the office areas, so becoming a braced frame system. To create the stability of the roof, wind bracings will be installed in the roof and sides, between trusses and girders.

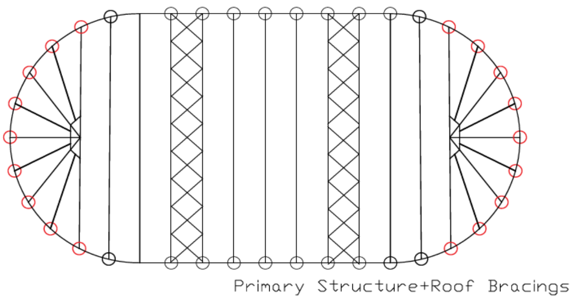


Figure 3-8 Roof Bracings

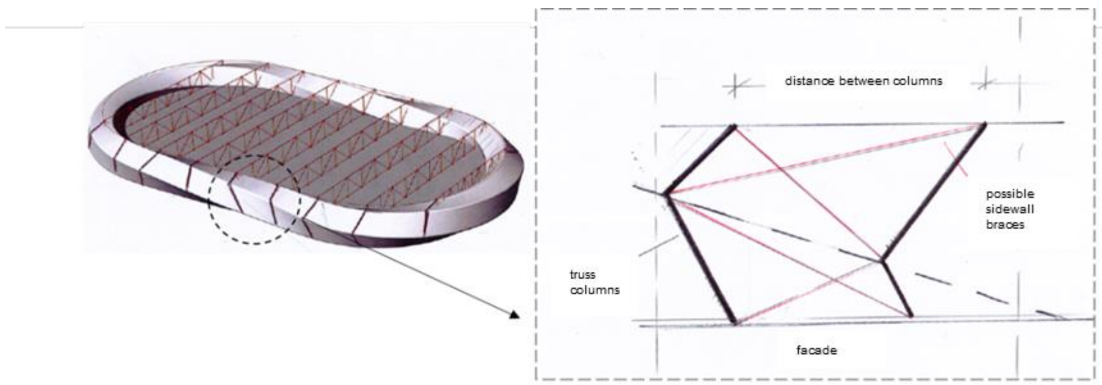


Figure 3-9 Braces Idea Columns

Force Distribution

The advantage of this system is that it works mainly in 2D. Purlins between the primary trusses redirect the roof vertical load to the primary structure. Vertical loads are distributed to the columns. Horizontal loads are also taken by the columns.

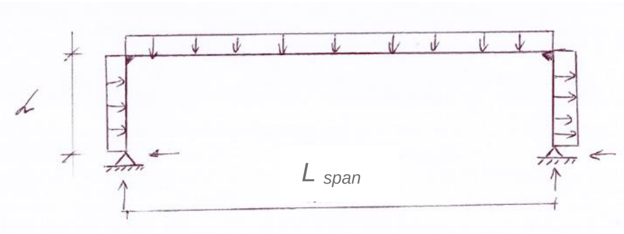


Figure 3-10 Force distribution diagram

Type of Truss

Initially the 2D-truss was assumed. During the concept calculation process, it was found out that for a given span length and vertical ULS load based on permanent loads, square 3D-truss will be twice as stiff as a plane truss with the same height. Also, 3D truss will provide with stiffness in horizontal direction.

For the concept design calculation of the required truss, see *Appendix 7: Concept Design Calculations*.

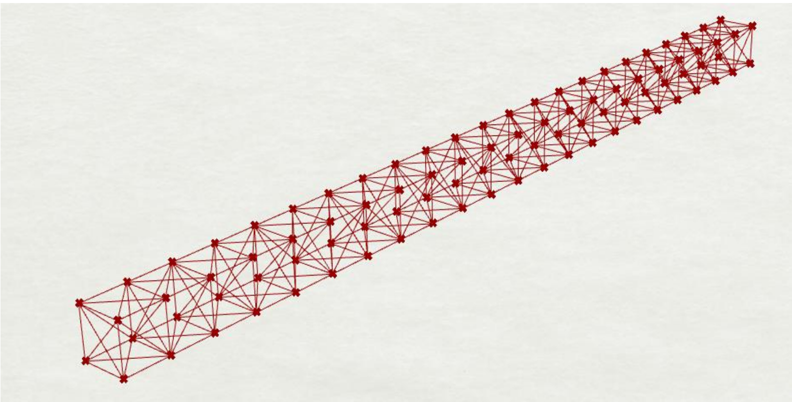


Figure 3-12 3D Truss Grasshopper Trial Model

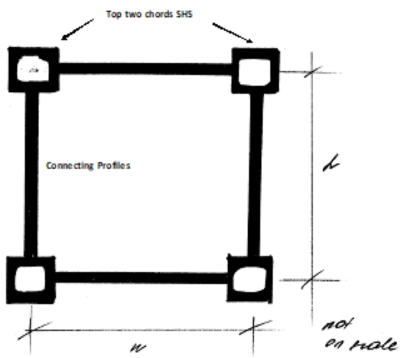


Figure 3-12 3D Truss Concept Cross-Section

For now 3D-truss is proposed as a concept. However, it is worth to highlight that during the parametric design and optimization of the span and column amounts, it can turn out that 3D truss will not be necessary or not necessary in all locations. Thus, at the preliminary design stage this have to be considered in more details.

Connections

The connections between the horizontal and vertical elements in the portal frame are fixed. One of the consideration requirements of the current roof design is demountability. Bolted connections are the better option in this case. Since the truss is bolted in top and bottom chords, fixed connection is created. The columns are supported on the hinges. Also, the possibility of the prefabrication of the trusses in the smaller parts will be considered to ease the transportability on the building site and easier demountability.

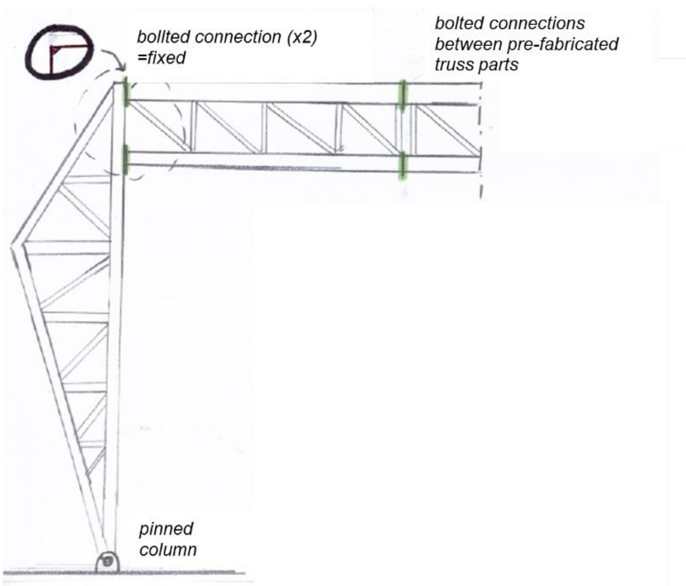


Figure 3-13 Connections in the system

Estimated Properties

Roof steel structure dimensions:

Primary 3D-truss	*7600*	*mm*
Secondary Members (purlins)	*250*	*mm*
Column Truss Height	*30*	*m*

Roof Steel Structure Weight:

Primary 3D-trusses	*19000*	*kN*
Secondary Members (purlins)	*950*	*kN*
Truss Columns	*6600*	*kN*
Total Weight Steel Structure	**2700**	**ton**
Roof Only	**2000**	**ton**

For detailed calculations see Appendix 7: Concept Design Calculations

Advantages

- Span length required can be realized
- Relatively simple and straightforward roof system
- Roof is self-supported structure
- The shape created with the portal truss frame is structurally appealing and visible from outside; a lot of interesting possibilities for façade design are possible
- The roof can be designed to accommodate extra facilities such as solar panels, of course, dimensions of the primary trusses can be reviewed because of that
- Adequate/efficient solution for the hidden roof structure

Disadvantages

- In case of 3D truss fabrication can be more expensive
- Lateral support of the roof has to be well-thought to fulfill sufficient stability of the total structure
- A lot of connections

Main Difficulties

- The variation of the column design to create a desired shape. Possibly, even the column trusses on both sides of the portal frame will be of the different shape. This has to be carefully considered later during design considerations
- No curvature of the roof at this moment is considered. At the later stage, the accumulation of the water has to be taken into the account

Parametric Design Opportunities

Preliminary design will be done parametrically, therefore the possibilities for the various parameters are worth to consider at this stage to understand what are the prospects of the system for the optimization.

Aesthetics	Efficiency
Overall shape variation on the façade side	Columns locations
Truss columns shape	Truss design optimization: center to-center distance, truss shape, etc.
	Secondary members optimizations
	Circular part structural optimization

Alternative 2: Cable-Net

Goal of the alternative

The cable-net alternative was the first, which arose when this assignment was given. Since the original rendering of the sport complex represents the saddle-shape arena (see Figure 1-1). The main goal of this alternative is to consider the possibility to create a light-weight roof and see if it can fulfill the requirements.

Shape & Roof Structure

The main difference of the cable net roof structure-it is really thin and light in comparison to the mentioned above alternative of the truss structure. The shape of the roof is double-curved. The roof structure shown in the Figure 3-14 shows the initial design concept investigations. Two main structural elements are pretensioned cable-net and compression ring which support the tension forces.

Main Structural Elements

The primary structure of this variant consists of the two main components:

- **Cable-net**
- **Compression ring**

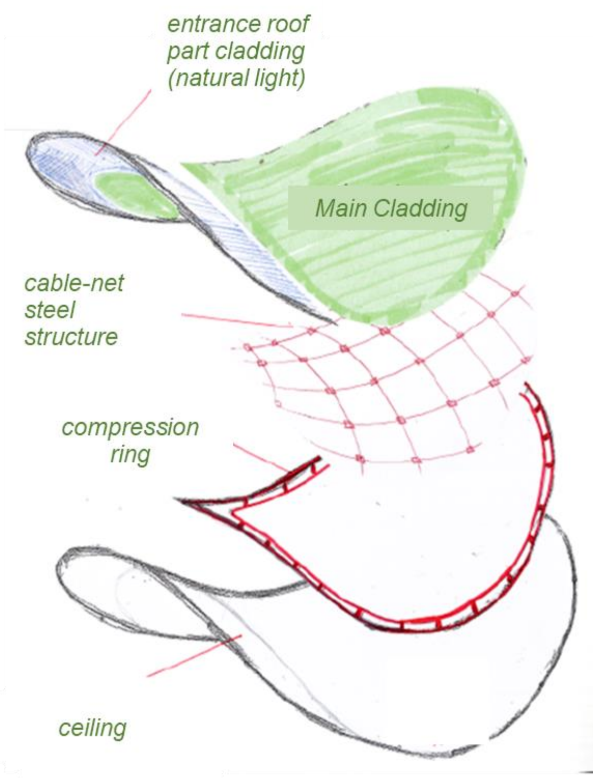


Figure 3-14 Cable-net roof structure

The load distribution of the cable net is not linear, in 3D. The double-curvature of the roof requires a form-finding approach with the software or by means of scaled physical modelling (Coenders, 2008). The concept development of these elements are based on the Case Study 3, analysis of the cable net roof of London 2012 Velodrome (see detailed case study in *Appendix 4: Case Studies*). Based on comparison of the dimensions, loads and shape, the information from the velodrome is applied in for the cable-net concept assumptions.

Cable-Net

Cable-net is a prestressed double-curvature membrane structure made out of the pretensioned cables spanning in two direction to be able to support self-weight, cladding, ceiling and exposed live loads. These tension forces have to be supported by the outside support structure-compression ring. The load distribution of the cable net is not linear, it is distributed in all directions. Therefore, shape of the roof defines the stiffness. If the double-curvature form of the cable-net not found correctly, the roof will not be able to withstand loading conditions. However, the correct form allows the cable-net span huge spans.

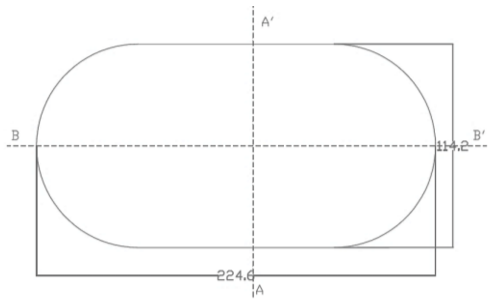


Figure 3-15 Arena Layout Sketch

The primary structure of the roof consists of a doubly curved cable net covering the total area of the roof. The maximum horizontal span is about 104 m in one direction and about 215 m in another direction (assuming that the compression ring is of about 5 meter wide).

The final dip in the completed state is based on the case study sag ratio analysis (see *Appendix 4: Case Studies*) and is 6.6 m between the center of the roof and the highest cable termination. The corresponding cable rise in the longer span direction is 7.85 m (see Figure 3-16).

The initial assumption is to use exactly the same cable-net system as in London Velodrome to be able to start with something. The cable roof consists of pairs of 36mm diameter spiral strand cables, separated by 120mm. The pairs of cables are arranged at 3.6m centers in both directions. The cables have swaged end fittings and are to be fabricated to a dead length: no adjustment to cable length is possible once the cables have been fabricated. The cables have a Galfan coating, which is suitable for external environments, while the nodes are galvanized (Expedition, 2013).

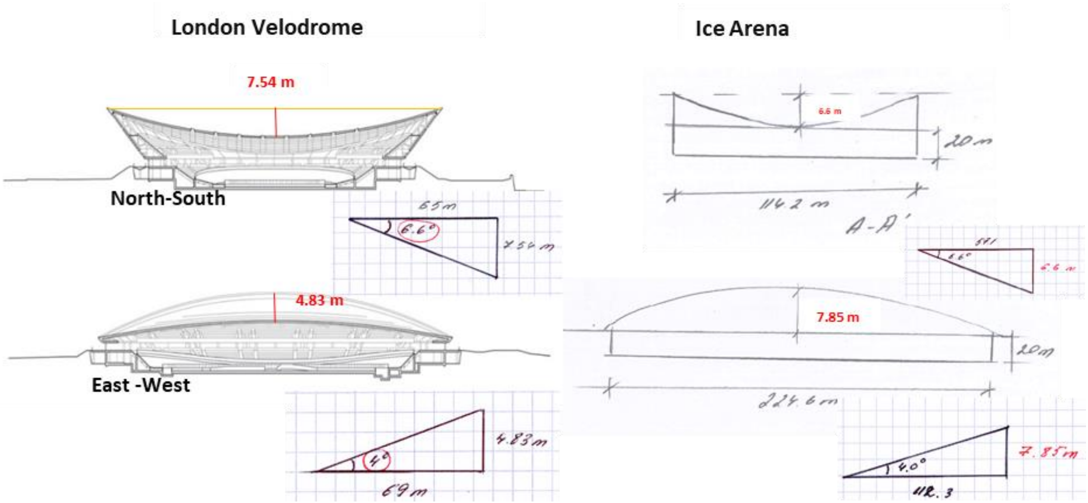


Figure 3-16 Sagging of the cable-net: London Velodrome and Ice Arena

Compression Ring

The compression ring repeats the shape of the arena outline. The development of the compression ring can be found in Figure 3-17*).* The total compression ring sytem is subdivided into two parts: circular part and straight part. The circular part is assumed to be a compression part but a straight part is also subjected to the significant bending therefore the sections are designed for bending as well.

The concept design considers 5 meter width of the compression ring. The arrangement of the web members is governed by the need to limit secondary stresses in the chords. The chords are made out of circular hollow sections (CHS). For the concept design calculation of the compression ring (see *Appendix 7: Concept Design Calculations*).

The roof cables are stressed against a steel ring truss which runs around the perimeter of the roof.

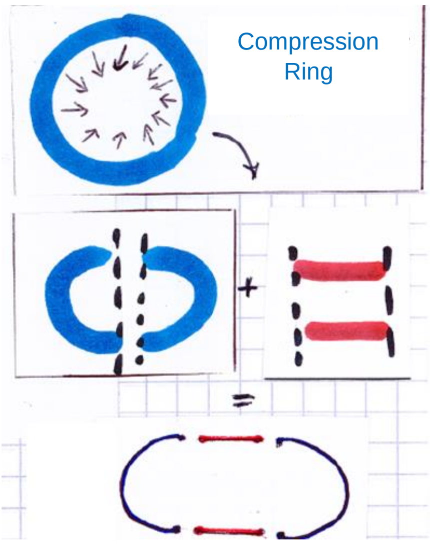


Figure 3-17 Compression ring design approach

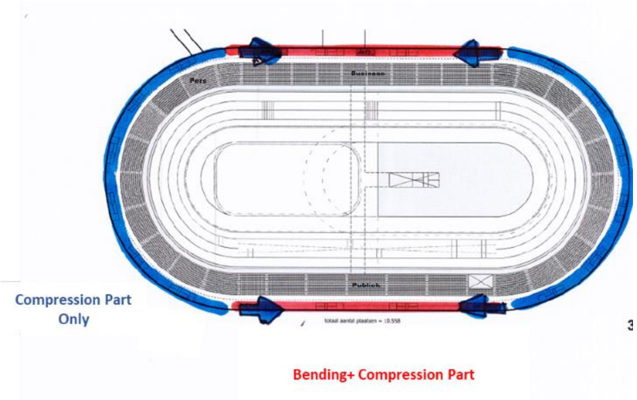


Figure 3-18 Compression ring concept design

The ring truss provides several structural purposes:

- Provides a reaction to the cables
- Transfers cable forces to the column and guy cables
- Provides a perimeter compression member which carries a proportion of the cable forces at high level
- Directly supports roof cladding located above the truss (Expedition, 2013).

Connections

Steel nodes clamp the two pairs of cables together at every location where the cable pairs will cross. The nodes are made up of three forged elements which clamp the cables (top, middle and bottom plates) (see Figure 3-19). The nodes are used to support the roof cladding system. Cables of the roof are attached to compression ring every 3,6 meter from the inside and each above each column from the outside in the special pinned connection (see Figure 3-20).

Figure 3-19 Nodes clamp in cable-net (Arnold et al., 2011)

Figure 3-20 Cable and compression ring connection (Arnold et al., 2011)

Compression ring is placed on top of the columns. It is connected with the fixed connection (bolted or welded). Column is fixed on the ground and connected to the core of the structure.

Stability

Stability is provided by the connection of the roof structure and columns to the cores of the superstructure of the ice arena. Structure of the roof doesn't distribute load linearly, therefore all elements work together to provide the stability of the roof. Thus, stiffness of the cable-net is very important. The cable-net prestress and shape of the roof has to be found in such way, that the surface remains under the tension even in the worst cases loading conditions.

Force Distribution

Under the gravity loads, the main convex cable in the cable-net is stabilized by the secondary concave cable which is prestressed and pulls it down for stabilization. The prestress force on the secondary cable in the cable-net is sufficient enough so the cable-net system is always in tension. The surface form is directly related to the magnitude of the pretension. The cables of the cable-net are attached to edge member, which acts under the compression in order to support the tension forces from the cable-net. Compression ring as mentioned above repeats the shape of the arena outline and supported each 10 meter by the column.

Cables of the cable-net are attached to compression ring every 3.6 meters. Initial assumption for the column distance between each other is 10 meter. This means that between two columns, at least 2 cable-net members are attached. The tension force of the each pair cable is 1300 kN, is based on the case study of the London Velodrome (Arnold et al., 2011).

Estimated Properties

<u>Roof Thickness</u>

Cable-net and roof package	*~700-1000*	*mm*

<u>Roof Steel Structure Weight:</u>

Cable-Net + Connections	*700*	*ton*
Compression Ring Weight	*630*	*ton*
Total Weight Steel Structure	**1300**	**ton**

For detailed calculations see Appendix 7: Concept Design Calculations

Advantages

- Fast construction
- Large saving in total embodied carbon dioxide than in heavy truss or arch systems
- Light self-weight
- The shape is aesthetically pleasing

Disadvantages

- High capital costs
- The compression ring is not circular, this is not efficient
- Vulnerable for extreme dynamic loading
- Installation of the roof package can be problematic

Main Difficulties

- Finding the correct form of the double-curved cable-net to insure sufficient system
- Determine such pretension which insures that the systems always works in tension
- The stability of the structure has to guaranteed if the cable-net is damaged by the external forces
- Connections design is very important in the cable-net design, have to be carefully considered.
- Tension in the guy cables will vary with angle changes which can increase tension forces significantly, this has to be optimized to a certain range of angles allowed

Parametric Design Opportunities

Aesthetics	Efficiency
Saddle shape curvature changes	Cables center-to center distances
	Sag ratio of the cable-net
	Compression ring optimization
	Columns location

Alternative 3: Hybrid Structure Cable-Net and Cable-Supported Structure

Goal of the alternative

This alternative is based on the cable-net and truss alternatives described above. Instead of the truss roof, the cable-net with compression ring is used and supported on the truss columns. The guyed cables are attached to the compression ring and column trusses and fixed at the ground. This allows to consider the roof as isolated structure form the superstructure. This will allow to prevent the locking of the forces between the two structures.

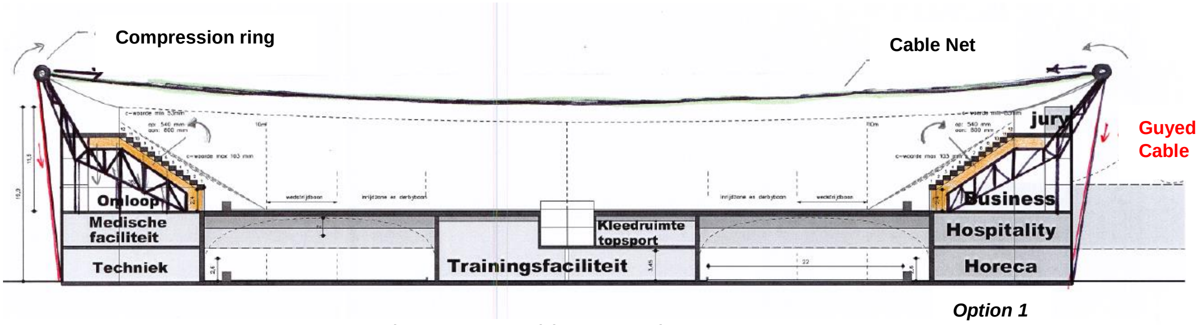


Figure 3-21 Cable-net: option 1

Shape & Roof Structure

The roof itself remain the same as in alternative 2. However, the roof connected now to the outside load-bearing structure which is independent from the core of the structure. Below, two options are considered for load-bearing structure of the roof.

Options Outside Roof-Support Structure

<u>Option</u> 1 (Based on London Velodrome Case Study)

This design idea is and integration of structural principle used in the London Velodrome, see case study in *Appendix 4: Case Studies*: to minimize the dimensions of the compression ring, the steel structure is installed under the tribunes. Steel structure supports the compression ring.

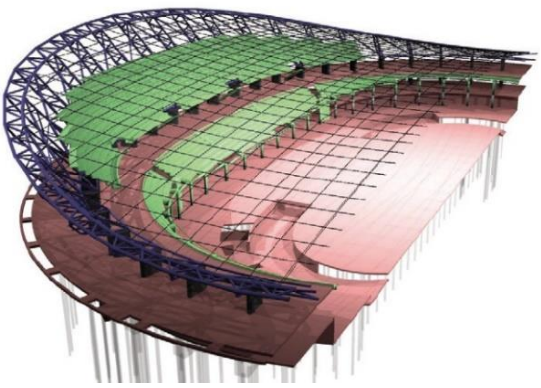


Figure 3-22 3D model roof structure London Velodrome (Expedition, 2013)

Force Distribution

Due to large pulling force, the moment on the structure is significant. The grandstand structure due to downward load on the steel structure creates a counter moment and balance the moment due to tension in the cable-nets. This design allows to minimize the dimensions of the edge support-compression ring. In this case roof and outer arena structure are connected and work together, which is not typical for the stadium structures.

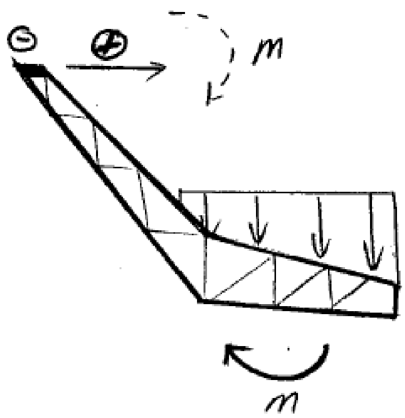
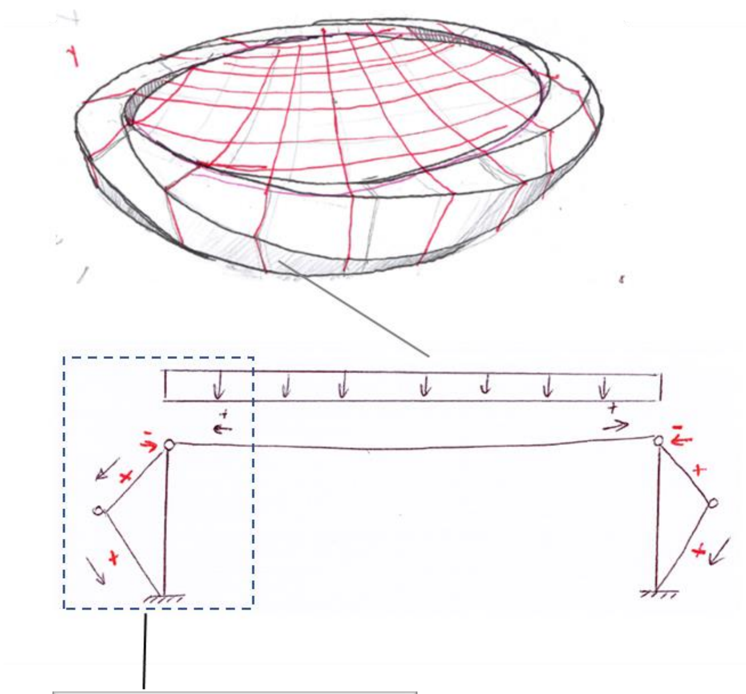


Figure 3-23 Force distribution option 1

Since the superstructure of the ice arena is out of the scope and not a lot of information is given at this moment how it will be organized, option 1 discussed above, is not considered for the further development of the concept stage, because requires a lot of investigations. Option 2 is introduced instead, using a different structural principle but considers the minimized edge support as well. It offers the design of the self-supported roof.



Option 2

The following option gives the alternative structural solution to the variant 1: truss system. Instead of using horizontal 3D trusses as a preliminary structure, roof structure is done with cable-net roof. The roof remain to be supported on the steel truss columns. Shape remain the same as in variant one and tension forces are brought to the ground with the cables. Compression ring partially take the tension forces since cables in the cable net are located every 3-4 meters (will be further discussed in more details). The rest of the tension forces from the cable-net roof are redirected to the ground. Cables leading to the ground do not allow the column structure with the compression ring to rotate inwards.

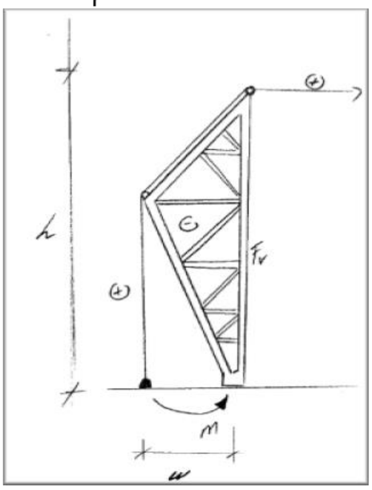


Figure 3-24 Cable-net system within the designed shape

Main Structural Elements

The primary structure of this variant consists of the following components:

- **Cable-net**
- **Compression ring**
- **Columns**
- **Guy Cables**

First two elements cable-net and compression ring are assumed to be of the same design as of London Velodrome. Below, in this chapter, more information will be given about the following elements.

Cable-Net

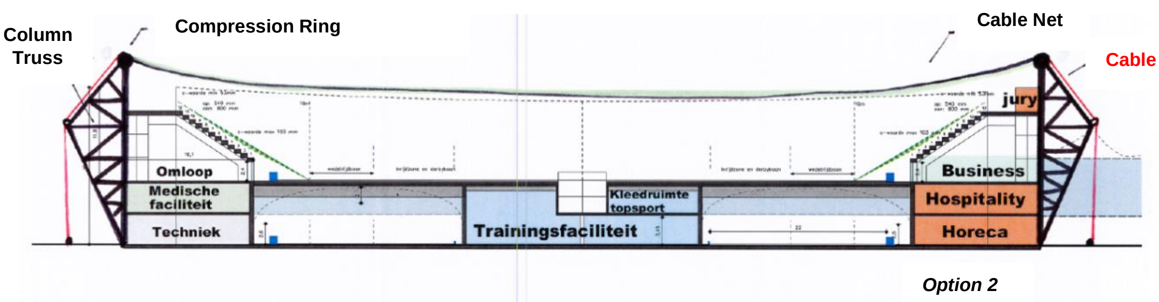


Figure 3-25 Cable-net: option 2

The primary structure of the roof consists of a doubly curved cable net covering the total area of the roof. The maximum horizontal span is about 114 m in one direction and about 225 m in another direction.

The final dip in the completed state is based on the case study sag ratio analysis and is 6.6 m between the center of the roof and the highest cable termination. The corresponding cable rise in the longer span direction is 7.85 m (see Figure 3-16).

The initial assumption is to use exactly the same cable-net system as in London Velodrome to start with something. The cable roof consists of pairs of 36mm diameter spiral strand cables, separated by 120mm. The pairs of cables are arranged at 3.6m centers in both directions. The cables have swaged end fittings and are to be fabricated to a dead length: no adjustment to cable length is possible once the cables have been fabricated. The cables have a Galfan coating, which is suitable for external environments, while the nodes are galvanized (Expedition, 2013).

Compression Ring

In London Velodrome, the ring truss consists of a pair of 457CHS chords with smaller CHS web members. The separation of the two chords varies around the structure, and is a function of the geometry of the gutter and orientation of the rib trusses and roof profile. The arrangement of the web members is governed by the need to limit secondary stresses in the chords. The width of the truss varies from 3.6m at the northern point to 2.0m at the lowest points.

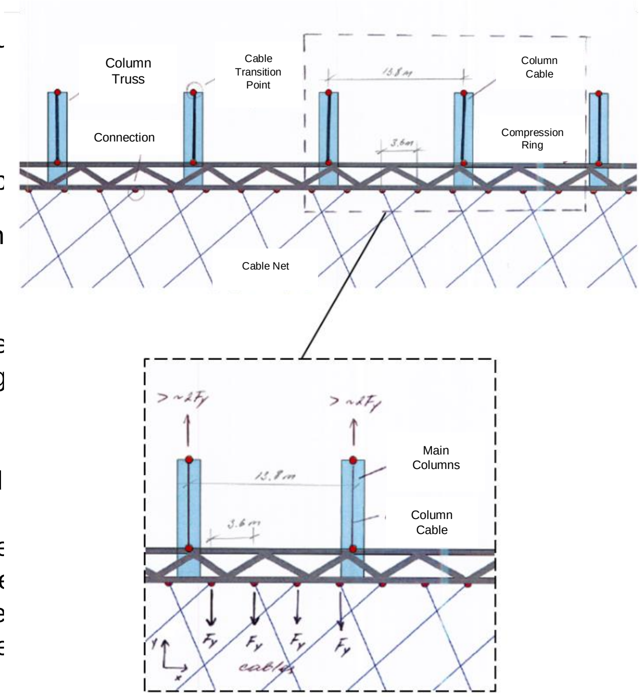


Figure 3-26 Top View: Cable-net + Compression ring + Column Truss + Guyed Truss

The roof cables are stressed against a steel ring tru
ring truss provides several structural purposes:

• Provides a reaction to the cables

• Transfers cable forces to the column and guy cab

• Provides a perimeter compression member which

• Directly supports roof cladding located above the

In Figure 3-26 the sketch shows how the compre
located at the top of the column truss (blue rectang

Truss Columns

Truss columns are similar to the columns described
form (see Figure 3-24). Columns are transfering
horizontal wind and roof loads. Since the cable-ne
the cable-net vary in height. The most minimum he
façade height of 20 m provided by the architect. The
the highest attachement point is of about 26.6 mete
the range of 20-27 meters.

Guy Cables

The cable will be attached to the outer chord of
chord each column truss until the middle interme
ground (see Figure 3-24). The idea behind using this cable is to minimize the dimensions of the compression ring and prevent all the cable-net and compression ring system from rotation inwards. The horizontal components of the cable thrusts are absorbed by the ground. The column is acting as a guyed mast and acts in axial compression

Connections

Steel nodes clamp the two pairs of cables together at every location where the cable pairs will cross. The nodes are made up of three forged elements which clamp the cables (top, middle and bottom plates) (see Figure 3-27) . The nodes are used to support the roof cladding system. Cables of the roof are attached to compression ring every 3,6 meter from the inside and each above each column from the outside in the special pinned connection (see Figure 3-28).

Figure 3-27 Nodes clamp in cable-net (Arnold et al., 2011)

Figure 3-28 Cable and compression ring connection (Arnold et al., 2011)

Compression ring is place on top of the column truss. It is connected with the fixed connection (bolted or welded). Column is fixed on the ground. And cable attached to the column is pinned at the ground.

Stability

Stability is provided by the total structure itself. Structure of the roof doesn't distribute load lineally, therefore all elements work together to provide the stability. Therefore, stiffness of the cable-net is very important. The cable-net prestress and shape of the roof has to be found in such way, that the surface remains under the tension even in the worst cases loading conditions. Cables attached to the columns are preventing the column form rotation.

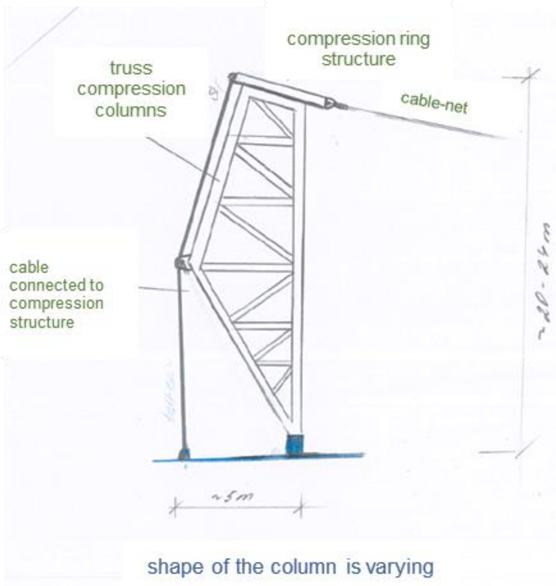


Figure 3-29 Detail Column

Force Distribution

Under the gravity loads, the main convex cable in the cable-net is stabilized by the secondary concave cable which is prestressed and pulls it down for stabilization. The prestress force on the secondary cable in the cable-net is sufficient enough so the cable-net system is always in tension. The surface form is directly related to the magnitude of the pretension. The cables of the cable-net are attached to edge member, which acts under the compression in order to support the tension forces from the cable-net. Compression ring is on the top of the compression truss column. To avoid overturning of the truss column inwards due to pulling force of the cable-net, to the outward chord of the compression ring guyed supported cables are attached (see Figure 3-24). Guyed cables are in tension, this creates a significant compression in the truss column.

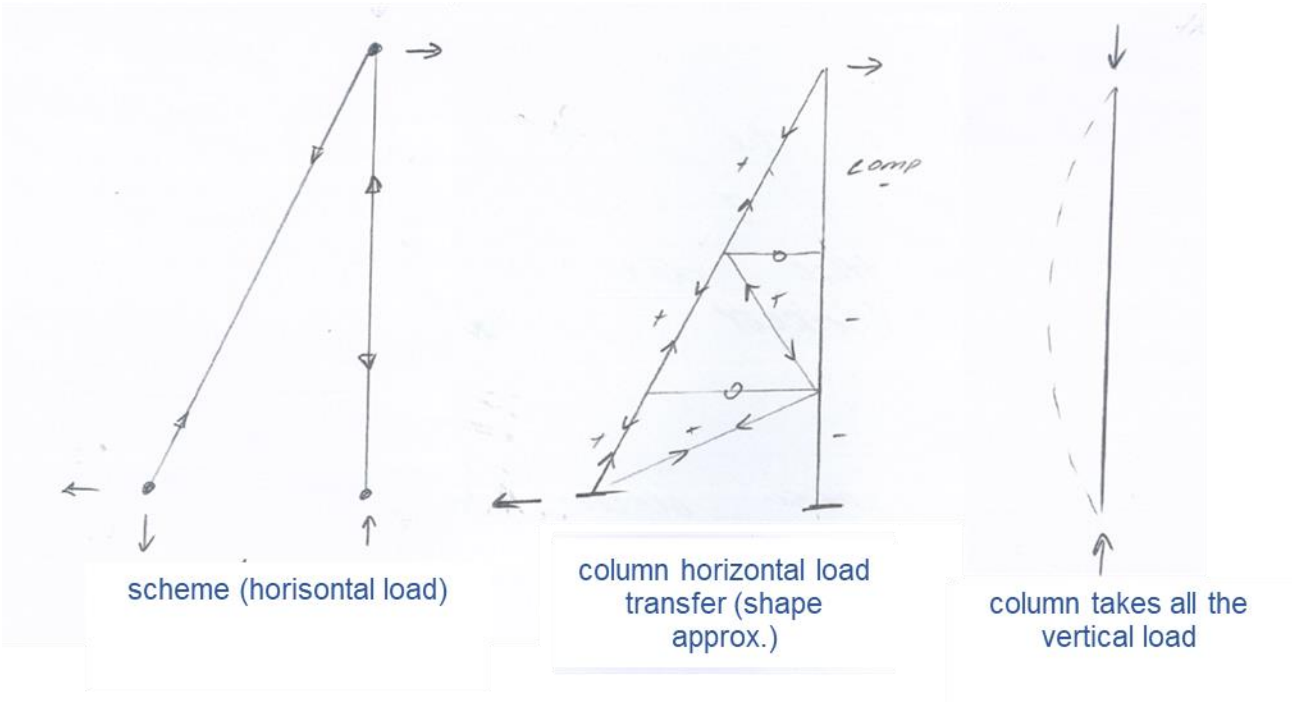


Figure 3-30 Horizontal and Vertical Forces Transfer: Cable, Columns Truss, Column (vertical chord)

Cables of the cable-net are attached to compression ring every 3.6 meters. Initial assumption for the column distance between each other is the same as in variant 1 - 13.6 meter. This means that between two columns, at least 3-4 cable-net members are attached. If each cable of the cable pair has a tension force maximum of 650 kN (Arnold et al., 2011), then for four pairs the total tension force will be 5200 kN. Each guyed cable has at least a tension of about 2600 kN.

Estimated Properties

Roof steel structure dimensions:

Primary structure arch	*30*	*m*
Secondary members (purlins)	*250*	*mm*

Roof Steel Structure Weight:

Primary structure arches	*1400*	*ton*
Secondary Members (purlins)	*950*	*kN*
Tie rods	*6600*	*kN*
Vertical tie rod supports		
Total Weight Steel Structure	**2700**	**ton**

For detailed calculations see Appendix 7: Concept Design Calculations

Advantages

- Fast construction
- Large saving in total embodied carbon dioxide than in heavy truss or arch systems
- Light self-weight
- The shape is aesthetically pleasing

Disadvantages

- High capital costs

- Preferred for the roofs without large dead load: in case of the ice arena, a lot of additional materials for environmental control will be installed.
- Vulnerable for extreme dynamic loading
- Installation pf the roof package can be problematic
- Cables are “steaking out”, the shape is not that “clear” any more

Main Difficulties

- Finding the correct form of the double-curved cable-net to insure sufficient system
- Determine such pretension which insures that the systems always works in tension
- The stability of the structure has to guaranteed if the cable-net is damaged by the external forces
- Connections design is very important in the cable-net design, have to be carefully considered.
- Tension in the guy cables will vary with angle changes which can increase tension forces significantly, this has to be optimized to a certain range of angles allowed

Parametric Design Opportunities

Aesthetics	Efficiency
Saddle shape curvature changes	Cables center-to center distances
Overall Shape Variation of the façade part	Sag ratio of the cable-net
Truss Columns Appearance	Compression ring optimization
	Columns location

Alternative 4: Arch Structure

Goal of the alternative

A correctly designed arch structure can result in a light-weight alternative, in comparison to the truss design, this will be investigated within this variant.

Shape

The shape of this alternative differs from the architect rendering shape and the mobius shape created for truss and hybrid alternatives. The roof surface is curved and arches spanning from side to side create a shape of a dome above the superstructure. The total curvature creates an approximate maximum height of the roof structure of 30 meters.

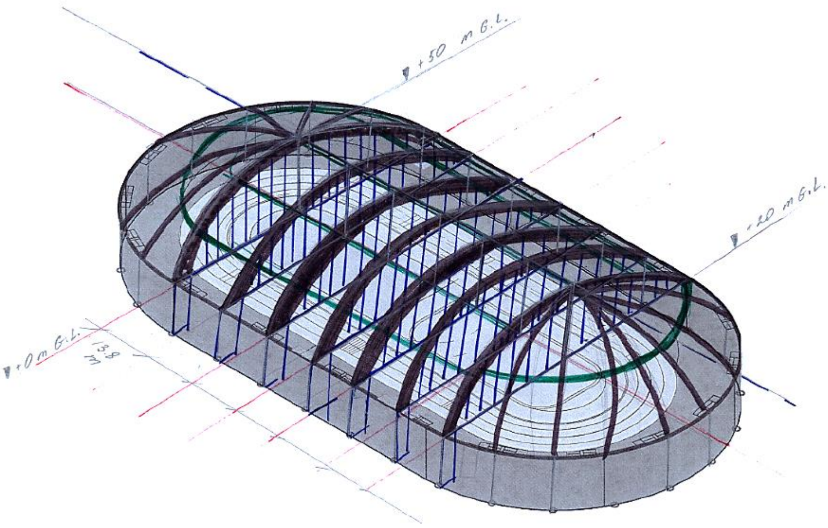


Figure 3-31 Arch System Application 3D-Sketch

Roof Structure

The roof will be built from the steel arches. Arches span from one façade side to another and are 4 meter wide on their ends. The initial distance between the arches are taken as in the alternative with truss structure (13.8 meter, which creates more or less symmetrical geometry). Later this can be reconsidered and optimized with the parametric design. To avoid huge thrust forces from the arches transferred to the columns, the tie rod will be installed which will be in tension. Also, tie rod will be used to support the ceiling frame below the roof structure. Tie rod will be supported by the vertical members to minimize the bending. For the global buckling secondary members will span between the arches.

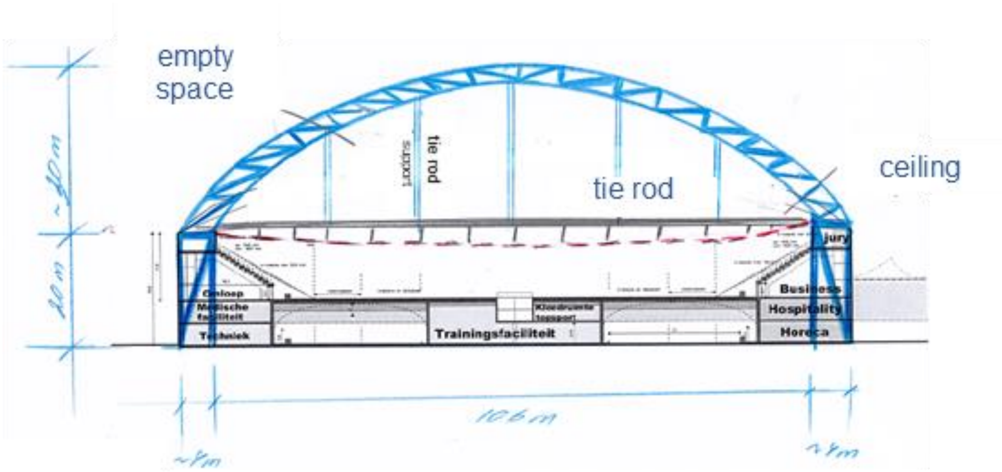


Figure 3-32 Arch System Application Cross-Section

Supporting

The steel arches can be supported by the concrete or steel columns/piers and stability will be provided by the cores of the building. The height of the arches 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 will be provided by the secondary members between the arches, cores of the building and connections between the arches and the columns.

Force Distribution

The main forces will concentrate in the stiff arches. The arches have to be correctly designed to have mainly the compression forces, this forces will be taken by the tie rod between two ends of the arch, tie rod is in tension. Columns will take the vertical loads.

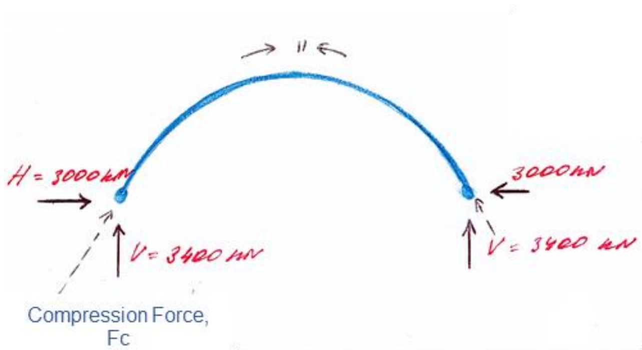


Figure 3-33 Force Distribution in the Primary Arches

Estimated Properties

<u>Roof Thickness</u>

Roof height	*~30*	*m*
Purlins	*250*	*mm*

<u>Roof Steel Structure Weight:</u>

Primary arch girders	*1400*	*ton*
Tie rods	*160*	*ton*
Vertical tie rod supports	*96*	*ton*
Purlins	*110*	*ton*
Total Weight Steel Structure	**1700**	**ton**

Advantages

- Efficient for large span
- If arch action is used correctly, a reduction of the overall structure steel weight can be realized
- Tie rod prevents horizontal forces on the columns and allows to attach the ceiling to it
- The shape of the roof is smooth and interesting variations of the overall shape can be realized, including options for the façade and cladding

Disadvantages

- Empty unused space between ceiling and cladding
- Connections are more complicated
- Installation procedure is much more complicated
- Smaller the arch height, larger the thrust forces

Main Difficulties

- The installation will require larger equipment and construction area
- Maintenance will be more complicated due to the curved shape

Parametric Design Opportunities

Aesthetics	Efficiency
Height of the arches	Columns locations
	Arch member design optimization
	Secondary members optimizations
	Circular part structural optimization

3.4.3 Future Prospects Matrix

This chapter covers the future prospects for each alternative. The following matrix was created based on the personal communication with (Graham)…

Alternative/ Criteria	Alternative 1: 3D Truss-Portal Frame	Alternative 2: Cable-Net	Alternative 3: Hybrid System	Alternative 4: Arch System
Sustainability	Solar Panels, demountable and reusable structure	Less steel, less embodied carbon emissions	Less steel is used, less embodied carbon emissions	Area below the cladding can be used for hot/cold air accumulation.
Maintainability	The roof has to be designed with about 5 degrees inclination to allow water remove from the roof surface. In this case top truss can be designed with such inclination. Gutters are located at the location of the connection between columns and truss girders. Also, the ladders have to be installed somewhere at this location to have an excess the gutters and the roof for cleaning and maintenance. The color of the coated cladding has to be preferably not solid, otherwise fading is really obvious. Columns are exposed to the outside.	Overall shape is very advantageous for water accumulation, however gutters will be located at the location of the compression ring. The excess to the roof has to be carefully considered. The cable-net is covered from both sides, cannot be inspected, therefore have to be galvanized to insure non-rusting.	Gutters will be located at the location of the compression ring. The excess to the roof has to be carefully considered. The cable-net is covered from both sides, cannot be inspected, therefore have to be galvanized to insure non-rusting. Also, the ladders have to be installed somewhere at this location to have an excess the gutters and the roof for cleaning and maintenance. The color of the coated cladding has to be preferably not solid, otherwise fading is really obvious. Columns are exposed to the outside.	However, the shape is more advantageous for water management, since the gutters are outside, so less maintenance will be required. The same as mentioned in the truss variant, the color of the coated cladding has to be preferably not solid, otherwise fading is really obvious. If non-metal cladding is chosen, than it has to have the same life-span as the total structure.
Durability	Have to be designed in such way that it remains functional during the entire life-span. Maintenance have to be carefully taken into account, especially with the water management, to avoid leaking inside of the structure.	Cladding and structure must have the same life span duration. In case of cable-net, the structure itself is very stiff, however if something really bad will happen (failure of the column or some elements of the cable-net), the total roof structure is endangered.	Cladding and structure must have the same life span duration. In case of cable-net, the structure itself is very stiff, however if something really bad will happen (failure of the column or some elements of the cable-net), the total roof structure is endangered.	Similar to the arch.

Life-Cycle Costs	Construction and demountability costs will be more or less basic in this case, than in comparison with cable-net for example. Also, the structural elements can be reused. Maintenance is a bit less complex than in arch or cable-net alternatives.	Although overall structure is much lighter than other alternatives, installation and demountability will be really expensive. Maintenance is quite complex, therefore special facilities have to be designed, thus maintenance costs can be also significant.	Similar to cable-net alternative. Truss columns and compression can be reused after demountability	Constructability and demountability will be more expensive due to larger overall dimensions of the arches Due to circular shape, special Equipment has to be designed and installed in order to be able to clean and inspect the roof, e.g. rails. Thus, maintenance considerations can be more expensive in this case.
Demountability	Reusable; bolted connections are more advantageous; shorter steel members are preferred	Cable-net is not reusable PFTE cladding is not reusable Only the compression ring is reusable. Compression ring has to be designed in smaller pieces.	Partially reusable, because of the presence of the truss columns and compression ring; bolted connections are more advantageous ; shorter steel members are preferred in the truss columns.	Reusable; bolted connections are more advantageous ; shorter steel members are preferred; slightly more complex than in the truss alternative
Constructability	Construction process is quite basic. Several cranes are required to install columns and truss girders. First, the columns are installed and connected to the anchors in the concrete blocks. To stabilize the columns temporally, the props are required in both directions. Prefabricated truss girders parts (~10 meters) are delivered by the trucks to the site and assembled with spliced bolted connection. By the cranes on the two ends the truss girder is installed and bolted to the columns to create a portal frame.	Installation is very complex and requires very special consideration. Pretension elements are generally difficult for installation. Ideally, all the elements have to be installed at the same time, than a lot of cranes and pretension devices are required. The cable-net and connection can be assembled on the floor of arena and then lifted as a total structure and pretensioned at the compression ring. Otherwise, counter moments are created if the cables are not installed simultaneously.	Several cranes are required to install columns and truss girders. First, the columns are installed and connected to the anchors in the concrete blocks. To stabilize the columns temporally, the props are required in both directions. Compression ring is installed on the top of the truss columns. The cable-net and connection can be assembled on the floor of arena and then lifted as a total structure and pretensioned at the compression ring.	Arch structure will be more complex for installation than truss. Arches will be delivered even in smaller pieces than the straight truss, because of the curvature. Larger cranes will be required for the installation. Preferably to install the arches in couples, so two arches are installed simultaneously with temporary bracing between them to avoid fall over. Due to the presence of the tie rods, only the vertical forces (and horizontal wind load) are acting on the column. Therefore, not a lot of difficulties with connecting to the columns, hinges on both sides, since tie rods prevent arch expansion.

3.5 Selection of Alternatives: Multi-Criteria Analysis

Analysis of the above described alternatives is implemented by the multi-criteria analysis. Below in this section the main outlines and results of the MCA are given. Additional overview of the MCA be found in *Appendix 8: Multi-Criteria Analysis*.

3.5.1 Criteria & Sub-Criteria

The design criteria described in 3.3.2 are split into the several sub-criteria to be able to evaluate each design criteria more thoroughly. The grade for the sub-criteria is given based on results from the alternative developments and the in-company discussion with the more experienced specialists.

Table 3-2 Design Criteria & Sub-Criteria

Aesthetics	**Functional Requirements**
Exposure of the structure	Connecting Facilities: ceiling and cladding
Attractiveness of overall shape	Climate control
Possibilities for the façade and cladding design	Usable area
Integration shape & structural system	Light restraint
Parametric design possibilities: aesthetics	
Efficiency	**Future Prospects**
Weight of the primary structural steel	Sustainability
Ceiling support	Maintainability
Cladding support	LCC (Life-Cycle Costs)
Shape/force distribution	Durability
Efficiency of the space	Demountability
Architectural Element integration	Constructability
Parametric possibilities: Efficiency Improvement	

Weight Factors

As mentioned in interview section 3.3.1, people who determine criteria in this research are: architect as a client and project manager of the engineering firm. Therefore, they have a right to distinguish the importance degree of each of the criteria. Skater and structural engineer voice is also taken into account but as of a sub-stakeholders. During MCA it was discussed and excepted to consider the following percentage of the so-called voice weight for each interviewee (see Table 3-3 below).

Table 3-3 Voice Weight

Architect	60% weight of the total voice	60%	43%	= 60% / 140%
Project Manager	40% weight of the total voice	40%	29%	= 40% / 140%
Skater/User	40% from weight of the total voice of the architect	24%	17%	= 24% / 140%
Structural Engineer	40% from weight of the total voice of the Proj. manger	16%	11%	= 16% / 140%
		140%	100%	

The overall percentages are converted to the sum of 100% for more representable numbers.

Based on the voice weight and grades from each interviewee given for design criteria, the following weight factors are applied for the MCA:

Table 3-4 Total Weight Factor

Weight/Criteria	Architecture (Aesthetics)	Functional Requirements	Efficiency	Future Prospects
	2,9	**2,6**	**1,9**	**2,6**

The total score given to each of the alternatives is multiplied by these factors. More info about this can be found in *Appendix 8: Multi-Criteria Analysis.*

Final Results MCA

The final outcome of the multi-criteria analysis is:

Truss alternative scored the maximum overall grade. In Table 3-5 below it can be seen that truss alternative has significantly different result while others have similar lower overall grades. This means that sensitivity analysis is not required in this case.

Table 3-5 Total Score MCA

MCA	Concept 1: 3D Truss	Concept 2: Cable-net	Concept 3: Hybrid	Concept 4: Arch
Total Score	**18,7**	**16.2**	**16.2**	**15.2**

3.6 MCA results discussion

The MCA results discussion is based on the main multi-criteria analysis table given in *Appendix 8: Multi-Criteria Analysis.*

Aesthetics

Truss system scored the most in this criteria, simply because of the structural exposure and overall look of the shape, Cable-net structure can give a smooth and delicate shape, however this shape is highly dependent on the tension forces in the cable-net, therefore the cable-net scores less in this case. Arch alternative is a shape solution on its own but nothing innovative in this solution: a lot of train station or large halls use arch design. Parametrically speaking truss structure gives also more possibilities to work with both: structural and shape developments.

Functional Requirements

In case of the functional requirements, the alternatives scored similar results. For example, arch and truss alternatives allow more straightforward and traditional solutions for the cladding and ceiling supports than in case of the cable-net. Moreover, cable-net sagging ratio is calculated for the specific weight, it might be very sensitive for extra loads in future. Better light restrain can be achieved in case of alternative truss and hybrid, as the light is blocked from both sides: roof and façade.

Efficiency

In terms of structural efficiency cable-net and truss systems have the same highest score. Cable-net is a light-weight solution with reduced use of steel, also the roof package thickness is significantly lower. Efficiency of the space use in case of the truss and arch systems is reduced. On the other hand, truss system integrated in the portal frame creates an isolated individual structure which is already stable by its own and relatively independent of the inner building. This is considered as one of the strongest features of this alternative.

Future Prospects

Although cable-net is a light-weight structure, with the minimized material use, prefabrication, installation, maintenance and demountability of it can be more complicated. Truss and arch alternatives, in this case, use more traditional and well-known methods. But arch transportation, installation and maintenance are still more complex in comparison with the truss system. All the alternatives have the same grade for life-cycle costs. This can be explain by the fact that some of the structures are cheaper to construct or less material is used, but maintenance costs, for example, will be very significant than of the other alternatives. This has to be, of course investigated on the detailed level.

3.7 Conclusion

Truss system within the portal frame structure integrated with the rotated shape give the most optimal solution within this research. Structural design can be considered separately of the main structure. Ceiling and cladding supports can be done in the traditional way with use of fixing frames and purlins. Pre-fabrication and installation are relatively simple and commonly-used. Prefabricated smaller pieces of the truss elements are bolted on site and demountability is, therefore, also relatively simple with the possibility of the structural reuse. Pitched shape of the roof surface allows the rain-water accumulation, however the surface of the roof can allow a convenient roof access and maintenance. Rotated shape and structural integration open interesting parametric research possibilities. Overall this alternative is considered as the one which can fulfill the main question of the current research and, therefore, is continued at the next design stage: final design in the following chapters.

4 Final Design Input

In the previous chapter, the truss system is determined by the multi-criteria analysis as the most potential structural system to continue with. The concept design of this alternative is further developed on the preliminary design stage and in this chapter the summary of the final design input is summarized. This chapter is given in full version in *Appendix 9: Design Input Final Model,* where the application of Eurocode is described in details.

4.1 Design Criteria

Starting Points

- The shape of the roof is the rotated mobius-like shape proposed in the concept study
- The design consists of parallel trusses supported by the columns in the horizontal part of the roof and radially distributed trusses in the circular parts of the roof
- The façade height is 19.9 m, the roof structure is designed above this height
- The main structural material will be S355 steel. If required, other steel types can be used

Boundary Conditions

- The structure should be suitable to be built in the area of Den Haag
- The roof structure should be designed according Eurocode (NEN-EN 1990, 2011)

4.2 Cladding, Façade & Ceiling Design Assumptions

These design assumptions are based on the consideration of the latest developments in terms of materials and design. The personal view on the design possibilities together with the structural integration and efficiency led to the following design decisions which have to be considered in the structure's loading as superimposed loads.

4.2.1 Force of Cladding and Façade

Successful cladding and façade design can be a very powerful tool to improve overall structural impression and highlight the designed shape. Design investigations are done, the main purpose of which is to get an perspective to the future design possibilities and give the client the idea proposal.

The main points of consideration were:

- Cladding and façade in shape integration
- Use of primary and secondary façade
- Exposure of structure
- Light, LED, etc.
- Perforated metal
- Glass and perforated plates for partial light restriction
- EFTE membrane façade

Several design developments are considered. Multi-layer façade with perforated thin steel plate is one of the ideas. Another idea is to make an impression of one continuous solid shape with the use of metal sandwich panels on the roof, pre-coated with the color matching the façade. Façade can be done with semi-transparent EFTE material, covering columns. This will allow a partial light block (natural shadow in the main building) and structural exposure. Below, these two design developments are briefly summarized. As mentioned, it is a proposal only and one of the ideas will be taken as a reference for the load input for the final design.

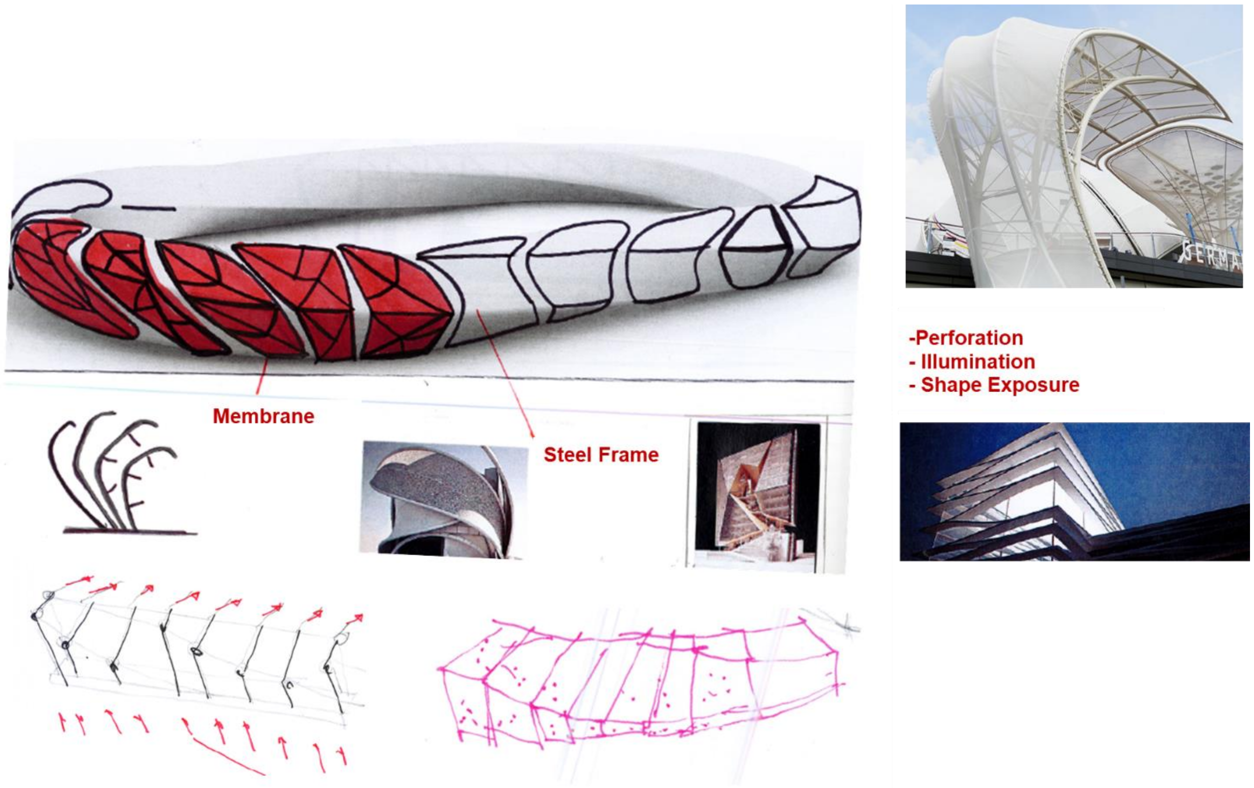


Figure 4-2 Sketch book cladding and façade design developments

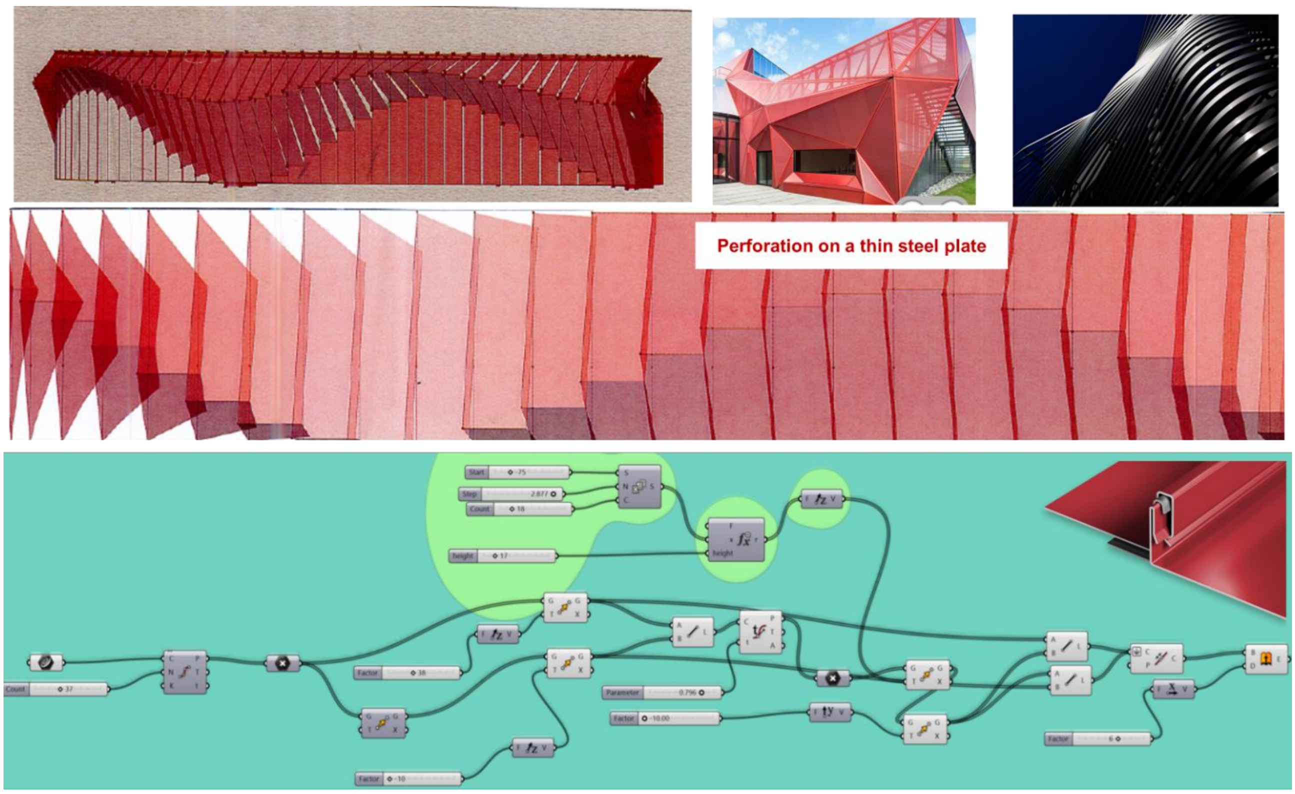
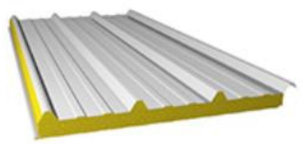


Figure 4-1 Parametric investigations on façade design possibilities

4.2.2 Thin-Plate Roof Cladding



For the roof cladding a cold-formed thin steel plate sandwich panel from ArcelorMittal is considered (PromistyFire3005T). It can be done for various insulation thicknesses and length/span of the package. Also, various coating systems can be applied which can protect the roof cladding from sun-light, corrosion, etc.

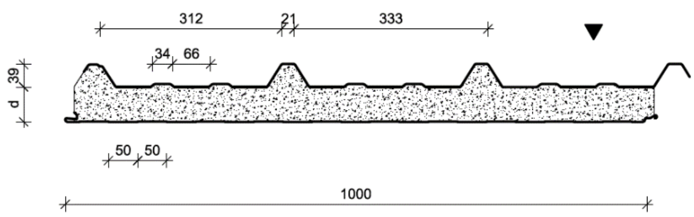


Figure 4-3 Promistyl Fire 3005T ((ArcelorMittal Construction Nederland , 2017)

The maximum span between purlins is **6.4 m**, which is determined based on the wind and snow loads calculated for the roof structure (ArcelorMittal Construction Nederland , 2017). The weight is **26.5 kg/m²**

$$Q_{cladding} = 0,4\ kN/m^2$$

(This includes also the weight approximation of the secondary purlins which are out of the structural design).

Cladding Coating

To protect the roof cladding from the environmental actions, the coating can be applied. ArcelorMittal offers sustainable solution (ECCA-Granite HDX) for this purpose which fulfills the following:

Figure 4-4 Application case of pre-coated cold-formed steel cladding (ArcelorMittal Construction Nederland , 2017)

- Good UV-resistance (beneficial to sustain environmental conditions inside the arena
- Corrosion resistance
- Provide long-term aesthetics of the cladding surface (about 5 years)
- Produced in sustainable way
- Provides resistance against weather conditions (up to 35 years)

4.2.3 Membrane Façade

A light-weight membrane façade is considered for the design. It can be nicely integrated within the shape and give an impression of a solid shape, can be also designed for special LED illumination and so on. Researching different suppliers, to find the weight of the membrane such as EFTE membrane, it was found out that the typical weight is about 400 g/m² ((Nowofol, 2019). However this weight doesn`t include the structural material needed to fix the membrane. Therefore, at this point, weight which includes both façade material and architectural steel is considered:

Figure 4-5 EFTE Facade impression (Archdaily, 2019)

$$Q_{façade} = 0,1\ kN/m^2$$

4.2.4 Bamboo Ceiling

For the ceiling design, bamboo material is considered. It is a sustainable, durable and lightweight material. At the same time it is very strong material and easy to maintain. Bamboo is high-resistant to humid conditions. Moreover, the warm color can give an overall pleasing and authentic impression of the arena interior. The weight of the bamboo ceiling is within the range of 4-**12 kg/m²** ((Derako, 2019).

Figure 4-6 Ceiling Impression: Richmond Olympic Oval (Architect, 2010)

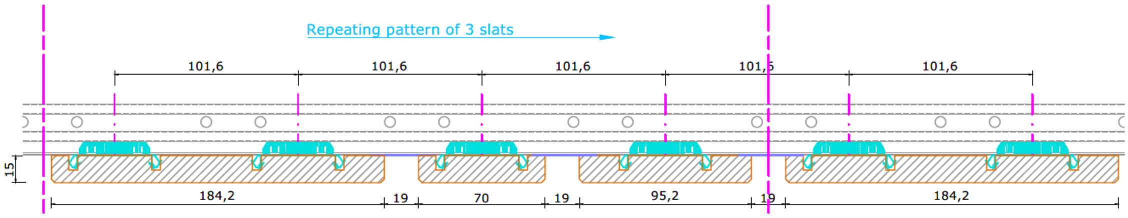


Figure 4-7 Bamboo Ceiling Cross-Section (Derako, 2019)

4.3 Load Overview

Load Cases

In this design multiple load cases will be used. A brief overview of all load cases is given in the table below.

Table 4-1 Load Cases

Load Case	Type	Description	Load [kN/m²]
1	Permanent	Self-weight steel	(is automatically determined in calculations)
2	Permanent	Superimposed loads: Cladding	0.40
3	Variable	Imposed loads	1.00
4	Variable	Vertical Wind Load	-0.86
5	Variable	Snow load	0.56
6	Permanent	Superimposed loads: Ceiling and Other Equipment	0.50
7	Permanent	Superimposed loads: Façade	0.10
8 (11)	Variable	Horizontal wind load (Zone D) (θ=0° and θ=90°)	1.14
9 (12)	Variable	Horizontal wind load (Zone E) (θ=0° and θ=90°)	-0.72
10 (13)	Variable	Horizontal wind load (Zone A) (θ=0° and θ=90°)	-1.72
14	Variable	Internal Wind Pressure (positive)	0.43
15	Variable	Internal Wind Pressure (negative)	-0.43

The description and calculation of the following cases is described in *Appendix 9: Design Input Final Model.*

Load Combinations

Based on the load cases mentioned above, the load combinations are done.

Table 4-2 Load Combinations description

Load Combination	ULS/SLS	Description
Combi1	ULS	Self-weight of steel structure and cladding
Combi 2	ULS	Imposed loads
Combi 3(4), 5(6)	ULS	Wind Load (θ=0°) and +/- internal pressure (comb. 5 and 6 are for columns)
Combi 7(8), 9(10)	ULS	Wind Load (θ=90°) and +/- internal pressure (comb. 9 and 10 are for columns)
Combi 11	ULS	Snow Load
Combi 12	SLS	Self-weight of steel structure and cladding
Combi 13	SLS	Imposed loads
Combi 14	SLS	Vertical Wind Load
Combi 15	SLS	Horizontal Wind Load
Combi 16	SLS	Snow Load

Table 4-3 Load Combination Overview

Load Combination	ULS /SLS	Combinations with partial factors	
		Roof Part	Column Part
Combi1	ULS	1.5*(LC1+ LC2 + LC6)	1.5*(LC1 + LC7)
Combi 2	ULS	1.3*(LC1+ LC2 + LC6) + 1.65* LC3	1.3*(LC1 + LC7)
Combi3(4),5(6)	ULS	0.9*(LC1+ LC2 + LC 6) + 1.65* LC4/LC14 or LC15	1.3*(LC1 + LC7) + 1.65*LC8/ LC9/ LC10/ LC14 or LC15
Combi7(8),9(10)	ULS	0.9*(LC1+ LC2 + LC6) + 1.65* LC4/ LC14 or LC15	1.3*(LC1 + LC7) + 1.65* LC10/ LC11/ LC13 /LC14 or LC15
Combi 11	ULS	1.3*(LC1+ LC2 + LC6) + 1.65*LC5	1.3*(LC1 + LC7)
Combi 12	SLS	LC1+ LC2 + LC6	LC1 + LC7
Combi 13	SLS	LC1+ LC2 + LC6+ LC3	LC1 + LC7
Combi 14	SLS	LC1+ LC2 + LC6+ LC4	LC1 + LC7+ LC8/ LC9/ LC10/ LC14 or LC15
Combi 15	SLS	LC1+ LC2 + LC6+ LC4	LC1 + LC7+ LC10/ LC11/ LC13 LC14 or LC15
Combi 16	SLS	LC1+ LC2 + LC6+ LC5	LC1 + LC7

4.4 Program of Requirements

All the requirements for the final design within this research are summarized. In this section, the requirements for the final structural design are described. The requirements are divided into three parts: architectural, functional and technical requirements.

Architectural Requirements

Nr. Demand	Name	Description	Source	Demanding Party
A.1	Façade height	Minimum façade height is 19.9 m	-	architect
A.2	Span	Minimal possible span is 103 m	-	architect
A.3	Column location	No columns in the grand stand and span area; first possible location of the column is at the top of the grand stands	-	architect
A.4	Ceiling	Roof structure should be designed with the account for the ceiling package	-	architect
A.4.1	Ceiling	Ceiling has a slight curvature with the higher points at the edges to account for warm and humid air not influence ice pad surface conditions	-	architect
A.4.2	Ceiling	Ceiling minimum height in the lowest point is 10 m from the ice surface	-	architect
A.5	Roof Cladding	Roof structure has to account for the cladding package support	-	architect
A.5.1	Roof Cladding	Cladding of the roof has to have minimum 0.5 m of insulation and reflective layer above and below insulation layer	-	architect
A.5.2	Roof Cladding material	Cladding material has to be representable and aesthetically pleasing	-	architect
A.5.3	Roof Cladding	Cladding package must block the light entering through the roof	-	architect
A.6	Roof structural material	The main structural material is steel	-	Engineering firm
A.7	Roof design	Structural system design of the roof is appealing and clearly recognizable (either by visible structure or recognizable by the shape)	-	Engineering firm

Functional requirements

Nr. Demand	Name	Description	Source	Demanding Party
F.1	Durability	The roof structure must be durable and reliable	-	Engineering firm and architect
F.2	Area	The roof structure must cover the total building area of the ice arena of 23230 m^2	-	architect
F.3	Natural Light	Light inside the arena is restricted to keep certain environmental conditions	-	architect
F.4	Climate	Roof must insure stable environmental conditions inside the arena	-	architect
F.5	Climate	Roof must protect spectators and sportsmen from the outside environmental conditions	-	architect
F.6	Cladding	The roof structure has to account for the cladding package load and be able to resist it	-	architect
F.7	Ceiling	The roof structure has to account for the ceiling package load and be able to resist it	-	architect

F.8	Rain	The roof design must be able to resist water caused by rain	-	architect
F.9	Rain water	The water caused by the rain has to be redirected from the roof surface	-	architect
F.10	Sustainability	The roof have to account for sustainability	-	Engineering firm

Technical Requirements

General

Nr. Demand	Name	Description	Source	Demanding Party
T.1	Life Span	50 years	-	Engineering firm and architect
T.2	Safety Class	CC3	NEN-EN 1993	
T.3	Stability	The roof structure must be stable in all directions	NEN-EN 1993	

Loads

T.3	Load	The roof structure must resist permanent and live loads	NEN-EN 1993	Eurocode
T.5	Permanent Loads	Dead Load: self-weight, cladding, ceiling, façade, extra equipment	NEN-EN 1993	Eurocode
T.6	Live Load: Wind Load	q_{wind}=1.43 kN/m^2 (will be applied in two directions ((θ=0° and θ=90°)	NEN-EN 1993	Eurocode
T.7	Live Load: Snow Load	q_{snow}=0.56 kN/m^2	NEN-EN 1993	Eurocode
T.8	Load Combinations	See Table 4-3	NEN-EN 1993	Eurocode

Deflections

T.9	Roof Deflection	0,46 m – vertical deflection 0,10 m – horizontal deflection	NEN-EN 1993	Eurocode

Dimensions

T.10	Height	Building height without the roof is 19.9 m, structure is located above this height	NEN-EN 1993	Project Assumption
T.11	Width/Length	Minimum width and length correspond to the layout dimensions of the arena	NEN-EN 1993	Project Assumption

These are the minimum set of criteria which the final design have to fulfill. This will be verified in the last design stage and conclusion on the final design is based on this set of criteria.

5 Final Design Methodology

In this chapter, the development methodology of the final design is described. The general principles of the structural geometry principles and the way the geometry is parametrically developed are given. Software choice and parametric modelling principle used in this research is discussed. Furthermore, the procedure for the structural optimization and verifications is stated.

5.1 General Assumptions

Shape and Dimensions

- Shape of the roof from the top goes around the perimeter of the building layout (see Figure 1-2)
- Roof is slightly pitched (around 5 degrees) for rain water accumulation
- Shape of the roof-column structure corresponds to the mobius-like shape proposed in section 3.2
- Most of the members are modeled initially as CHS (Circular Hollow Sections): aesthetics and stability reasons

Supports

- Structure is supported at the bottom of the vertical column members with hinged supports

Load Combinations

- Load combinations are used as described in section 4.3
- Imposed loads are used for estimation of purlin cross-section only (as the most conservative)

Material

- All of the members are made of S355, as the most common steel grade

Connections Assumption

- The connections between the trusses and column structure are modeled as fixed connection (two hinges on top and bottom chords)
- All connections are modeled as hinges

Maximum Deflection and Unity Check

- The maximum global vertical deflection of the structure is 460 mm
- Maximum horizontal deflection in the highest point of the column is 100 mm
- Maximum unity check for strength and stability is 1.0.

5.2 Software Used

5.2.1 Grasshopper

The program used for the parametric design is Grasshopper, which is a visual code environment based on Rhinoceros. The geometry input is determined by coordinates, vectors and lines/curves. All the geometry input is developed in Grasshopper. And the link with SCIA Engineer is done by using XML code in Grasshopper developed within Iv-Consult. There were other possibilities to export Grasshopper model, for example, using GeometryGym, however, it only works with geometry output, but XML is developed for load input as well (load panels, line loads, point loads), also, wind curve is included. Therefore XML code allows more parametric connection with SCIA Engineer. Besides that, the XML input includes nodes, supports and cross-sections by groups of elements. This means that SCIA Engineer model has all the required model input in the end, when SCIA file is generated.

5.2.2 SCIA Engineer

Verification and optimization of the structural performance of the designed roof structure is done in SCIA Engineer. All the required input is prepared within Grasshopper. When the SCIA file is generated, the verifications are done by linear analysis calculations. Linear analysis calculates the internal forces of the members and deflections for the static system. Based on that, maximum unity checks are determined and cross-section are optimized. Stability is also performed by the linear analysis. Buckling length of the individual members is considered.

5.2.3 Tekla Live-Link

Tekla live-link is used within Grasshopper to get a direct parametric connection with BIM software. Final technical drawings are obtained from Tekla, using the input cross-sections from SCIA.

5.3 Grasshopper Model

The parametric model and its description can be found in *Appendix 10: Parametric Model.*

5.3.1 Parametric Model Goal

The main goal of the parametric design within this research is to be able to fulfill two main goals: shape development and structural solution within the time-frame of the research. However, structural solution should be also close to the economical solution. Therefore, the link with parametric geometry in Grasshopper and SCIA Engineer can allow time-efficient analysis about the structural behavior for varying parameters and, therefore, more optimal structure. This means, that whenever one of the geometry parameters is adjusted in Grasshopper, the only thing has to be done is to re-run XML code and new SCIA file is generated for the new geometry. The same is applied for the Tekla Live-link which is regenerated automatically when geometry in Grasshopper model is adjusted.

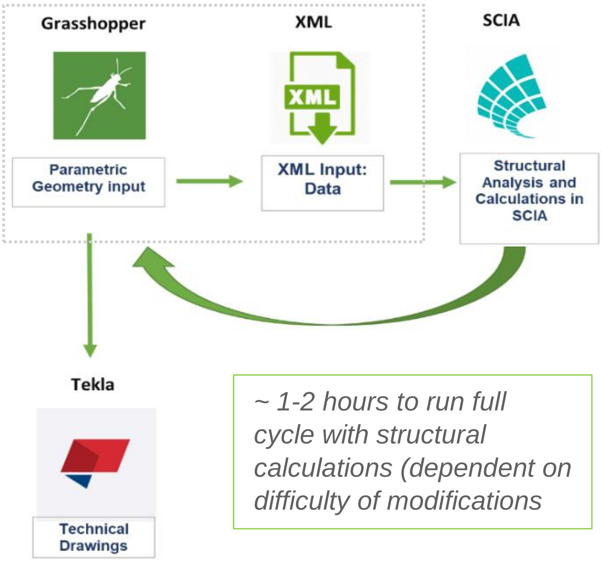
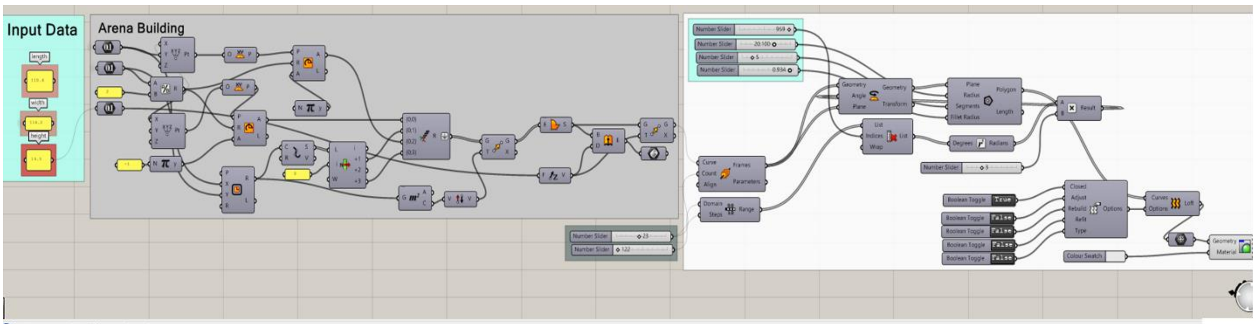


Figure 5-1 Parametric Design Methodology



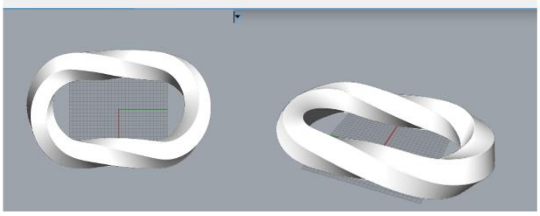


Figure 5-2 Initial geometry design investigations in Grasshopper

Characteristics of Design

The first part of the Grasshopper model includes the geometry input: shape and structure of the designed arena. All the geometry input is parametrically developed in the model. The model has its boundaries, but on the other hand have a set of parametric adjustments possibilities. These are explained further in this chapter.

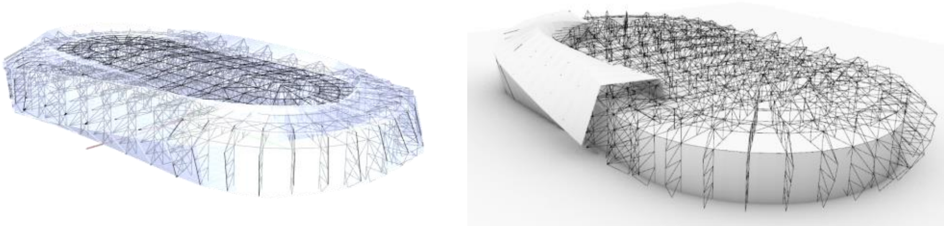


Figure 5-3 Final Design

The final variant is an extended development of the truss alternative described in section 3.4.2. However, columns design in the concept stage was not thoroughly covered, since it was not yet known how to integrate them properly within the rotated shape. This is done with the parametric modeling. In this section, the explanation of the main blocks of the model and the logic behind the geometry development is covered. In Figure 5-3 the final visual outcome of the shape and structural system combination development are represented.

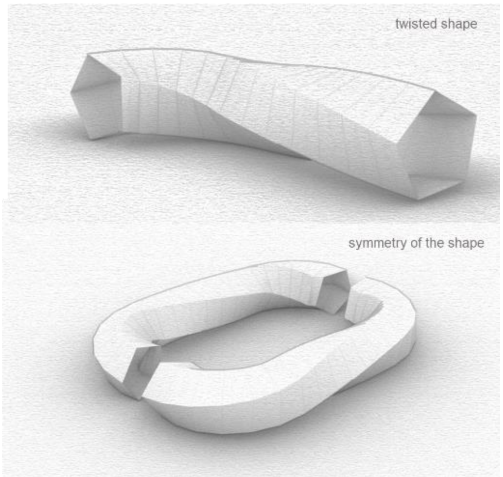


Figure 5-4 Shape Development

Shape Development

The main concept behind the rotated shape in the model is a twisted pentagon around the outline of the arena layout. A set of planes with the local coordinate systems are created at the locations of each potential column. This location is connected to the slider, thus column position can vary. At each plane, the frame with several faces is created (five faces has shown the best visual result). With the generation of the mathematical expression, each following pentagon frame with the plane is rotated by a certain ratio around its own axes. Ratio of the rotation was adjusted until the last two frames could merge and "close" the rotated shape. The ratio of the rotation also has to be proper enough to have an optically balanced rotation of the shape. In ideal mathematical situation the cross-section of this shape would give a so-called - mobius strip. However, the aim of this shape development is to get an impression of the mobius shape. Therefore, during this research it is called Mobius, not as a perfect mathematical shape but more as a visual perception of the arena geometry.

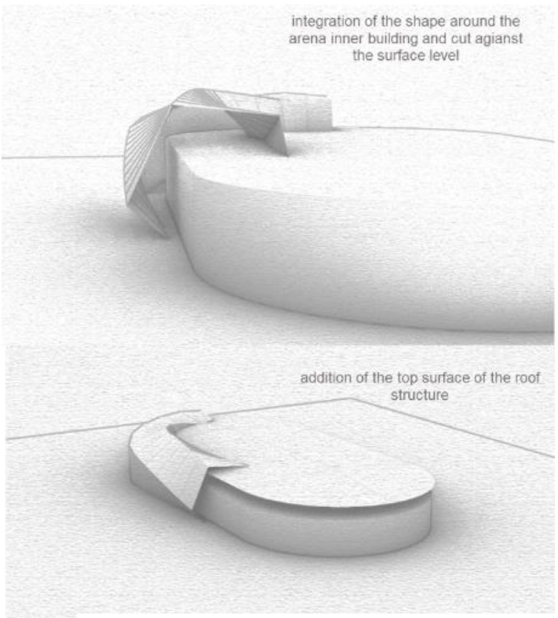


Figure 5-5 Alignment

The central structural design idea is to integrate a portal frame within this shape. When the portal frame is placed, it cuts the shape on both sides. Two columns, which are repeating the shape in the location of the cross-section, would have two different geometries. To avoid too complex structural investigations due to unpredictability of the portal frame behavior for such large span (the stiffness of the columns must be the same!), the decision is to consider initially the symmetrical situation. This is done by simply cutting the shape through the longer part and mirroring one of the sides (see Figure 5-4).

Alignment

Inner building is modeled as an extruded the layout shape of the arena with the façade height of 19,9 m. This shape is a boundary condition for the roof structure: no structure inside this shape, everything is modelled around it. This allows to provide enough space for the hanging curved ceiling below the roof structure.

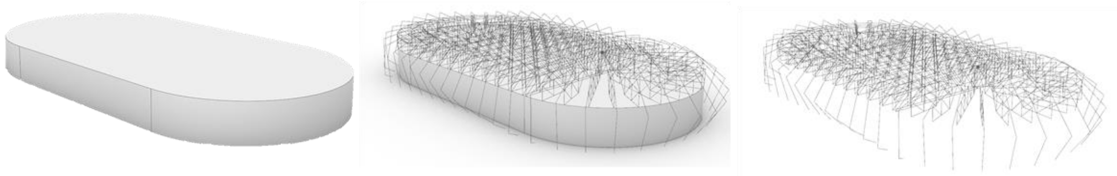


Figure 5-6 Alignment of Structure: Shape & Structure Integration

Two other boundary surfaces are created to trim the shape of the top of the roof and the ground level: pitched roof truss structure surface and surface below the arena building geometry. Pitched roof surface is connected to the sliders of the truss height, therefore, the location where the rotated shape cuts through the roof surface, varies accordingly the truss height changes.

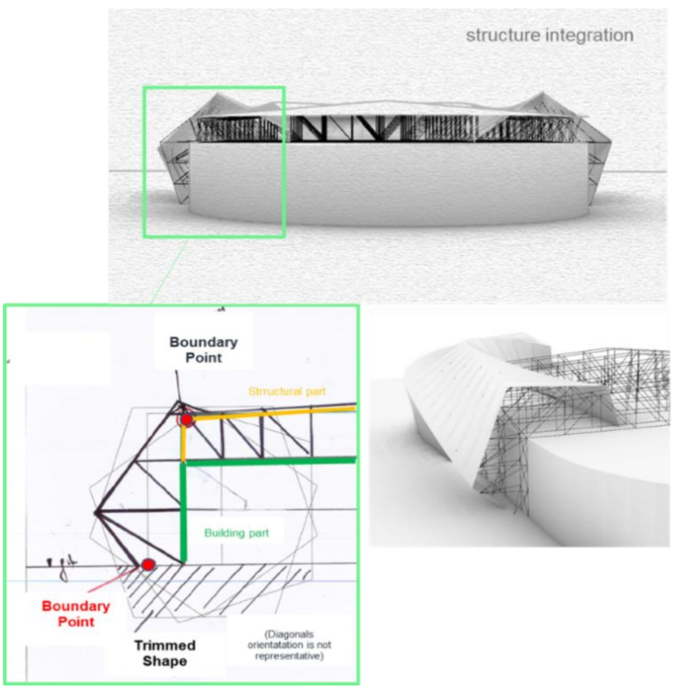


Figure 5-8 Structure Integration

As described in the previous section, the rotated shape is placed and trimmed against three shapes. However, the radius of the pentagon have to be just enough to go a little bit above the roof surface in every point of the arena. This means that radius for the truss height of maximum 7,6 m have to be up to 30 m. If the pentagon is placed against the building exactly in the middle, the column width becomes 15 m, which leads to significant material and space use. To be able to provide stability of the column, it is assumed that it has to have two connecting points on the ground for moment transfer. Thus, pentagon is increased in radius, shifted downwards and inside the building. It is represented in Figure 5-8.

Structural Design Blocks

In this part, the description of the main elements of the roof structure is given. For clear explanation of the design strategy, the roof structure is divided into three sub-groups (Figure 5-7):

- ***I. Rectangular part***
- ***II. Circular part***
- ***III. Outer Portal Frame***

+Purlins and Braces

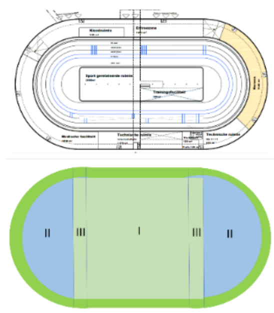


Figure 5-7 Design Blocks Scheme

Rectangular Part

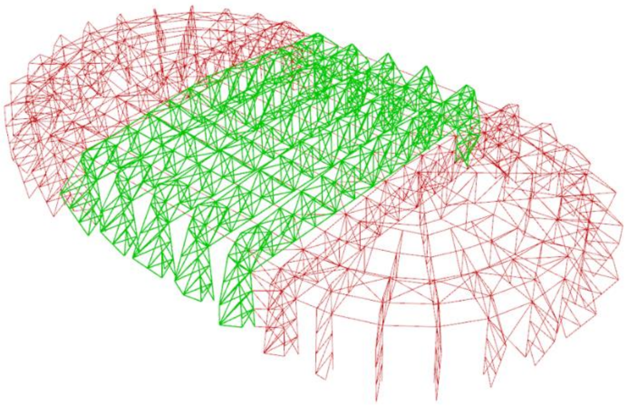


Figure 5-9 Rectangular Part Structure

- The rectangular part consists of the parallel 3D Pratt trusses with the same distance between each other.
- 3D trusses are in the moment connection with the outer columns, which will make it to work as portal frame.
- Portal frame is chosen to create an overall stability of the arena building by itself, avoiding a complex brace system in the building.
- The span of each truss is equal to the width of the arena building of 114.2 meters.
- Trusses are rectangular 3D trusses; the rectangular shape can be explained by the way the truss is attached to the column, since it is a part of the portal frame structure. Truss is connected to the column on the top and bottom chords, which means the bottom chord is not in tension only as in a case of a simply supported truss.
- Trusses are Pratt truss with the tension web members.
- The diagonal web members at the ends of the truss can work under compression due to moment connection with the column, this is taken into account in the parametric model (Figure 5-10). Diagonals can be flipped if required. Initial calculations are done with downward diagonal orientation for all of them.

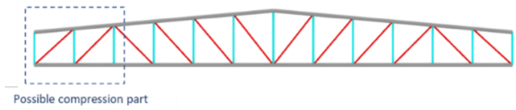


Figure 5-10 Assumed Truss Diagonal Webs

- Angle limits for the web members in the truss are 35°-55°, this is a parametric input.
- The angle of the web members will determine the location of the vertical webs, at each vertical web member the roof purlin is attached.
- The minimum distance between the purlins is 6.4 meters (see section 4.2.2), the smallest distance is determined by the minimum angle of the web members in the truss.
- Two trusses which form the 3D truss are connected between each other with the top and bottom lateral struts (yellow), sway side braces (black) and top and bottom lateral braces (dark blue) (Figure 5-11). These configuration is not parametric, taken as a boundary condition geometry. But all the angles and respectively the amount of these members have a freedom for changes.

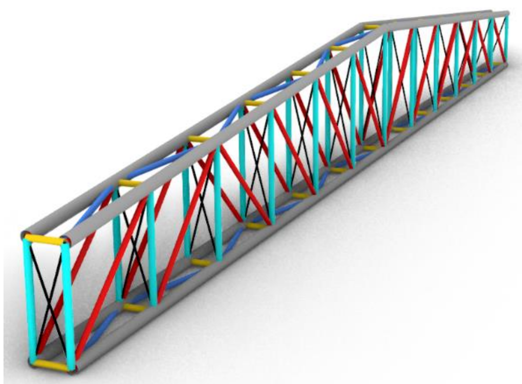


Figure 5-11 3D Truss components grouped by the colors

Column Design

Columns of the rectangular and outer portal frame blocks (see I and III in Figure 5-7) are of a 3D shape, and circular part (II) columns are 2D, however the geometry design principle in the model is used the same for both types.

Outer part of each next column is different, it means every column have to have an individual design. However, the idea is to create a similarity pattern for all of the columns. This is done by placing the vertical columns under the end points of the 3D truss. This vertical trusses are divided to several sections (adjustable) and connected by the braces for buckling restraint. At the location of the braces-

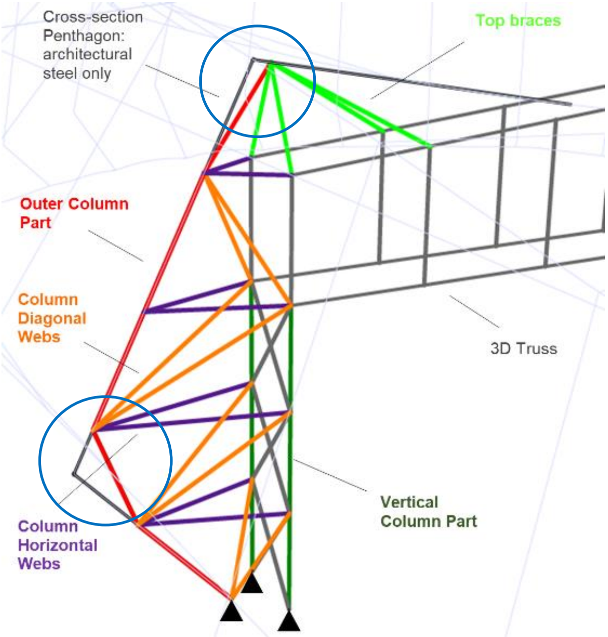


Figure 5-12 3D-Column Design Scheme

columns connections, horizontal members are projected to the cross-sectional outer shape (trimmed pentagon). Between the horizontal webs, the diagonal webs are placed. End points of the horizontal webs are connecting between each other, forming so-called outer chord of the column truss. In some cases outer chord is not merged with the cross-sectional shape, in this case the left-over part of the shape is considered as architectural steel only (see circle in Figure 5-12). Top part of the column above the truss is done in the same way for all the trusses. Braces are placed above the end points of the truss and connected to the cross-sectional shape and second raw of vertical members. The rest of the shape is also considered as an architectural steel. All diagonal webs positions and amount of the webs are parametric

Outer Portal Frame

Outer portal frame is the first and the last portal frames of the rectangular part. The main boundary conditions is that all the circular part trusses are supported by the 3D truss of this portal frame. It means that the load action on this frame will differ as on the other trusses. Circular part trusses will act as a point loads on this truss. For this reason, the outer portal frame is separated in the model. It has exactly the same geometry input as other portal frames but cross-sections are expected to be different. Moreover, if the geometry adjustments are required, the outer portal frames can be adjusted individually without the influence on the rest of the geometry.

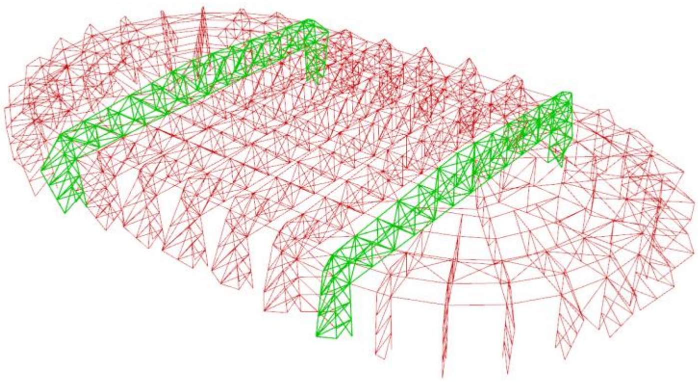


Figure 5-13 Outer Portal Frame

Circular Part

- Trusses of the circular are assumed to be 2D as they have twice shorter span and, thus, the required stiffness can be reached by the 2D truss. Also, the connection with the outer 3D truss will be more convenient.
- Trusses of the circular part are also Pratt truss, orientation of the diagonals is downward but parametrically adjustable.
- Trusses aim to the mid-point of the top outer chord of the 3D truss.
- To avoid the connection of up to 10-14 trusses in one location, which also gives a huge concentrated load, the proposed solution is to separate the circular part into the several sections and put a so-called transition girder in between the sections.
- The transition girder is attached to the large 3D Truss in the location of the vertical web members which are about 2-3 vertical webs away from the center of the truss. This location can be parametrically changed in the model.
- Shorter trusses are attached at the top chord to the transition girder with the hinge (Figure 5-16).
- Load from the shorter trusses is distributed by the transition girder to the longer truss top chord as a point load (hinge connection).
- Longer trusses are attached to the top chord of the large 3D truss with the hinges (Figure 5-15).

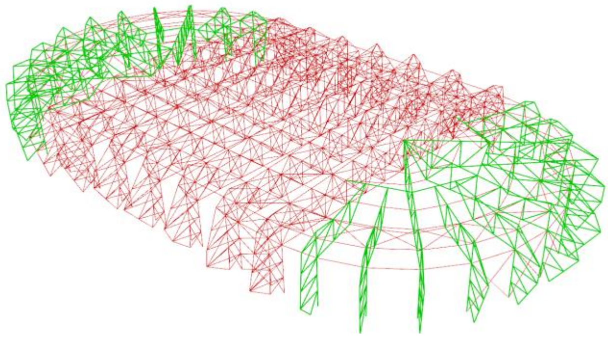


Figure 5-15 (a) Circular Part Structure

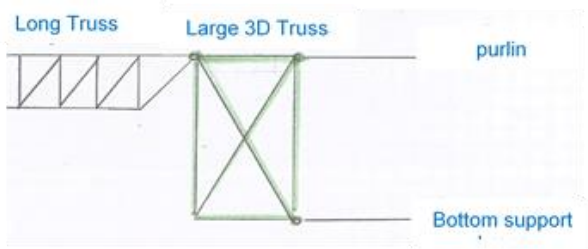


Figure 5-15 (b) Location of the attachment of the truss to the 3D truss

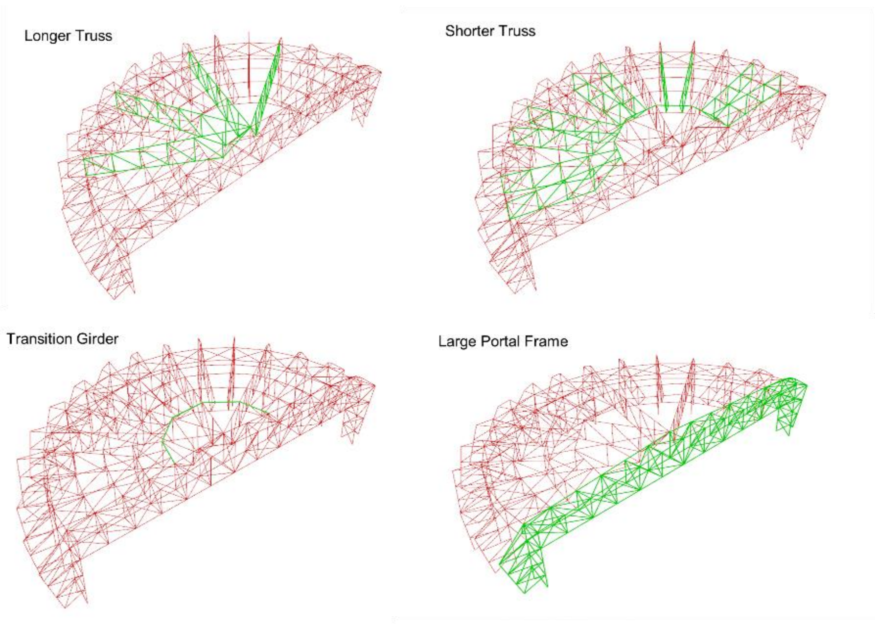


Figure 5-16 Circular Part Components

- The torsion will be introduced to the 3D truss since the large point load acts at one side, therefore it is initially assumed that the purlin and brace attached at the bottom of the vertical web member from the other side will be a torsional restrain (Figure 5-15).
- Columns of the circular part are 2D, however, the development of geometry is done in the same way as 3D-columns in the rectangular part.
- It is important to notice that columns on one side of the circular part are not the same as the columns of the opposite circular part.

Braces & Purlins

Purlins are considered as a secondary elements of the roof. One set of purlins is designed, they play a role of stabilizing members of the roof and cladding support. The maximum distance between purlins has to be 6,4 meters as mentioned above. But in the model purlins are placed at the location of each vertical web of the truss. This distance is more than 10 m. This means that for cladding support it is not sufficient. Therefore, the design included purlins are considered as primary purlins and the rest which provide sufficient cladding support are considered as secondary and added to the cladding weight load (see section 4.2). As can be seen in Figure 5-17, purlins set has a certain pattern. This allows to keep track of distances and reach the similar lengths to be able to have ideally one or two types of cross-section for all of them.

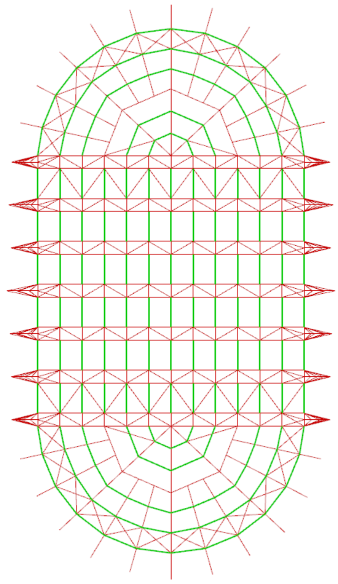


Figure 5-17 Purlins set

Braces are required for the global stability. Two sets of braces are modelled: roof braces and vertical braces. Roof braces are placed on the outer of the circular part and between outer portal frame and first portal frame of the rectangular part (see Figure 5-17 and Figure 5-18)

Vertical braces are placed between several columns in the circular part and between first two 3D columns of the rectangular part. During initial calculations in SCIA Engineer it will be checked whether the additional secondary members for stability are required. This is, therefore, further covered in section 6.1.1.

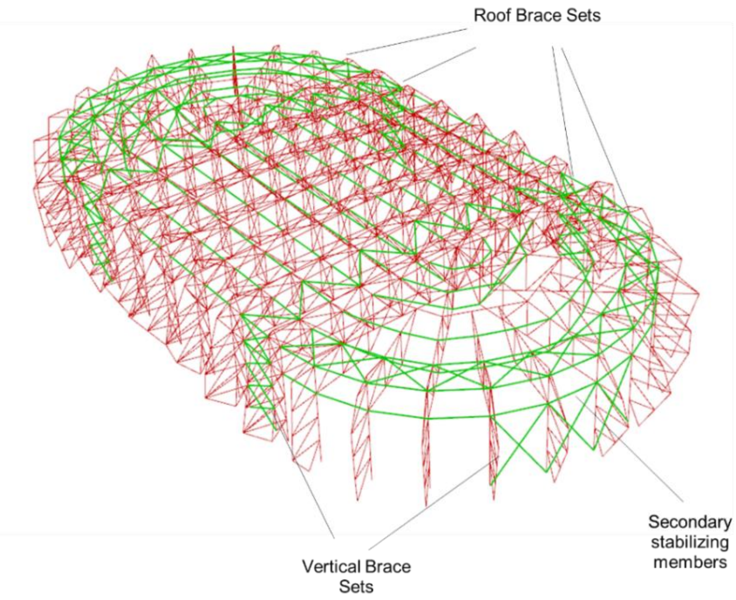


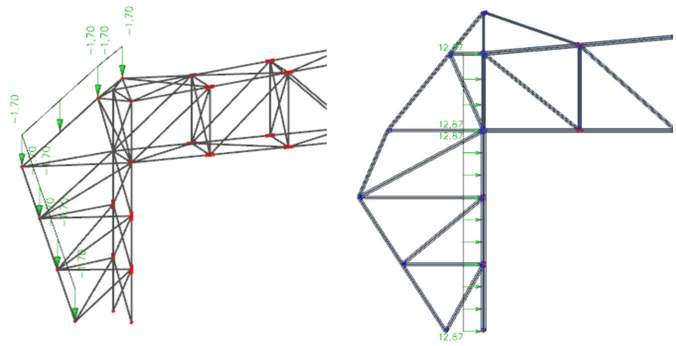
Figure 5-18 Braces &Secondary Members

5.3.2 Input to SCIA

The input to SCIA Engineer is prepared in Grasshopper and done with XML code within Grasshopper. The XML code allows to generate everything required for SCIA model: elements, cross-sections, nodes, supports and loads. Below, in this section load input and cross-section input is described in more details as several assumptions had to be done.

Loads

All the loads can be divided into: vertical and horizontal loads. Vertical loads are dead loads, wind and snow loads. Also façade load is considered as vertical loads. All the load inputs on the roof part are done using load panels (see Figure 5-21). By simply selecting particular edge points of the trusses in Grasshopper, load panels are created. This points will vary if the truss positions will change, respectively the load panel will be parametrically adjusted.



Façade Load **Horizontal Wind Load**

Figure 5-19 Line Loads Input

Façade load is applied as a line load to the outer chord of each column structure. The load is acting always in Z-direction downwards (see Figure 5-19). The horizontal wind load is applied to the vertical part of the columns and the outer edges of the trusses (see Figure 5-19). This is considered as a sufficient assumption as column structure is in a moment connection with the truss. Of course, if the project is proceeding in future, horizontal load application development has to be considered more detailly, taking into account façade friction forces as well. To account for more than two wind directions, which might effect columns in the circular part, first columns of this part (see Figure 5-21) are loaded from two directions at the same time (e.g. wind area D and A). Since all the columns will have the same cross-sections, these first columns loads will be representative. All the load input is parametric.

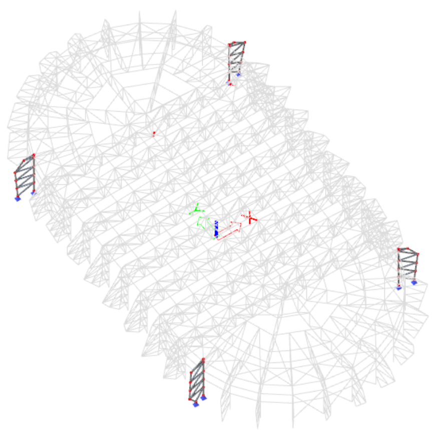


Figure 5-21 (a) Conservatively Loaded Columns

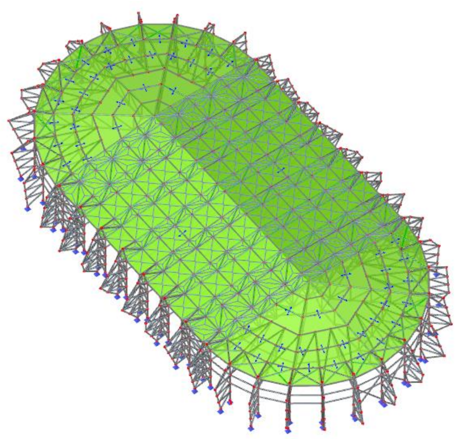


Figure 5-21 (b) Load Panels

Elements & Cross-Sections

Input for cross-sections has to be carefully done. Since the amount of cross-sections defined in Grasshopper will be later appeared in SCIA. Also, names of the members groups are not possible to create in Grasshopper. The following is done. First, all elements are grouped, so each group will get different cross-section. Overall, 39 types of groups are collected, this means 39 types of various cross-sections are defined. Thus, 39 cross-sections will appear in SCIA in the same order. Thus, it is possible to track the names and modify input in Grasshopper if later required. In Table 5-1 cross-sections are defined. The table helps to analyze final results.

Table 5-1 Cross-section groups

Rectangular Part	***3D trusses***		chords	CS1
			web and braces members	CS2,CS3
	columns		vertical column	CS7
			web and braces members	CS9,CS10
			outer chords	CS8
Outer Portal Frame	***3D trusses***		chords	CS13
			web and braces members	CS14,CS15
	columns		vertical column	CS19
			web and braces members	CS20, CS21
			outer chords	CS14
Circular Part	***2D trusses***	***long***	chords	CS27
			web members	CS28, CS29
		short	chords	CS23
			web members	CS24, CS25
	columns		vertical column	CS30
			web and braces members	CS32, CS33
			outer chords	CS31
Transition Girder				CS26
Purlins				CS38
Braces			vertical braces	CS37
			roof braces	CS35,CS39

5.3.3 Tekla Live-Link Input

Final technical drawings are done using Tekla model. In order to get a Tekla file, Grasshopper plug-in called Tekla Live-Link is used. This process is also parametric, all the geometry in Tekla model change respectively the changes in Grasshopper. However, the cross-section input is done manually, since the cross-section libraries of Grasshopper and Tekla are different. Input for Tekla is prepared in advance, but cross-section input is done when the SCIA Engineer model is calculated and verified.

5.4 Optimization

One of the aims of the parametric model in this research is a possibility to optimize a steel use. Several parameters are integrated in the model specifically for this purpose. These are distances between the columns and location of the transition girder. The model has several others, such as height and width of the trusses, but these can be chosen by common sense. The higher the truss, stiffer it is. Thus, the highest truss depth ratio is chosen (L/15=7.6 m). The width of the truss is chosen in such way that all the diagonal members and braces are around 35-55 degrees. This parameters are always in the model and if required can be changed.

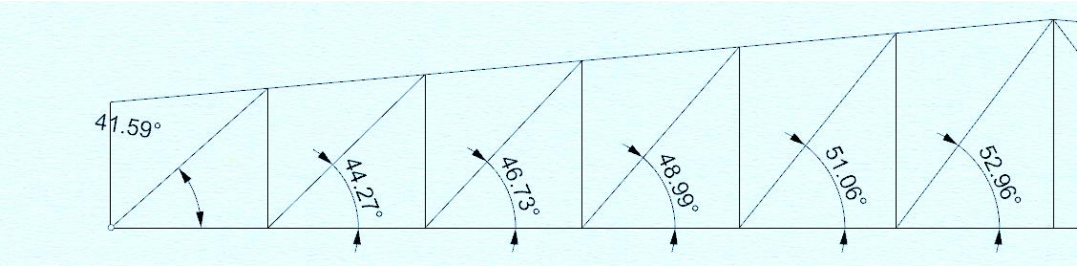


Figure 5-22 3D Truss: Diagonal members angles

Distances between the columns are done individually for circular and horizontal parts, since the division into the equal segments is only possible separately. In Table 5-2 the optimization parameter are summarized.

Table 5-2 Parameters for Optimization

Parameter	Range	Starting Value
Center-to center distance between columns: rectangular part	10 m - 18.4 m	10 m
Center-to center distance between columns: circular part	11.9 m /14.9 m	14.9 m
Transition girder location	position 1/2	position 1
Cross-sections	-	-

Non-round values of the center-to center distances can be explained as following: the length of the rectangular and circular parts outlines is divided by the number of assumed segments between the trusses this gives the exact length between the columns. In other words, the length between trusses is dependent on the natural number of trusses/columns. The same is applied in the circular part. However, circular part is more complex in geometry and the boundary assumption is done. The pattern of the trusses is the following: 2 short trusses connected to the transition girder followed by 1 long truss connected to the large truss. This pattern can be applied only with the column ctc distances of 11.9 m and 14.9 m. The largest weight is expected to be for the rectangular part, thus circular part ctc optimization is limited to these two values due to time-consumption of the optimization process. Another optimization parameter is location of the transition girder. Two possible locations are checked (see Figure 5-24).

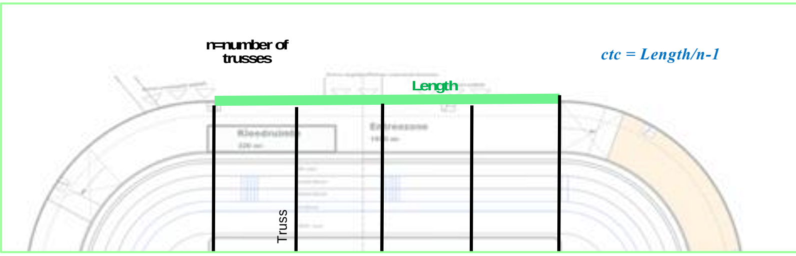


Figure 5-23 Center-to-center distance

Optimization Process

There is a high number of possible parameters combinations. Optimization is, therefore, done separately for each parameter. The optimizations are applied form biggest influence to the smallest to avoid a need of a looped optimization. First, center-to-center columns distance in the rectangular part are optimized. This parameter is the most influential (horizontal part is the expected to be the heaviest due to large span 3D trusses) and is done until the turning point of the optimization graph is obtained. This is now the input for the next optimization block. Secondly, ctc distance for the circular part are compared. Finally, the girder locations are analyzed. The starting values for the first optimization can be found in Table 5-2. The most optimal combination of parameters is then used for the final structural verifications and technical drawings.

The optimization process is done by use of auto-design function in SCIA-Engineer. This functions allows in several loops, optimize cross-sections height for the lowest steel-weight, while satisfying stability and strength unity checks. Due to stiffnesses variations, the Auto-design has to be run several times to get a stable results when cross-sections are not changed anymore. This function has to be consciously used for structural design, as several drawbacks of Auto-design is an optimization of the elements not taking into account the future change in stiffness effecting the load distribution of the other elements. However, it is considered as sufficient for the initial optimization stage, keeping in mind these features.

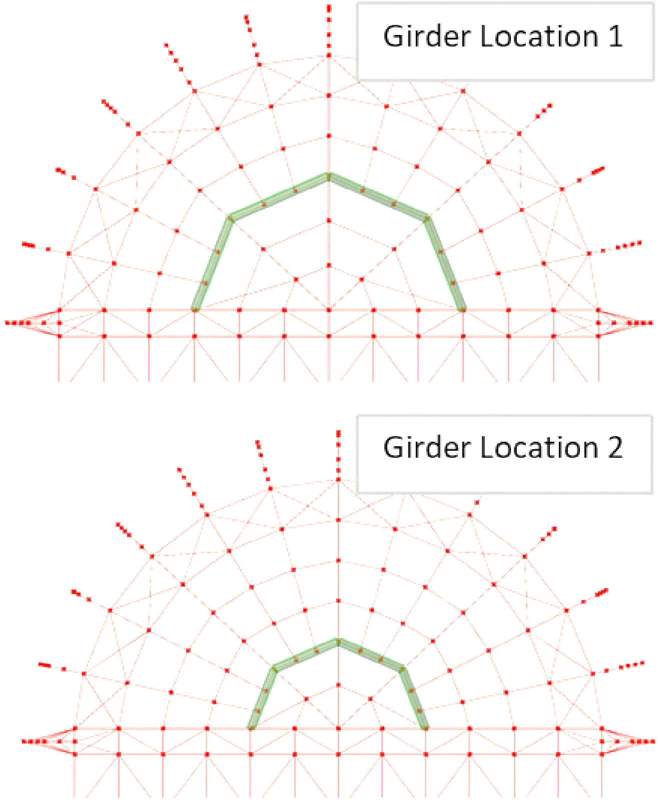


Figure 5-24 Transition girder position

5.5 Final Structural Verifications

The design with the most optimal parameters combinations has to be further verified in more thorough way. The Auto-designed sections have to be checked whether they are practical. The way Auto-design function determines the cross-sections is: it selects the diameters and thicknesses going up or down in the same type of cross-section. In other words, cross-section can be relatively small in diameter but with a high thickness. This is not optimal for connections design at the later stages. For check of the maximal deflections, the 3D global deflections are checked for the vertical and horizontal deflections. Unity checks are verified for the strength and stability.

6 Results and Discussion

In this chapter the results of the optimization and structural verifications are stated and interpretation of the results is discussed. The most important aspect on this final stage is to able to explain results of the calculations in a logical way to prevent wrong conclusions. This task is challenging due to amount of data, both: geometric and structural. Small uncertainly or mistake, such as incorrectly placed loads or hinges might cause a significant effect on the quality of results or unexpected structural behavior. This has to be carefully and critically analyzed and verified. SCIA Engineer report with structural calculation results of the final model can be found in *Appendix 11: SCIA Report.*

6.1 Initial Model Verification

6.1.1 Input Validation

When the first SCIA file is generated from Grasshopper, it is verified, whether the input (loads, hinges, amount of cross-sections, presence of all members) appears as it is designed to be. Several runs were done to eliminate several errors. After this is done, data export from Grasshopper works automatically good.

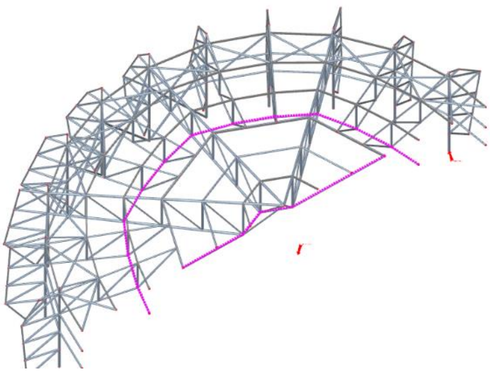


Figure 6-2 Secondary Stabilizing Members

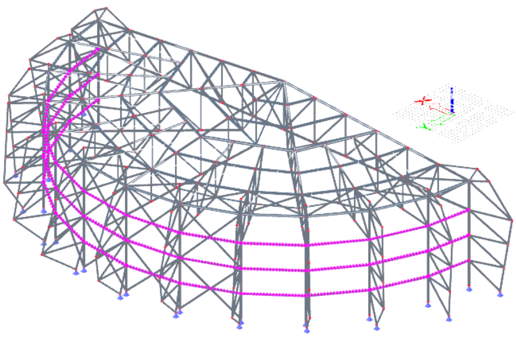


Figure 6-1 Secondary Stabilizing Members

The next step is to verify the global behavior of the structure. During check of global deformation, strange deformations were found in the circular part: trusses tended to deform upwards and sideward around their own axis. This is explained by the absence of the supports at the lower chords end (only top chords are hinged to the transition girder and 3D-truss). This problem is solved by simply adding extra secondary stabilizing members (see Figure 6-2). In circular part columns excessive sideward deformations were found. To prevent buckling events, extra members were also added (see Figure 6-1).

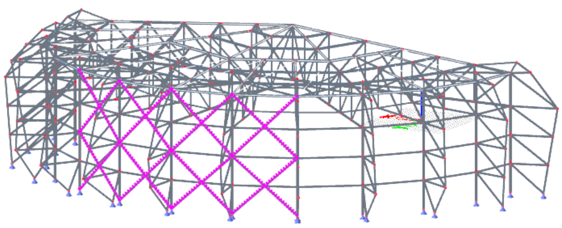


Figure 6-3 Adjusted vertical brace system

Vertical brace system in the circular part (see Figure 5-18 in Section 0), has appeared insufficient and is adjusted to more efficient solution, with better diagonal angles and support from the top chords of the truss to the bottom of the chord (see Figure 6-3). This allowed to prevent sideward deformations of the columns and extremely large cross-sections of the braces and columns.

Another addition to the stability braces is done. Portal frames in the horizontal part are initially considered as a solution for the horizontal movements of the structure. However, when the portal frames are connected between each other with the purlins only, the horizontal part doesn't behave as one structure. In this case portal frames might have a tendency to move one by one, which will cause uneven deformations. To prevent this behavior, additional brace system is added to the roof between the portal frames (see Figure 6-4).

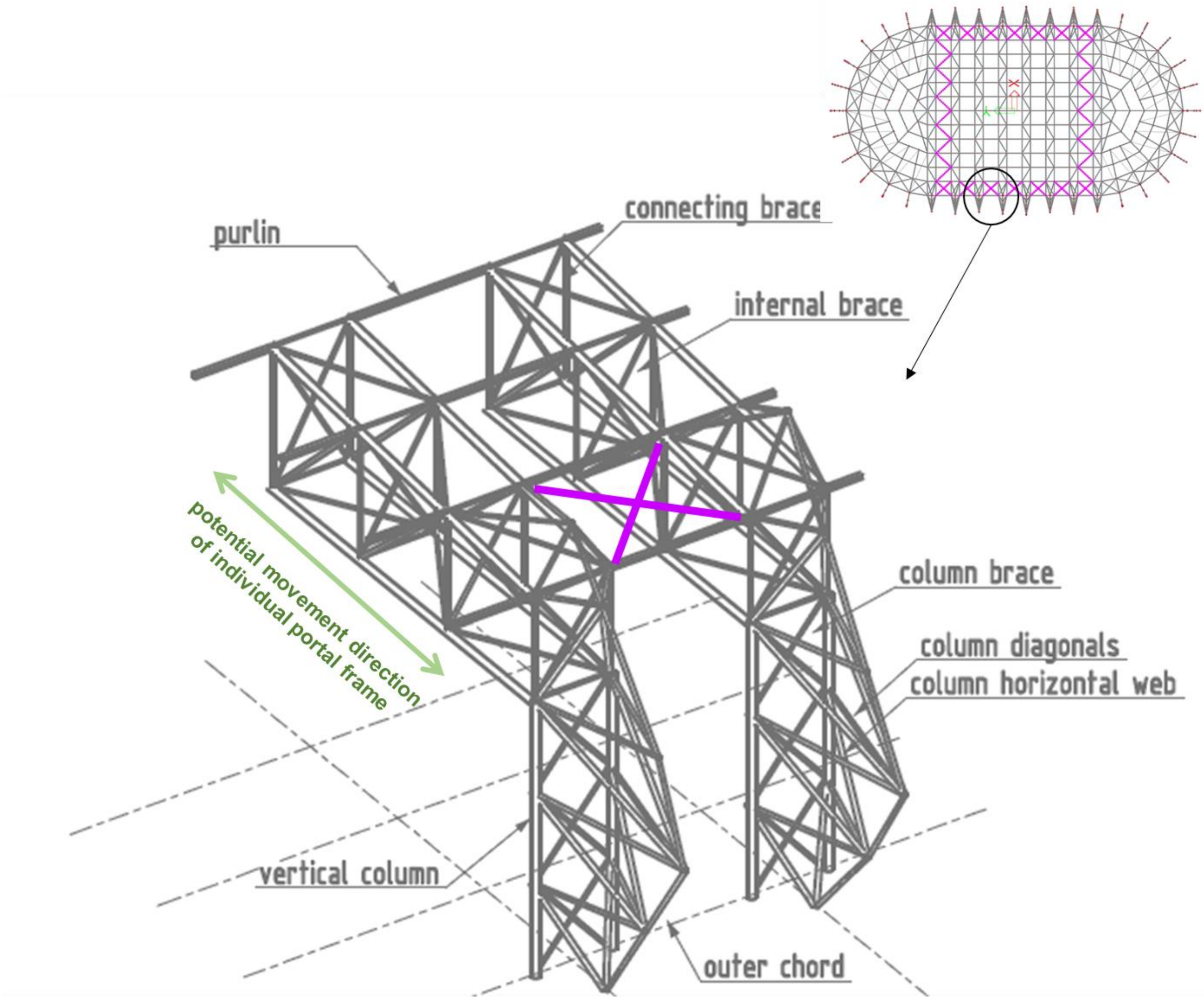


Figure 6-4 Portal Frames Connecting Braces

6.2 Geometry and Material Use Optimization

Once the global structural behavior is checked and geometry adjustments/additions are done, an optimization of the overall structure is done. In this section, the results of three steps of optimization is given and explained.

6.2.1 Center-to-center Columns Rectangular Part

The first phase of the optimization process is to optimize a center-to-center (ctc) distance of the portal frames in the rectangular part (incl. outer portal frame). The starting value is 10 meters (the other numbers are not round due to exact division of the side to the equal length segments, see section 5.4). In this case the amount of portal frames is 12. The amount of portal frames will decrease, with the minimum of 7 portal frames with the ctc distance of 18,4 m.

In Figure 6-5, the trendline indicates that the most optimal ctc distance is 15,8 m. In this case the amount of portal frames is 8.

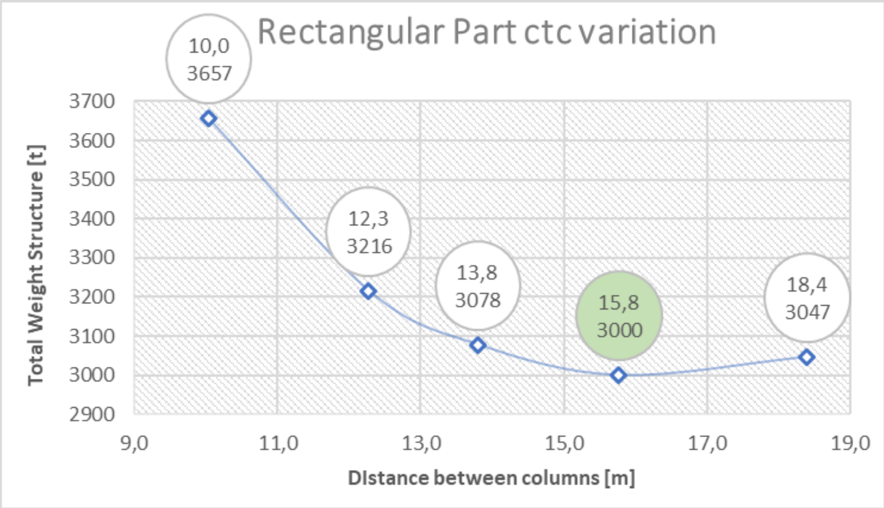


Figure 6-5 Optimization step 1

This result can be explained in the following way: every time the ctc distance changes, the amount of portal frames decreases, respectively the total weight decreases. But at a certain turning point, the number of portal frames is not decisive anymore. The cross-sections have to be stiff enough to withstand loads form the large ctc distance. Chords, columns and, especially purlins getting much larger in size to fulfill the required stiffness. Thus, c.t.c. distance of 15.8 m gives more optimal result in terms of required stiffness and amount of trusses. This option is now the input for the next optimization steps.

6.2.2 Center-to-center Columns Circular Part

In case of the second phase optimization, the aim is not to find the turning point anymore but to compare the first result where ctc 14,9 m in the circular part is used, with the other option: 11,9 m. In Figure 6-6 can be seen, center-to-center distance of 14,9 m in circular part more preferable.

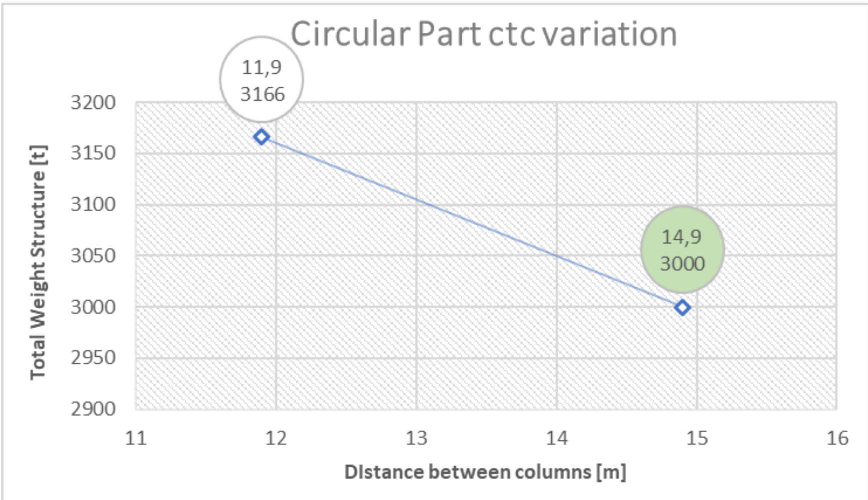


Figure 6-6 Optimization step 2

The explanation for that is the amount of elements for the smaller ctc is significantly larger: one more long truss and two extra shorter trusses and respectively columns (see Figure 6-7). In this case, it is more preferable to increase cross-section sizes than amount of elements. There is a very important advantage of this result. Center-to-center distances are now similar for rectangular and circular parts, which can be beneficial for visual structural perception. The optimization results from the first two phased is now the input for the final optimization check.

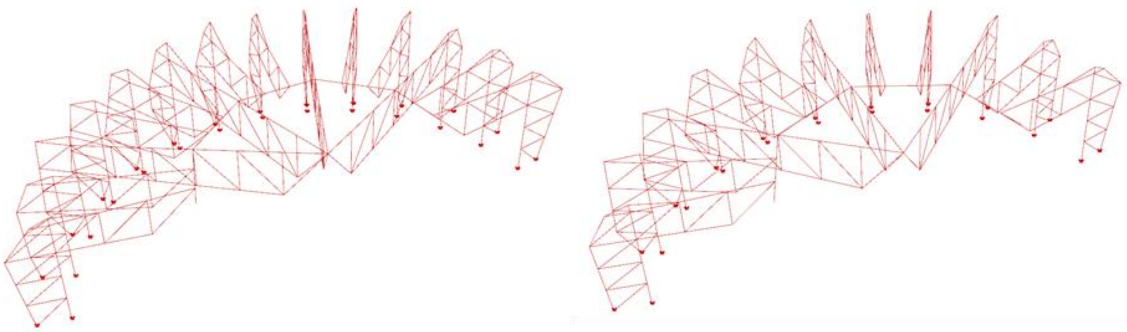


Figure 6-7 Center-to-Center Distance: Circular Part Comparison

6.2.3 Transition Girder Location

The third optimization phase is a comparison of transition girder locations. Indications of the girder positions can be found in the chapter above in Figure 5-24. When girder is placed in the location 1, the weight is less. This result was expected. There is two reasons for larger weight. First, the load from the circular part is more concentrated in the middle of the outer portal frame truss (for position 2). This gives larger middle moment in the 3D truss, which requires larger cross-sections to satisfy the stiffness. Secondly, the shorter trusses are longer for the second position.

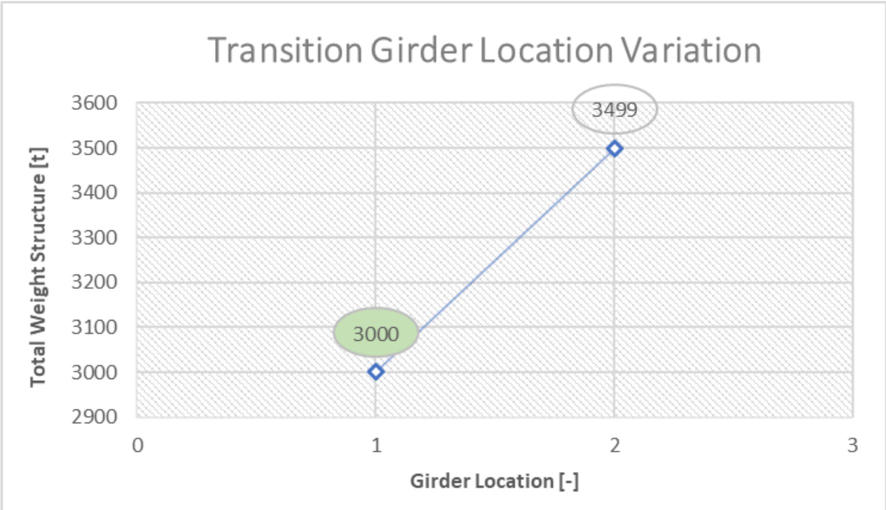


Figure 6-9 Optimization step 3

6.2.4 Optimization Summary

The summary of the optimization results is sh the portal frames is 15.8 m (8 portal frames) girder is located further form the geometrica optimized geometry is now used for more preliminary design technical drawings.

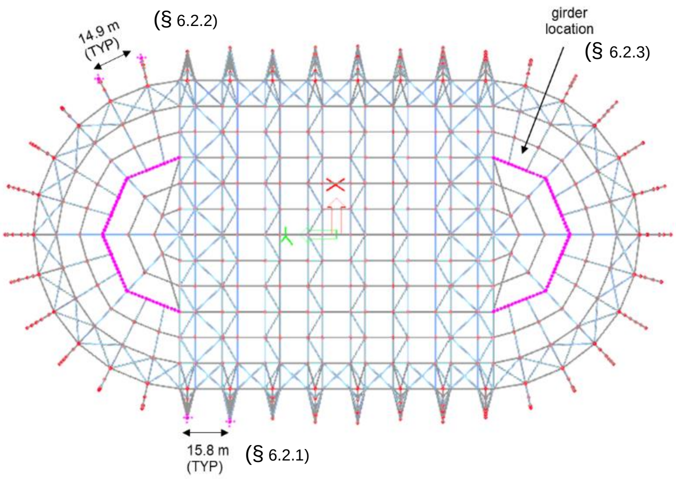


Figure 6-8 Optimization Summary

6.3 Structural Checks

In this section, the final optimized design is checked for the Eurocode requirements summarized in Section 4.4.

6.3.1 ULS Check

Summary of the unity checks with the corresponding decisive load case for the member groups is given in Table 6-1 below. The structural changes of the members dimensions within SCIA Engineer were done until all 39 cross-section groups had an overall unity check below 1.0. Overall unity check in SCIA Engineer corresponds to the strength and stability, the highest of two is taken as an overall. Member stability check is done automatically by SICA according the Eurocode, however, have to be critically analyzed and checked whether the program considers the correct buckling lengths, otherwise setup has to be adjusted. Full unity check table can be found in *Appendix 11: SCIA Report*.

Table 6-1 Unity Checks

Part	Cross-section location			Cross-Section Identification in SCIA Report	Max. $UC_{overall}$	Decisive Load Case
Rectangular Part	*3D trusses*		chords	CS1	0.84	ULS11 (Snow)
			web and braces members	CS2,CS3	0.91	ULS1,ULS7 (Wind)
	columns		vertical column	CS7	0.94	ULS1 (DL)
			web and braces members	CS9,CS10	0.96	ULS1 (DL)
			outer chords	CS8	0.84	ULS7 (Wind)
Outer Portal Frame	*3D trusses*		chords	CS13	0.76	ULS1 (DL)
			web and braces members	CS14,CS15	0.86	ULS1 (DL), ULS7 (Wind)
	columns		vertical column	CS19	0.91	ULS6 (Wind)
			web and braces members	CS20, CS21	0.85	ULS1 (DL), ULS6 (Wind)
			outer chords	CS14	0.84	ULS7 (Wind)
Circular Part	*2D trusses*	*long*	chords	CS27	0.99	ULS1 (DL)
			web members	CS28, CS29	0.92	ULS1,ULS7 (Wind)
		short	chords	CS23	0.86	ULS1 (DL)
			web members	CS24, CS25	0.82	ULS1,ULS7 (Wind)
	columns		vertical column	CS30	0.85	ULS4 (Wind)
			web and braces members	CS32, CS33	0.95	ULS1 (DL)
			outer chords	CS31	0.88	ULS1 (DL)
Transition Girder				CS26	0.51	ULS1 (DL)
Purlins				CS38	0.80	ULS11 (Snow)
Braces			vertical braces	CS37	0.65	ULS4 (Wind)
			roof braces	CS35,CS39	0.86	ULS11 (Snow)

Purlin Verification for Imposed Load (Maintenance)

Imposed maintenance loads are not considered for the global calculation, as it would be too conservative to apply it to the overall roof structure. However, it is checked whether the design cross-sections for the primary purlins are sufficient enough during maintenance. The purlin with the largest unity check is chosen and maintenance load is applied. The unity check for this purlin during imposed load is now exactly 1.0. The conclusion is that the cross-section is sufficient during imposed load combination (Combi 2 in Table 4-3, see Section 4.3). At this design stage it is considered as a sufficient check, however, more thorough analysis of the locally applied loads have to be done if the design proceed to the further stage.

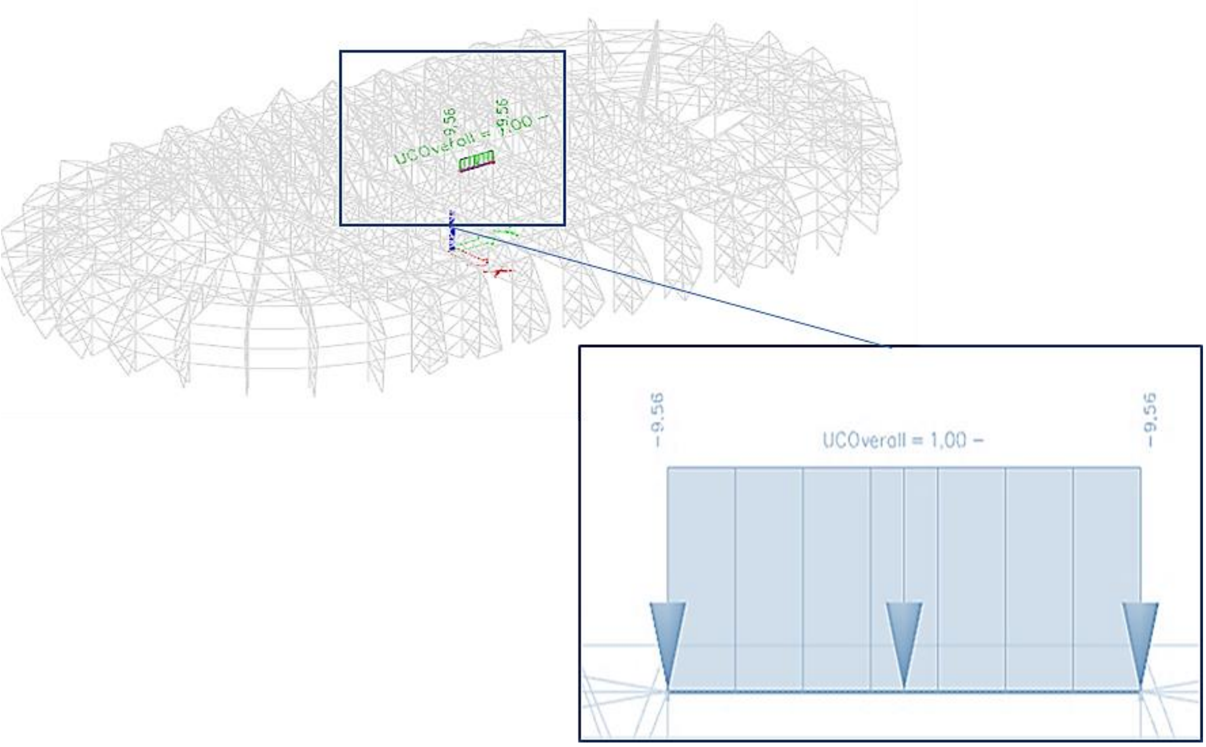


Figure 6-10 Locally Applied Imposed Load

Main Cross-Sections

The dimensions of the members have to be sufficient enough for the strength and stability unity checks, but also logical in terms of sizes and practical to use. It is a very complex process especially for the large structure as this where members are really sensitive for the changes of stiffness of the other members. In Table 6-2 the most important groups of cross-sections are shown. So far, these dimensions give a stable situation where unity checks, stiffness and overall weight are in balance.

Table 6-2 Cross-sections

Part	Cross-section location			Cross-Section Identification in SCIA Report	Cross-Section	Total Mass [mT]
Rectangular Part	*3D trusses*		chords	CS1	CHS406.4/16.0	423
	columns		vertical column	CS7	CHS508.0/8.0	65
Outer Portal Frame	*3D trusses*		chords	CS13	CHS457.0/8.0	81
	columns		vertical column	CS19	CHS508.0/8.0	22
Circular Part	*2D trusses*	*long*	chords	CS27	CHS406.4/16.0	93
		short	chords	CS23	CHS323.9/10.0	59
	columns		vertical column	CS30	CHS457.0/12.5	83
Transition Girder				CS26	HEA500	27
Purlins				CS38	RHS400/300/10.0	259
Braces			vertical braces	CS37	CHS355.6/12.5	1121
			roof braces	CS35,CS39	CHS406.4/16.0 CHS323.9/8.0	154
Total mass of the structure is given in Section 6.3.3						

Outer Portal Frame and Transition Girder Verification

Analyzing the results for dimensions, the following is noticed: outer portal frame does not have larger cross-sectional dimensions than the portal frames of the horizontal part. This can be seen comparing top chords (CS1, A= 196 cm^2 >CS13, A= 140 cm^2) and columns (CS7 = CS19). However, some of the secondary members, such as webs of the trusses are larger for the outer portal frame. The conclusion is the following, transition girder does not take as much vertical load as it was initially expected and thus doesn't transfer that large load it to the outer portal frame. Taking a closer look to the structure in the circular part, the following is noticed: column structure and truss are in the moment connection and, therefore, especially in case of the short truss, the massive and wide column part takes significant part of the load (up to ~90% in some parts), due to counter moment and overall column stiffness. However, since the circular part is connected to the outer portal frame, horizontal loads (due to wind) are transferred through the outer portal frame and roof brace system to the foundation in the horizontal part, therefore web members of the outer portal frame are larger than of the rest of the portal frames.

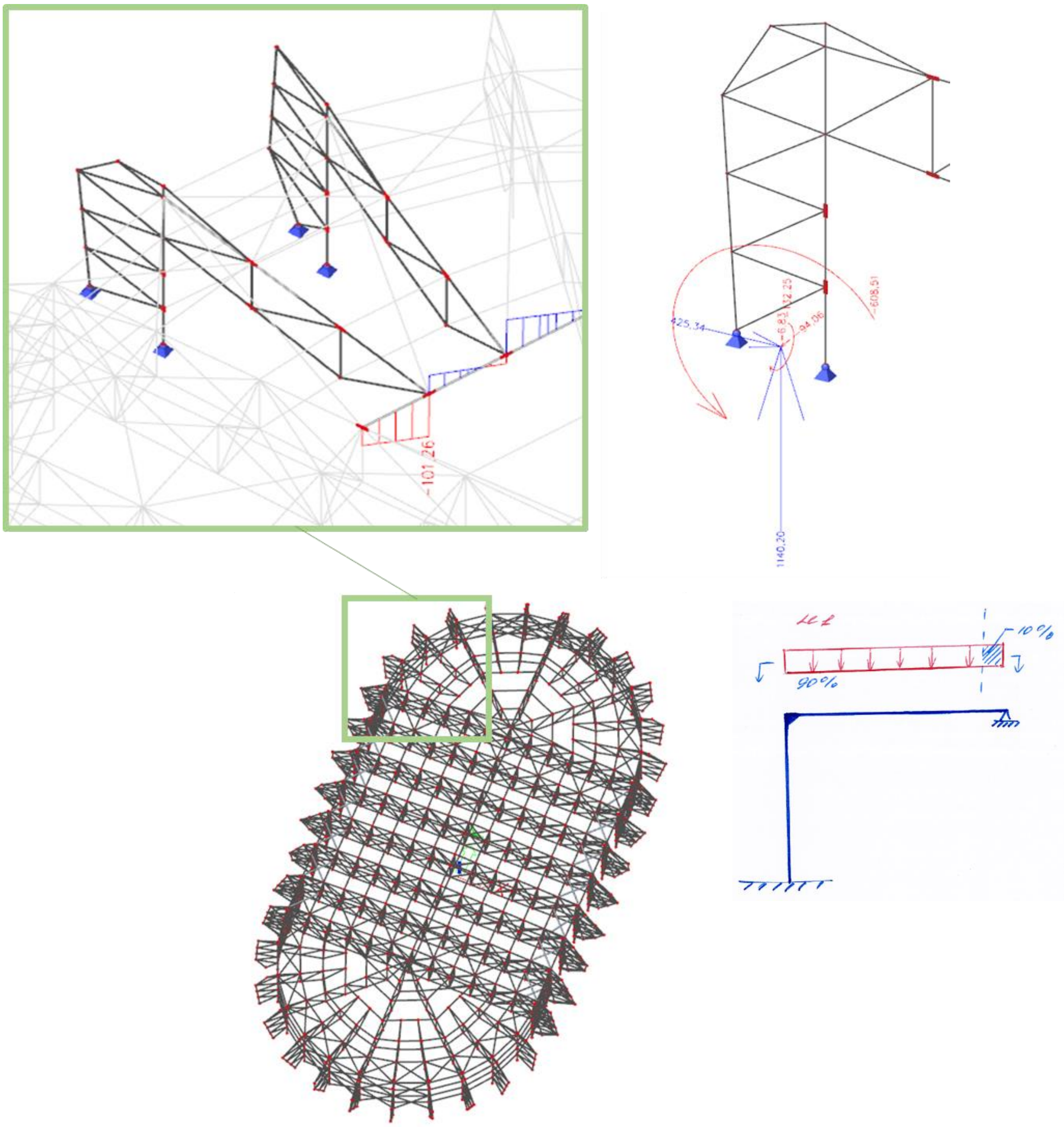


Figure 6-11 Transition Girder Verification

6.3.2 SLS Check: Deflection

Strength and stability are checked and show sufficient result according Eurocode. The next step is to verify whether the structure is stiff enough. To verify this, the 3D displacement of the overall structure is checked in z, x, and y directions during all SLS loads.

Vertical Deflection

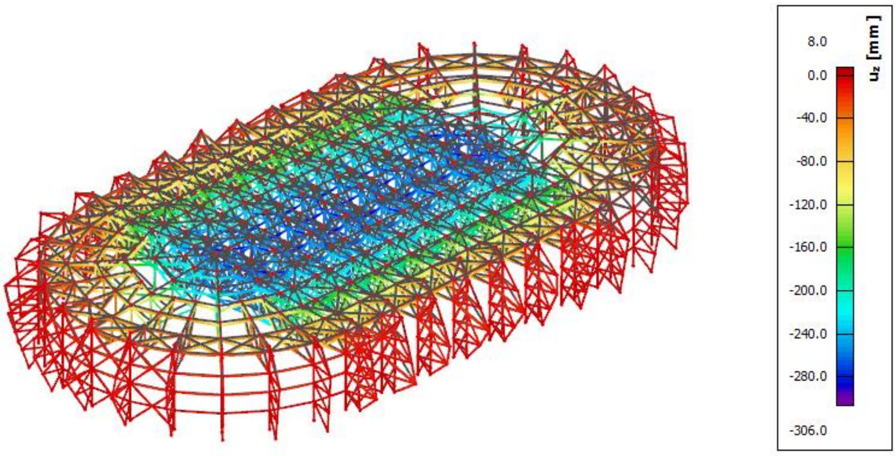


Figure 6-12 Global deflection (z-direction)

Overall vertical deflection for the truss span of 114m cannot be more than 460 mm. Total deflection of the structure is not more 306 mm in this case (Figure 6-12), which is sufficient. The maximum deflection of the individual portal frames is than checked for all SLS combinations and dead weight only (Figure 6-13).

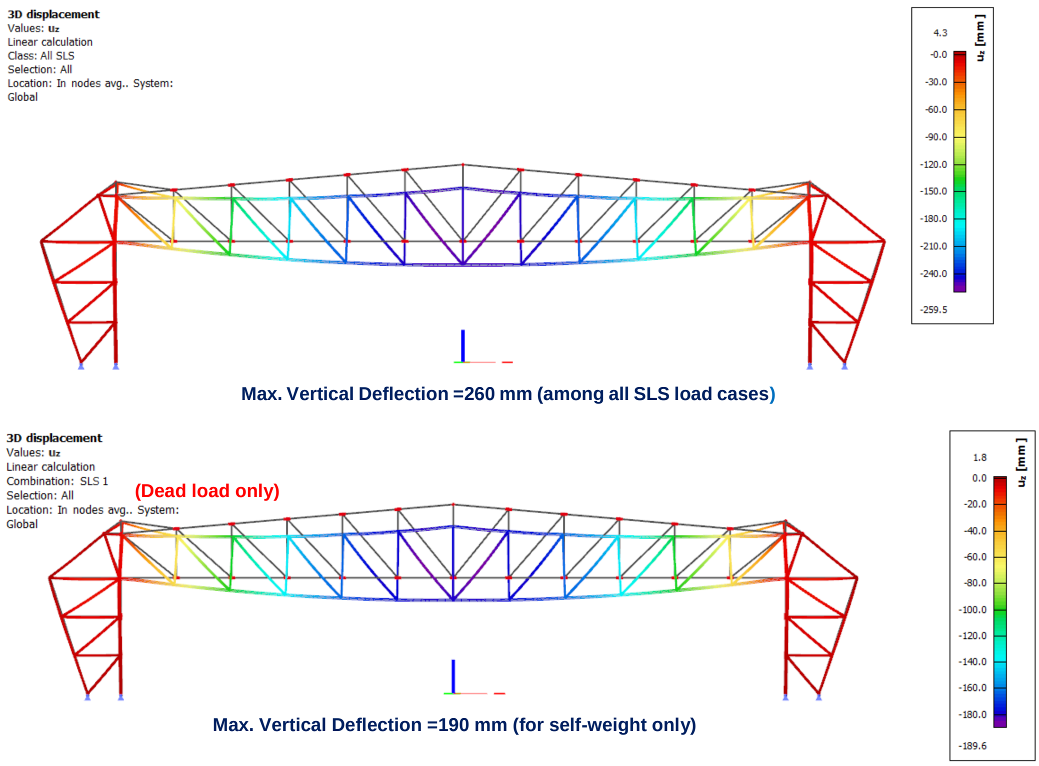


Figure 6-13 Portal Frame Vertical Deflection

It is assumed that for the dead weight, the structural elements are precambered. On Figure 6-13, it can be seen, that the difference between maximum deflection for the live-loads and dead weight loads is relatively insignificant:

$$Max. actual\ vertical\ deflection = 260\ mm - 190mm = 70\ mm$$

This is perfect for aesthetics reason. Precamber of the structure is not a must any more. One more conclusion is that the stiffness is not governing in this case, but strength and stability are.

Horizontal Deflection

Global horizontal deflections are checked in two directions. No unusual structural behavior is noticed. The maximum deflections are much less than stated in Eurocode (<100 mm).

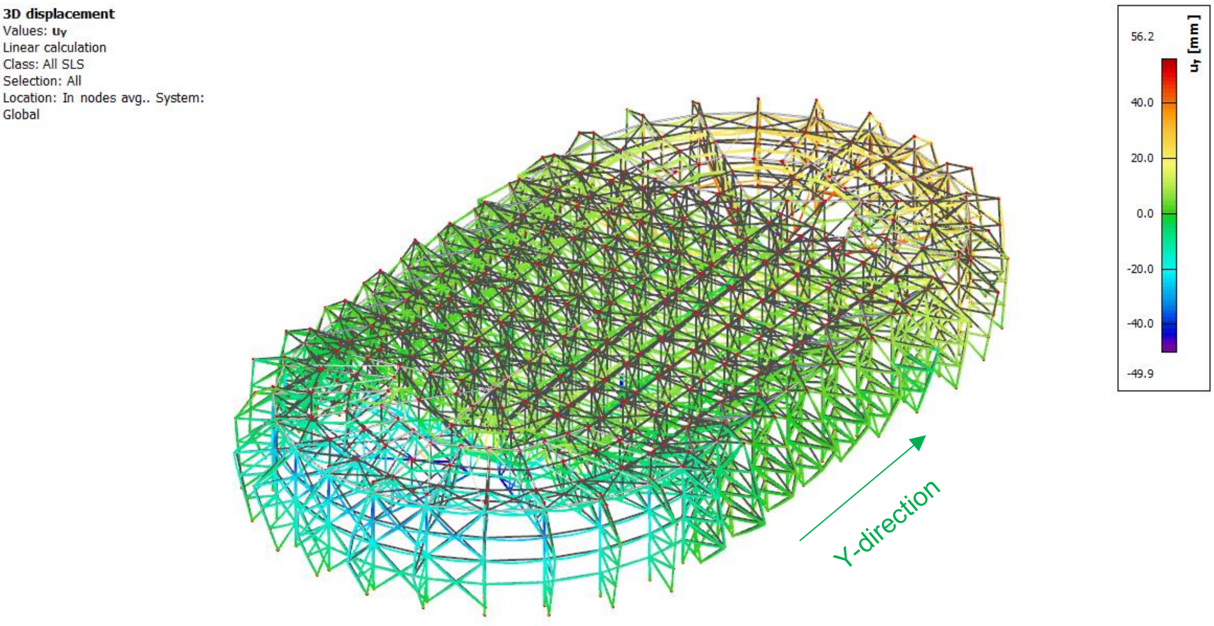


Figure 6-15 Global deflection y-direction

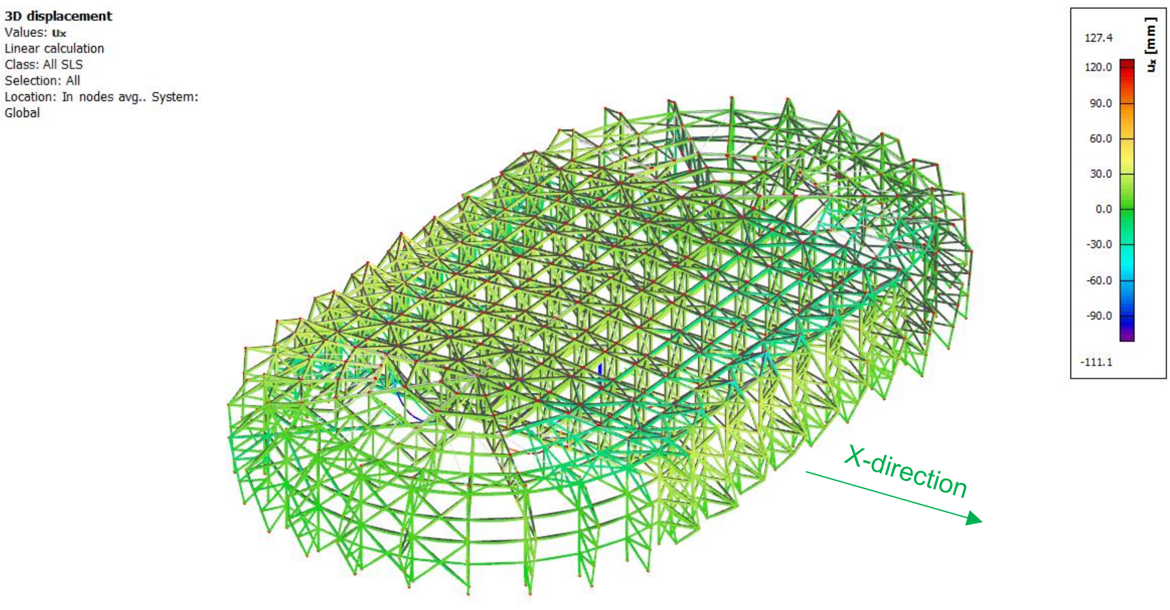


Figure 6-14 Global deflection x-direction

6.3.3 Bill of Material

Table 6-3 Bill of Material Summary

	Total Mass [mT] (rounded)
Overall Structure	2900
Roof Only	2080

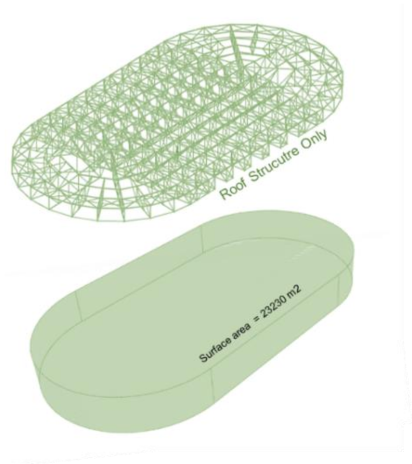


Figure 6-16 Roof Structure Only

The total weight is appeared now slightly less than during optimization as shown in Section 6.2, the Autodesign only was used to obtain results for the optimization. For the final design several cross-section groups were manually optimized.

From the table can be seen, the roof structure is the main weight of the total system (70% of the total weight), with the corresponding 70% of the overall surface area.

Concept Design vs Final Design

To verify whether the concept design assumptions were feasible, the final design is compared with the concept phase design.

It can be seen in Table 6-4 that the weight calculated at the concept stage is similar to the final design weight, although braces were not included at that stage. Good estimation of the top chord in the rectangular part truss is done, in the final design the cross-section is less due to fact that the considered self-weight of the structure for concept design was very conservative - 2 kN/m^2, which is now ~0.9 kN/m^2 in the final design. Purlin cross-section is on the contrary almost 2.5 times larger in the final design, which can be explained by the length of the purlin which is now twice longer and amount of purlins is a bit less (larger distance between purlins in the final design). It can be seen, even though there are several differences between the concept and final design developments, they can be explained. This means, that the assumptions done at the concept development phase can be considered as reliable.

Table 6-4 Concept Design vs Final Design

Comparison/Design Stage	**Concept Design**	**Final Design**
Weight (without braces and secondary stabilizing members)	*2700 ton*	*2640 ton (2900 ton incl. braces)*
Truss Shape		
Facade Height	*30 m*	*19.9 m*
ctc columns	*13.8 m*	*15.8 m*
n Columns	*42*	*38*
Length 3D Truss	*114 m*	*114.2 m*
Height 3D Truss	*7.6 m*	*7.6 m*
Width 3D Truss	*7.6 m*	*5.6 m*
n purlins between 3D trusses (1 row)	*15*	*13*
Top Chord (truss rectangular part)	*SHS400*400 (t=16 mm)* *A=24452 mm^2*	*CHS406.4/16.0* *A=19600 mm^2*
Purlin	*SHS250*250 (t=6.3 mm)* *A=6100 mm^2*	*RHS400*300 (t=12.5 mm)* *A=16700 mm^2*
Purlin length	*5 m*	*10.2 m*

6.3.4 Support Reactions

Total Vertical Support Reaction

The resultant of all support reaction has to correspond to the self-weight of the steel structure, if everything is modelled correctly. The total support reaction for self-weight load case is determined and appeared to be exactly equal to the weight of the structure (see *Appendix 11: SCIA Report).*

$$\frac{Resultant\ Support\ Reaction\ [kN]}{g} = Total\ Weight\ [mT]$$

$$\frac{28342\ [kN]}{9.81} = 2889\ [mT]$$

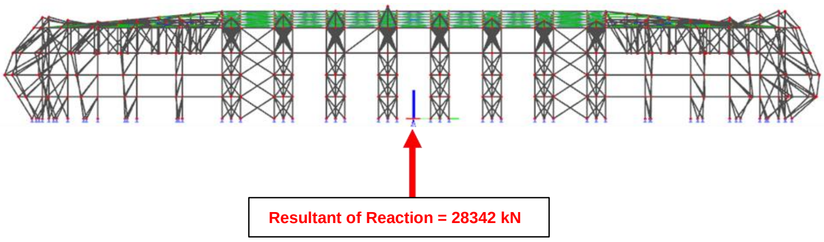


Figure 6-17 Resultant of Reactions

6.3.5 Foundation Concerns

Foundation design is out of the scope in this research, however it is worth to keep it in mind during structural design results analysis. The maximum downward support reaction is found in one of the portal frames of the horizontal part. The downward reaction in the support means a tension in the foundation (up to 1277 kN, see Figure 6-18), which is, of course, not the most preferable in terms of cost. Since the columns are varying in shape, such extreme (as in Figure 6-18) is local in the overall structure. This might be later solved with individual consideration of the particular columns with the most critical reaction forces.

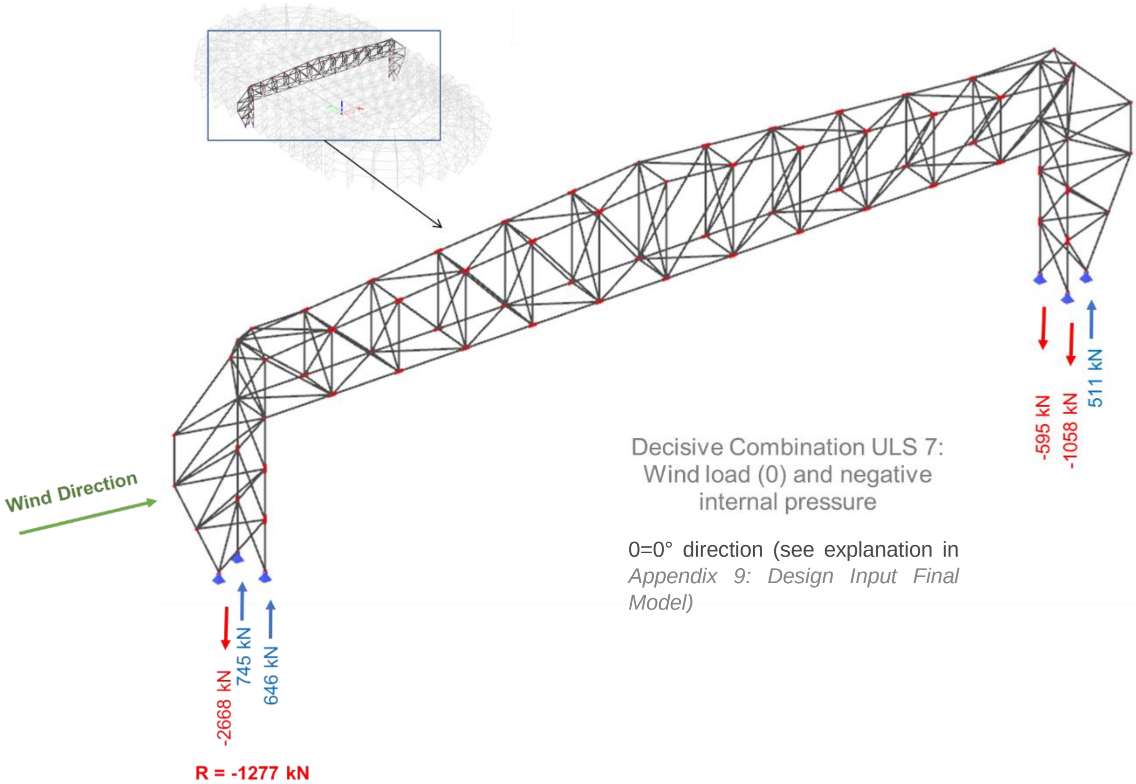


Figure 6-18 Maximum Downward Support Reaction

6.3.6 Proposed Connection Design

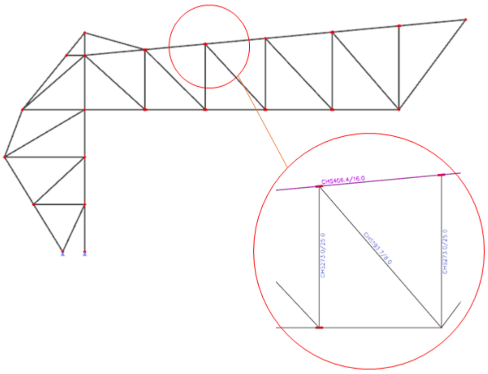


Figure 6-19 Location of the proposed connection (Long Truss)

Although the connection design is also out of the scope in this research, in terms of structural design project it takes a significant part. The dimensions of the truss elements are large. It is very important to take into account for future transportation, construction and demountability considerations. The structural elements are prefabricated for transportable dimension and will be connected on the building site. The best option for the connections in this case is a bolted connection, since welding on site is not a common practice and cost more. To make a connection estimation, 2D truss from the circular part was considered to design an approximate connection in IDEA (see Figure 6-19). Maximal normal forces from the SCIA Engineer are used. Double shear plate is used to reduce the amount of the bolts and size of the nodes. In Figure 6-20 the proposed connection is shown. This is not extensively elaborated for all of the connections and should be considered as an example how the connection problem can be tackled in future.

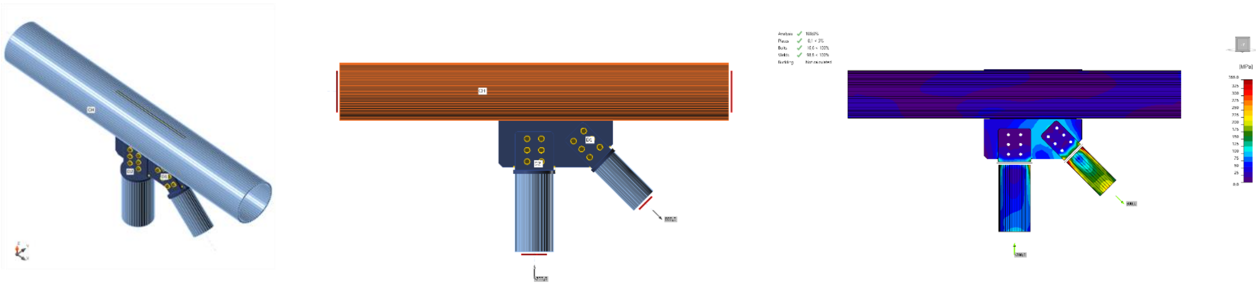


Figure 6-20 IDEA: Proposed Connection Design Trial

6.4 Tekla Drawings

The final design is structurally verified and cross-sections estimations are checked. The technical drawings can be done. Tekla live-link is used within Grasshopper to get drawings with the possibility to have design adjustments and automatic drawings regeneration when according design changes. Several drawings are done for 3D view, top and side views and several cross-sections. The drawings show the most important features of the final design. These can be found in *Appendix 12: Tekla Technical Drawings*.

7 Conclusions and Recommendations

In this chapter, the conclusion of the research project is described. This is done by checking of the program of requirements given in *Section 4.4(page 50).* Each of the requirements have to be fulfilled in this research, therefore verification and the method of its implementation is done. After that conclusions are drawn. Furthermore, the recommendations are described.

7.1 Program of Requirements Check

Based on the tables: see Section 4.4(page 50)

Architectural Requirements

Nr. Demand	Description	Check	Measure of Fulfillment	Reference
A.1	Minimum façade height is 19.9 m	✓	Minimum façade height is 19,9 m remains “untouched”, the roof structure is designed above this building height	Section 4.1, p.45
A.2	Minimal possible span is 103 m	✓	Minimum span is not used, the structure is design around the arena main building, the span of the designed structure is 114.2 m	Appendix 12: Tekla Technical Drawings
A.3	No columns in the grand stand and span area; first possible location of the column is at the top of the grand stands	✓	Column structure supporting the roof is located outside the arena building	Section 4.1, p.45
A.4	Roof structure should be designed with the account for the ceiling package	✓	Ceiling package is estimated and applied as a dead load during calculations	Section 4.2, p. 47
A.4.1	Ceiling has a slight curvature with the higher points at the edges to account for warm and humid air not influence ice pad surface conditions	✓	Since the structure is designed above the minimum arena building height, there is enough space for the required ceiling support and curvature	Section 4.2, p. 47
A.4.2	Ceiling minimum height in the lowest point is 10 m from the ice surface	✓	*See line above*	Section 4.2, p. 47
A.5	Roof structure has to account for the cladding package support	✓	Roof cladding package is included to dead load input	Section 4.2, p. 47
A.5.1	Cladding of the roof has to have minimum 0.5 m of insulation and reflective layer above and below insulation layer	✓	Roof cladding package includes insulation and reflective layers	Section 4.2, p. 47
A.5.2	Cladding material has to be representable and aesthetically pleasing	✓	Roof cladding is representable with sufficient life-span, thus aesthetical appearance in durable. Moreover, protective coating can be applied which maintains the life-span of the cladding and can be done in various colors	Section 4.2, p. 47
A.5.3	Cladding package must block the light entering through the roof	✓	Roof cladding completely blocks the light, coating with UV-resistance can be applied to increase reflective features	Section 4.2, p. 47
A.6	The main structural material is steel	✓	Roof bearing structure is made of steel	Section 4.1, p.45
A.7	Structural system design of the roof is appealing and clearly recognizable (either by visible structure or recognizable by the shape)	✓	Architectural design development is done, rotated shape is proposed for design. The shape brings the structure outside and make the emphasis on architectural and structural design combination.	Section 0, p. 54

Functional requirements

Nr. Demand	Description	Check	Measure of fulfillment	Reference
F.1	The roof structure must be durable and reliable for the entire life-time	✓	The structural design considers the life-span of 50 years, aesthetically and safely-wise structure is sufficient (deflections and unity checks are satisfying)	Section 6.3, p. 68
F.2	The roof structure must cover the total building area of the ice arena of 23230 m^2	✓	The roof structure covers the building fully	Section 4.1, p.45
F.3	Light inside the arena is restricted to keep certain environmental conditions	✓	The roof cladding package proposed is absolutely light-tight, coating layer on the cladding surface and UV-reflection which prevents heating of the roof surface	Section 4.2, p. 47
F.4	Roof must insure stable environmental conditions inside the arena	✓	The roof cladding package proposed is absolutely air-tight, light-tight and water-tight	Section 4.2, p. 47
F.5	Roof must protect spectators and sportsmen from the outside environmental conditions	✓	*See line above*	Section 4.2, p. 47
F.6	The roof structure has to account for the cladding package load and be able to resist it	✓	This is included as a dead load in the calculations	Section 4.2, p. 47 Section 4.3, p.47
F.7	The roof structure has to account for the ceiling package load and be able to resist it	✓	This is included as a dead load in the calculations	Section 4.2, p. 47 Section 4.3, p.47
F.8	The roof design must be able to resist water caused by rain	✓	The roof cladding package is watertight	Section 4.2, p. 47
F.9	The water caused by the rain has to be redirected from the roof surface	✓	The roof is pitched with the angle of 5 degrees	Section 5.1, p. 52
F.10	The roof have to account for sustainability	✓	Bolted connections between the truss elements consider the future demountability and reuse of the structural parts. Air and water-tight roof cladding design with UV-resistant coating keep stable environmental condition inside, this lead to reduced energy use on excessive heat and humidity reduction. Later on the use of solar panels can be integrated on the roof surfaces.	Section 6.3.6, p. 75 Section 4.2, p. 47

Technical Requirements

General

Nr. Demand	Description	Check	Measure of Fulfillment	Reference
T.1	Life span is 50 years	✓	These is taken into account by Eurocode use	Appendix 9: Design Input Final Model
T.2	Safety Class CC3	✓	Is applied according Eurocode	Appendix 9: Design Input Final Model
T.3	The roof structure must be stable in all directions	✓	Stability brace systems are designed, no stability failures are found during final verifications (double-check is done whether SCIA Engineer implements stability checks correctly), stability unity checks are below 1.0.	Section 0, p.59 Section 6.1.1, p. 64 Section 6.3.1, p. 68

Loads

T.3	Load: The roof structure must resist permanent and live loads	✓	The final design calculations verify that the structure resists all of the permanent and live loads considered in load cases, all unity checks are below 1.0	Section 6.3.1, p. 68
T.5	Permanent Loads: Dead Load: self-weight, cladding, ceiling, façade, extra equipment	✓	These are included in the final design calculations	Section 4.3, p.49
T.6	Live Load: Wind Load q_{wind}=1.43 kN/m^2 (will be applied in two directions ((θ=0° and θ=90°)	✓	These are applied in the final design	Section 4.3, p.49

T.7	Live Load: Snow Load q_{snow}=0.56 kN/m^2	✓	These are applied in the final design	Section 4.3, p.49
T.8	Load Combinations: See Table 4-3	✓	All load combinations stated by Eurocode are applied and final design satisfies all the load cases and their combinations, all unity checks are below 1.0	Section 6.3.1, p. 68
T.9	Roof Deflection: 0,46 m – vertical deflection 0,10 m – horizontal deflection	✓	Deflection of the roof is less than the allowable maximum for both: vertical and horizontal directions	Section 6.3.2, p. 71

The check of the research requirements is and it can be concluded that all of the sated requirements are fulfilled and covered within the final design development. The structure satisfies the architectural, functional and technical requirements stated by the key-stakeholders and Eurocode.

7.2 Conclusions

In this section, the overall thesis conclusions are summarized. This is now divided into three main parts which are considered the most influential phases of this research.

Parametric Design

Parametric design is successfully applied within the research. The parametric approach made the shape-structure integration feasible and allowed easy geometry changes during designing. The structure is designed from scratch, therefore, this tool was essential. The parametric input for the load panels and line loads, nodes and hinges, cross-section groups allowed an effective link with SCIA Engineer during calculations. Moreover, this also allowed to implement a structural optimization to avoid waste of steel. Thus, the final geometry includes an optimal amount of trusses and columns which give a satisfactory structural results. Tekla live-link within Grasshopper is another parametric tool which is implemented in this project. Tekla model is automatically regenerated when Grasshopper input is adjusted. Overall, parametric design use was a very beneficial experiment in this case and definitely can be recommended as an effective design practice for the future projects.

Structural Design

Shape

The structure is integrated within the rotated shape. Columns repeat the geometry of the architectural shape and each next column has a slight change in the shape of the outer column part. The geometry is symmetrical with symmetry line in the widest part. During calculations it is verified that this design works, but at some columns the reaction supports become very high this can cause problem with foundation design. This can be later solved with individual design consideration of the columns where the critical support reactions are found.

Optimization

Optimization routine is done and helped to get more optimal structure and reduce amount of the material needed. Therefore, the structural efficiency increased. Three parameters are separately checked and the outcome of each of the optimization step is then applied for the final design structural verifications.

Structural System

- Final structural design is checked for the strength, stability and stiffness. No serious issues were found for the global design, but some local modifications for the braces and stability members are done. Several cross-section groups are modified/optimized.
- Overall structural stability is provided by the portal frames with the rectangular trusses connected with the purlins and several sets of horizontal and vertical braces in the circular and rectangular parts of the structure. During structural calculations some of the braces sets initially assumed were verified and modified. Additional stabilizing members are added to support bottom of the trusses and create buckling restrains in the singular columns of the circular part.
- Structural principle with the use of portal frames in the rectangular part and radially located column-truss structures with the transition girder in between longer trusses in the circular part,

showed straight-forward and interpretable results. Although the initial assumption was that the transition girder will take most of the load from shorter trusses and, therefore, will help to redistribute load on the outer portal frame away from its center. The results showed that this is not the case and massive structure of the column takes up to 90% of vertical load in some locations. However, this solution with the transition girder cannot be underestimated due to fact that it also solves the problem of connection in the middle of the outer portal frame, where 11 trusses could meet.

- Structural verifications according Eurocode are done for the strength, stability and stiffness. All unity checks for the strength and stability are below the maximum of 1.0. Stiffness is checked by means of vertical and horizontal deflections. Global deflections were verified: maximum for horizontal and vertical deflections are not reached. Stiffness is not governing in case of the final design.
- Overall final structural design consists of the following elements:

  8 portal frames (with c.t.c. column distance of 15.8 m): 2 outer portal frames have slightly different cross-sections;

  11 radially distributed column-truss structures on each circular part (with c.t.c. column distance of 14.9 m): 8 shorter trusses connected to the transition girder and 3 long trusses connected to the middle of the outer portal frame;

  3 sets of horizontal braces sets on the roof part

  2 sets of vertical braces sets on the column part

  4 sets of secondary stabilizing members in the overall structure

  1 transition girder at each circular part

  1 set of purlins attached at the location of each vertical web of the trusses

  (see *Appendix 12: Tekla Technical Drawings)*

Total weight of the steel structure is:

$$Weight = 2900\ tons$$

All the research requirements are fulfilled and the results are verified. In Figure 7-1, the 3D-printed prototype of the arena final design is shown. The print is done from Grasshopper final design model version with the scale of 1:2000. The shape appears well-balanced and as the one which can add a value to the sport complex venue.

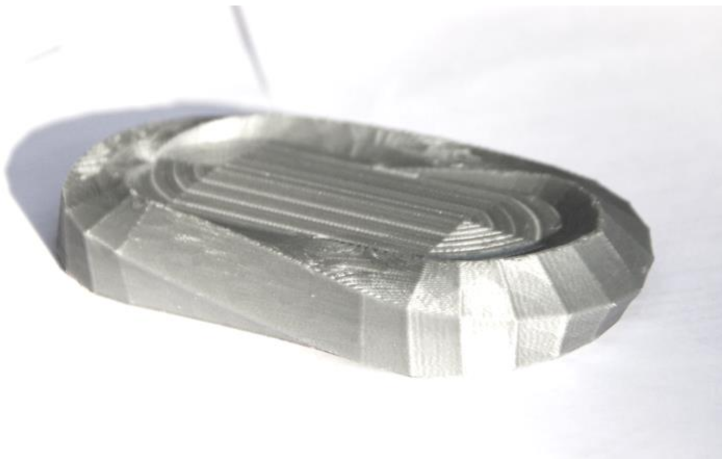


Figure 7-1 Mobius Arena: 3D-printed

7.3 Recommendations

This project is very broad and extensive. A lot of aspects of it were left-out or considered broadly to create a feasible thesis scope and make sure to cover all the most important facets: architectural, parametric and structural. However, looking critically on the work accomplished and understanding the aspects which were not detailly investigated, the following list of recommendations is done.

Parametric Design

Optimization

Parametric model can be improved by the use of optimization procedure within Grasshopper itself, for example using Galapagos and Karamba. However, it has to be kept in mind, the amount of data is very large, therefore, different optimization approach have to developed in order to be able to run Galapagos without program crash.

Shape

In terms of shape the next step could be to consider possibilities of non-symmetry and reach a continuous mobius shape. Of course, all the structural system will be effected by this but with the effective parametric model this problem should not be unsolvable.

Structural design

- Connection to the building

In this research the building of the arena is neglected, the structure is designed around it. However, it is really important to include the consideration of the outer roof structure with the building, as these both will have different dynamic behavior, thus interlocking forces have to be considered.

- Foundation

Foundation concerns are very important for the further consideration. The structure is designed now in favor of surface building but, the foundation is neglected. This have to be reviewed especially for the columns where the resultant forces are very large.

- Purlins development

Only primary set of purlins which connect portal frames and provide stability are now included. Others are taken as a dead load together with cladding. This must be further developed with the consideration of the connection with the 3D trusses. This process have to be carefully undertaken to avoid large local bending moments in the top chords of the trusses.

- Cross-section optimization

In this research, the structural design considered 39 groups of the various cross-sections for particular groups of structural elements (chords, diagonals, webs, etc.). This is sufficient as a preliminary design assumption. However, this could be optimized for a larger or smaller number of cross-section groups. For example, in some cases the cross-section is chosen for the most critically loaded member which get in the end higher unity check. At the same time other members form the same cross-section group have much less unity check. This might seem a waste of material. On the other hand, changing of cross-section with less unity check for smaller cross-section leads to the change of stiffness in the structure, and, therefore, different load distribution. As can be seen this is quite complex procedure which have to be carefully done. Also, the majority of the cross-sections are modelled with CHS. This can be also reviewed and optimized. Moreover, final results showed that stiffness is not governing for the designed structure. This can be reviewed and adjusted by, for example, adding extra braces in between truss webs, some of the critical cross sections can be then minimized as extra buckling restraints are added.

- Actions on Structure
    - Wind loads

Wind loading considered in this project is a conservative assumption. For the further design, this has to be reviewed. Wind load has to be applied in more than two directions as it was done at this stage. Also, wind on the roof surface has to be now taken individually for each wind area stated in the Eurocode. Moreover, shape factor of the outer façade part and friction of the façade has to be further considered.

    - Snow load

The snow load in this research was uniformly considered all over the roof surface. Sliding of the snow and "collection" at certain places is not considered, this might have a very significant local effects on the structure, thus, must be reviewed for more realistic loads distribution.

    - Extra loads:

Only the basic, normal load actions according Eurocode are considered and applied. However, during lifetime of the structure there will be several more load cases which have to be taken into account for the safety, serviceability and aesthetics. These are the following load cases:

        - Temperature
        - Maintenance
        - Installation loads
        - Accidental loads
        - Asymmetrical loads

- Connections

Various cross-sections are used in the design, which have own dimeter and wall thickness. Connections between the different cross-section can be complicated. Also, large internal force in the joint location can increase the difficulty and, therefore, cost of the connection. This have to be optimized to get win-win situation.

- Construction

Construction phase have to be well-thought. In case of the trusses, they are prefabricated in smaller pieces and transported to the building site. The truss length is large (114 meters), which means up to 5-6 truss pieces have to be bolted together on the building site. This can be time-consuming and expensive if not smartly designed. The installation sequence have to be well-prepared with the consideration of scaffolding, temporary supports, amount of cranes needed for erection and many more aspects.

- Robustness

Structural robustness have to be checked to insure that the removal of once elements will not cause the collapse of all of the structure. Although, portal frames in this case are assumed to be a very advantageous solution for the robustness, since each of them are relatively independent structural elements. But this has to be thoroughly investigated.

- Maintenance concerns

On the concept design stage maintenance was roughly discussed, but not further developed. Although maintenance concerns are very important for the durability of the structure. Access routes and gutters design have to be included to the design. The plan has to be done how the cleaning of the roof will be undertaken and what are the loads of this maintenance will affect the structure. Gutters have to be accessible for the cleaning of the collected debris, such as leaves, birds, etc.

- Architectural provisions

Further investigation have to be done on the architectural provisions to make sure that the structure can be integrated within the building and all the architectural requirements are balanced with the structural design.

- Sustainability

The roof surface of the arena is quite large and it could be a nice opportunity to use this space to produce energy, by means of solar panels or other source of heat collection. Ice arena needs an enormous amount of energy to get rid of the excessive heat near the ice surface and at the same time to insure comfortable temperature for the sportsmen and spectators. It is already discussed that a good roof design can insure less energy consumption, but this can be even more improved by the use of green energy produced by the building itself.

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