IMd Raadgevende Ingenieurs

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Master Thesis

Preliminary structural design and financial feasibility study of a transportable multi-functional stadium

"Structural configuration of roof, grandstand and foundation of an A-venue demountable and transportable multi-functional stadium with a focus on minimizing recurring costs"

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Abstract

Large sport events require multiple large scale stadiums. However, often there is insufficient local demand to make use of all the stadiums throughout their lifetime. Hence, more and more high quality large scale stadiums, built for a onetime event, become vacant after the event.

This research aims to design the structural configuration of the roof, grandstand and foundation of a demountable and transportable multi-functional A-venue stadium. Furthermore, minimizing the recurring costs and assessing the financial feasibility of this stadium are emphasized in this research. A transportable stadium prevents the situation that an A-venue stadium becomes vacant.

A design philosophy is created based on literature study and common sense to steer the design process. The design philosophy consists of seven criteria. The importance of each criterion and the way the final design has adhered to this criterion is described below:

1. An even load spread will spread the occurring loads over multiple supports. This results in relative low and balanced support reactions. This is realized via radial frames and the connection between the roof structure and grandstand.
2. Stability during erection. When direct in- and out of plane stability is created, temporary structures are not necessary during (de-)construction. Hence, recurring costs are reduced. Stability during erection is realized as soon as two frames with stabilizing wind bracings are erected. From that point on, the other frames can be erected without the need for temporary structures.
3. A modular design improves the (de-)construction process due to repetition. Moreover, the segments do not require a specific location which improves the building organization process. Each loadbearing frame in the stadium is identical. Hence, a modular design is realized.
4. With an adaptable design the stadium can respond to different functional demands. Thus, the stadium can be used for multiple purposes increasing the potential revenue sources. The stadium is adaptable due to identical frames throughout the stadium. Frames can be added or removed to adapt to the desired pitch dimensions and capacity.
5. The amount of material should be minimized. It is influenced by the load transferring mechanism. Load transfer via normal forces, reducing the amount of material, is advantageous. In the design load transfer via normal forces is realized via bracings within the frame.
6. Optimize transportation means to minimize the recurring costs. The span of the horizontal grandstand and roof, and thus their dimensions, is designed to optimize the transportation means. Furthermore, the weight and not the volume restrictions are governing in this research.
7. Minimize assembly and disassembly procedures to minimize recurring costs. This is achieved with a modular structure which consists of hinged connections. Furthermore, the lightweight aluminum grandstand and roof plate minimizes the (dis)assembly procedures efforts.

The architectural shape is investigated which leads to the following three insights. 1. The long and short sides of the stadium are designed to be a segment of a circle with an identical radius. Hence, all segments throughout the stadium are identical. 2. A radius of 348 meter ensures that both the long and short side can be divided by a whole number of segments preventing the need for half span segments. 3. Furthermore, to ensure good viewing conditions, while creating a modular design, only three unique riser heights are applied in the stadium of 360, 450 and 550 mm.

The quest to design the optimal structural configuration of roof, grandstand and foundation leads to the following insights: [1]

Grandstand: A three stepped aluminum profile spanning 10,8 meters is the optimal structural grandstand design. The profile makes use of the riser height to create the necessary stiffness to

[1] In this research the roof and grandstand are divided in two separate components. The grandstand consists of the horizontal component, labeled grandstand, and a vertical component, labeled load bearing frame. The roof consists out of the roof loadbearing structure and the horizontal roof skin.

achieve this span. Next, the amount of assembly procedures is minimized with the floor and step integrated in one profile. The number of steps is optimized regarding transportation means and aims to minimize assembly efforts. Due to the light weight of the structure only 38 containers are necessary to transport the grandstand.

Roof skin design: An aluminum roof plate, height 200mm, spanning 5,4 meters between IPE 400 girders is considered to be the optimal structural roof skin variant. Due to its light weight, it is mendable for construction workers and its click-system minimizes assembly efforts. Successively, if any damage occurs to the roof skin during (dis)assembly, the damaged roof plates can be substituted easily. Only 13 containers are required to transport the horizontal roof skin and girders.

Roof loadbearing frame: The cantilever roof fixed to grandstand is considered to be the optimal roof design. An even load spread is realized through its connection to the grandstand. Next, temporary scaffolding structures are not required during assembly. Moreover, it is a modular and adaptable structure. Since the governing load combination is wind uplift, the light weight characteristic of aluminum is not advantageous. Thus, a steel roof loadbearing frame is considered.

Loadbearing frame design: The structural loadbearing frame is made from steel. Steel has good loadbearing characteristics and can be easily constructed with demountable connections. The field beams in the roof truss are configured to be loaded in tension under the governing (upward) load combination. Furthermore, a stiff structure is realized through bracings which assist in load spread and are designed to transfer both tension and compression forces. Therefore, the loads are transferred via normal forces in the grandstand loadbearing frame instead of bending. Thus, minimizing the amount of material and improving the load spread. Moreover, each corner is separated from the long- and short side via displacement joints to enable elongation due to temperature fluctuations. Stabilizing cable bracings are applied between the frames to ensure stability of each section between the displacement joints.

Foundation: A concrete pile foundation is recommended as the optimal foundation variant. A steel foundation is too expensive and a timber foundation is not capable of transferring the occurring forces into the soil. The stiffness of each foundation support is in line with the anticipated maximum load the support experiences. This improves the load spread. Furthermore, techniques are available to remove the concrete foundation afterwards with minimal efforts.

Financial feasibility: A study is performed to answer the following question: If an event organization is aware that the demand for the stadium will vanish after the event, will leasing a transportable stadium become more attractive compared to building a permanent stadium? A business case is performed which answers the following two questions. What are the costs to own and build a permanent stadium for a onetime event with little or none revenues after the event? What is the required lease fee to own and operate a financially feasible transportable stadium which is leased to organizations hosting a large event? Assuming that the transportable stadium aims to break even after 8 venues, has (dis)assembly costs of 18% of the total initial costs and 5% collateral damage after each venue, the required lease fee is €87 million to operate a financially feasible transportable stadium. If an organization of a onetime event abandons the stadium 3 years after the event, it still has to pay a total amount of €401 million for its permanent stadium.
Thus, with a lease fee of €87 million, the organizing entity only has to pay the owner of the transportable stadium 22% of the costs of a permanent stadium while having identical revenues compared to a permanent stadium. Hence, a transportable stadium is financially feasible. The considered conditions are discussed combined with a sensitivity analysis which assesses the impact when conditions are altered.

Key words
Transportable multi-functional stadium, civil engineering, structural design, roof, grandstand, foundation, recurring costs, financial feasibility.

Preface

Large sport events require multiple large scale stadiums. However, after the event some stadiums have no (local) demand and become vacant. A transportable stadium could prevent the catastrophe of a permanent stadium, built for 50 years, having no use after the onetime event.

This thesis is a sequel to work done by Anne den Hollander (2010) en Myrte Loosjes (2011). They attempted to transform a stadium with optimal viewing conditions into a transportable stadium. They concluded that the shape posed too many challenges to create an efficient transportable stadium. Hence, this thesis has a different approach.

The author set out to create, from scratch, the optimal structural design of a financially feasible transportable stadium in which the roof, grandstand and foundation are considered. Furthermore, a business case is conducted to assess the financial feasibility of a transportable stadium.

This thesis is based on the analysis of numerous structural design variants, a literature study regarding design for disassembly, helpful brainstorm sessions with experienced structural engineers and most importantly, common sense.

This thesis aims to provide the reader insight on the different aspects, and their impact, involved with the design of a transportable structure. I hope you will read it with the same amount of curiosity as I enjoyed while conducting this research.

Marcel Klomp,
The Hague,
May 2013

Acknowledgement

Although this document bears solely the name of the author. Several people played an essential part throughout this research.

First and foremost, I would like to thank the company IMd Raadgevende Ingenieurs for guiding me throughout this process, in particular Remko Wiltjer and Myrte Loosjes. IMd acted as an inspiring environment which gave me a clear insight in the world of a structural engineer. Moreover, I enjoyed both the on- and off topic discussions with Remko.

Furthermore, I would like to thank the chair of my committee, professor Rob Nijsse. His wise and broad knowledge assisted me in remembering that a structural design engineer is entitled to a design opinion.

Successively, I would like to thank Jules Verlaan. He encouraged me to set out my own course and assisted me with the ins and outs of a financial study.

Subsequently, I would like to thank Karel Terwel. Where the other committee members safeguarded that the big picture remained intact, it was Karel who ensured that the actual research and arguments were solid. His extensive feedback assisted me to ensure that all the ifs and buts were dealt with.

Moreover, I would like to thank Gem Beesterboer and his colleagues of Amsterdam Arena Advisory for the informative session in which the course of the business case was set out. Furthermore, I would like to thank Nardo Hoogendijk of Hollandia BV for providing me with actual large scale stadium's data to validate my cost indicators as well as a pleasant and inspiring conversation.

Finally, I would like to thank friends and family for their support and encouragement.

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Reader guide

This thesis is structured as follows:

Chapter 1 discusses the research proposal. The context of this research is presented as well as the research objective, research questions, research scope and the applied methodology.
Chapter 2 summarizes the main outcomes of the literature study in which the design for disassembly methodology, the stadium structural components and the financial feasibility is discussed.
Chapter 3 presents the applied design approach; The design philosophy as well as the design methodology is presented.
Chapter 4 discusses the stadium's architectural design. The pitch dimensions and lay-out types are discussed. Furthermore, the grandstand dimensions and riser heights are determined.
Chapter 5 discusses the building design classifications imposed by the building code as well as the list of requirements imposed by the building code, sport organizations and designer's preference.
Chapter 6 presents the optimal horizontal grandstand system. Different variants are derived from practice and theory and assessed on their performance on the design philosophy. Furthermore, the optimal span distance is determined and the optimal horizontal grandstand system is presented.
Chapter 7 presents the optimal roof skin system. Different variants are derived from practice and theory and assessed on their performance on the design philosophy. The optimal roof skin system is recommended.
Chapter 8 presents the optimal roof system. Different variants are derived from practice and theory and assessed on their performance on the design philosophy. Furthermore, a survey is performed to validate the performance of the variants on the design philosophy. After examining the top two performers the most optimal roof system is recommended.
Chapter 9 presents the loadbearing frame in which the foundation is also considered. Arguments are presented for the configuration of the loadbearing frame and interesting connection details are discussed. Furthermore, displacement joints are discussed and the stability between the displacement joints are discussed.
Chapter 10 discusses 3d images of the final design.
Chapter 11 presents the financial feasibility of the stadium via a business case. The costs of a permanent and transportable stadium are assessed. Furthermore, conditions are listed and the lease fee of a transportable financially feasible stadium is expressed as a percentage of the total cost of a permanent stadium.
Chapter 12 concludes the research and answers the research questions posited in Chapter 1.
Chapter 13 presents the recommendations for further research.
Chapter 14 reflects the research. The performance of the final design on the list of requirements is discussed. The applicability of the design philosophy on other civil structures is considered. Furthermore, the impact on the design process of altering the considered conditions is assessed.
The literature considered in this research is summarized in Chapter 15.

Table of content

1 Research proposal

1.1 Introduction

Several aspects inspired this research. These aspects are briefly discussed below.

Large sport events and their increasing desires

The past decades has shown an increasing competition between countries to host large sport events (Nixdorf, 2007). Due to this fierce competition, hosting countries promise the organizing committee stadiums and facilities which are almost too good to be true. Numerous previous editions demonstrated that although the hosting country realized a very high quality event with top facilities and stadiums, the local demand for these functions quickly diminished after the onetime event. The abandoned stadiums after soccer World Cups or Olympic Games have higher maintenance costs than operational revenues (ArenaAdvisory, 2013), Therefore, these stadiums are costly and undesired evoking the demand to prevent a stadium of being redundant after a large event (Reuters, 2012).

How to prevent a vacant stadium after the event

Mankind is realizing that natural resources are limited and that society should be more sustainable (UN, 2012). There are several options which an organizing committee can consider when it is aware that the local demand is insufficient to make economic use of all the stadiums after the event. These options are based on suggestions of Loosjes (2011) and displayed in Figure 1-1.

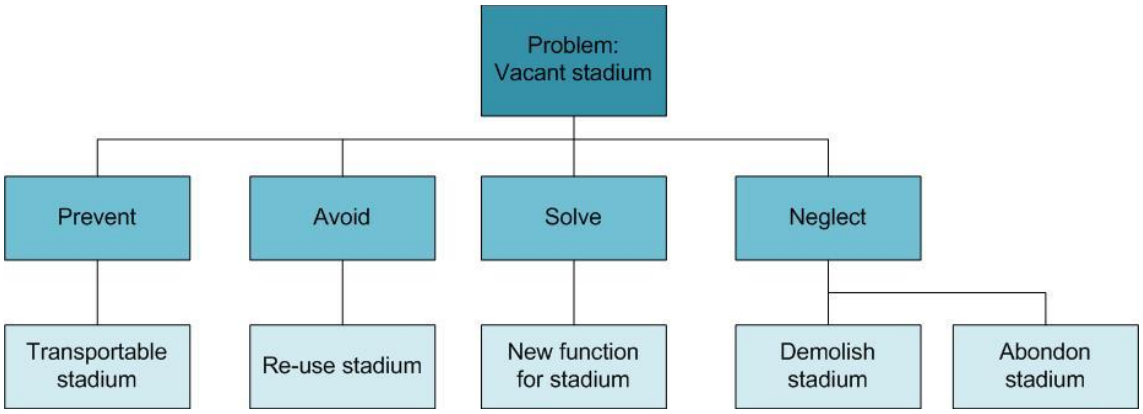


Figure 1-1 Measures to prevent a vacant stadium, based on Loosjes (2011)

Of the five possible solutions to prevent a vacant stadium, this research aims to design a transportable stadium. The measures to reuse parts of the stadium or create a new destination are also interesting solutions because they pose less structural challenges. However, these measures are already widely researched and applied in practice. Furthermore, when there is no demand to re-use the stadium or create a new function these solutions are not applicable. The option to demolish or abandon the stadium is unsustainable and will not be considered. Hence, this study aims to prevent a vacant stadium after a large sport event by designing a transportable stadium.

Knowledge on demountable structures

Multiple graduation researches have demonstrated that the design process of a transportable stadium has many dissimilarities compared to a permanent stadium (Loosjes, 2011). Most significantly, a transportable stadium will be erected, disassembled and transported multiple times. Therefore, minimizing the required efforts for these activities is vital to design an economically feasible transportable stadium.

Financial feasibility of a transportable stadium

Up to this point there is limited knowledge concerning the impact of different stadium shapes and structural configurations on the financial feasibility of a transportable stadium. This graduation research aims to provide insight in the effect of different structural configurations on the financial feasibility of a transportable stadium. Furthermore, a business case is performed to determine the financial feasibility of a transportable stadium.

1.2 Context

When a country wants to host a large sports event several questions arise. *How many stadiums are necessary to host the event? What is the required capacity for the stadiums? How much will a permanent stadium cost to construct and maintain for the upcoming 30 to 50 years? How much revenues will the stadium generate both during and after the event?*

Examples such as the World Cup of South Africa and the Beijing Summer Olympics demonstrate that the local demand is too small to make economic use of the stadiums build for a onetime event. Therefore, there is a growing demand for 'satellite' stadiums. These are not the permanent iconic stadiums used in the event promotion to win the bid, but functional stadiums necessary to create sufficient capacity to host a large sport event.

Up to this point there is only one example of a truly transportable sport stadium of such scale, the London Summer Olympics basketball arena. It was designed to be reused in the upcoming Summer Olympics in Brazil. Unfortunately, the Brazilian organizing committee has concerns regarding the financial feasibility of the basketball arena and an agreement has not been reached so far.[2]

In order to improve the financial feasibility, the stadium should host several functions. Therefore, it should be designed to be scalable to adapt to different pitch dimensions and different crowd capacities, with a capacity of 50.000 as a starting point.

Furthermore, to improve the financial feasibility the stadium should be employable in an as large geographical area as possible. Therefore, the stadium should be able to be transported overseas.

1.3 Research objective

The goal of this graduation research is to design the preliminary structural configuration of roof, grandstand and foundation of an A-venue demountable and transportable stadium with a focus on minimizing recurring costs. Furthermore, the financial feasibility of a transportable stadium will be determined.

1.4 Research question

The main research question which follows from the research objective is:

- *What is the optimal structural configuration of roof, grandstand and foundation of an A-venue[3] demountable and transportable stadium with a focus on minimizing recurring costs?*

In order to answer the research question, the following sub questions are defined:

- *What are the conditions for a financially feasible transportable stadium?*
- *Which typologies can be listed in current stadium roof, grandstand and foundation design?*
- *Which typologies are beneficial from a demountable and transportable point of view?*

[2] http://www.gazetadopovo.com.br/esportes/olimpiadas/conteudo.phtml?id=1269221

[3] A-venue represents a high quality stadium

1.5 Research scope

This research focuses on the structural aspects and financial feasibility of a transportable stadium. Hence, the scope includes the stadium's structural components and financial feasibility. Due to the defined amount of time for this research, the aesthetic appearance and climatic aspects of the stadium are excluded. Furthermore, it is assumed that an organizing country will pay more attention to the price than the appearance of a transportable stadium.

In this research the roof and grandstand have both been divided in two separate components. The grandstand consists of the horizontal component, labeled grandstand, and a vertical loadbearing frame component, labeled grandstand loadbearing frame. The roof consists of the roof loadbearing structure and the horizontal roof skin.

The following items are considered in this research:

- Structural configuration of:
  - Roof skin
  - Roof loadbearing structure
  - Grandstand
  - Grandstand loadbearing frame
  - Foundation
- Financial feasibility of the stadium suitable for 50.000 spectators.
- The stadium should adhere to demands defined in the Euro Code concerning stability, strength and stiffness.
- The stadium should be capable of handling moderate earthquakes.
- The stadium should cope with high wind speeds. However, hurricanes will not be considered. Their occurrence can be predicted and the event will be canceled. Furthermore, measures are taken to improve the stadium to withstand hurricane forces.
- The stadium should have flexibility underneath the grandstand to allocate functional areas.
- Structural fire safety design, the loadbearing structure should adhere to the fire safety demands imposed by the building code.
- The stadium should provide spectators excellent viewing conditions.

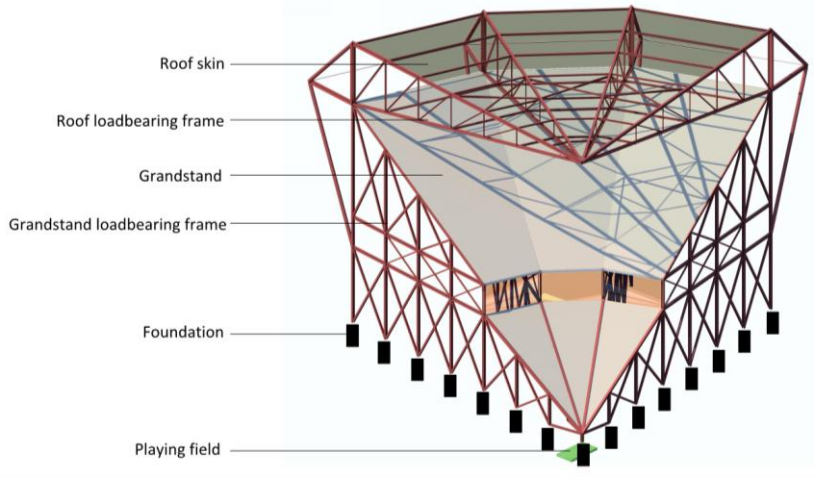


Figure 1-2 Overview of the structural components considered in this research

The following items are excluded in this research:

- Façade and cladding play a negligible role in the structural configuration of the stadium. They primarily influence the aesthetic appearance. Hence, they will not be considered.
- Heating, cooling, lighting, acoustics and ventilation of the stadium will not be considered.
- The playing field does not influence the loadbearing structure and will not be considered.
- Internal routing (sufficient escape corridor widths are considered) will not be considered.
- Fire safety design concerning smoke control and compartments will not be considered.

1.6 Research methodology

The research methodology is visualized in Figure 1-3. After defining the research objective, scope and research questions, the actual research can commence. The research is divided in two phases.

In Phase 1, the literature study aims to define assessment criteria derived from stadium functional demands, design for disassembly demands and financial demands. Furthermore, a typology study is performed. In the typology study the structural variants of roof, grandstand and foundation are discussed.
Phase 2 consists of a case study. The different variants, derived in the typology study, are assessed on their performance on the assessment criteria, derived from the literature study. Subsequently, the recommended structural components are integrated into a stadium design which is technically elaborated. Furthermore, a business case is performed to determine the financial feasibility of the transportable stadium.
Finally, an evaluation is performed. The research questions are answered and recommendations are suggested.

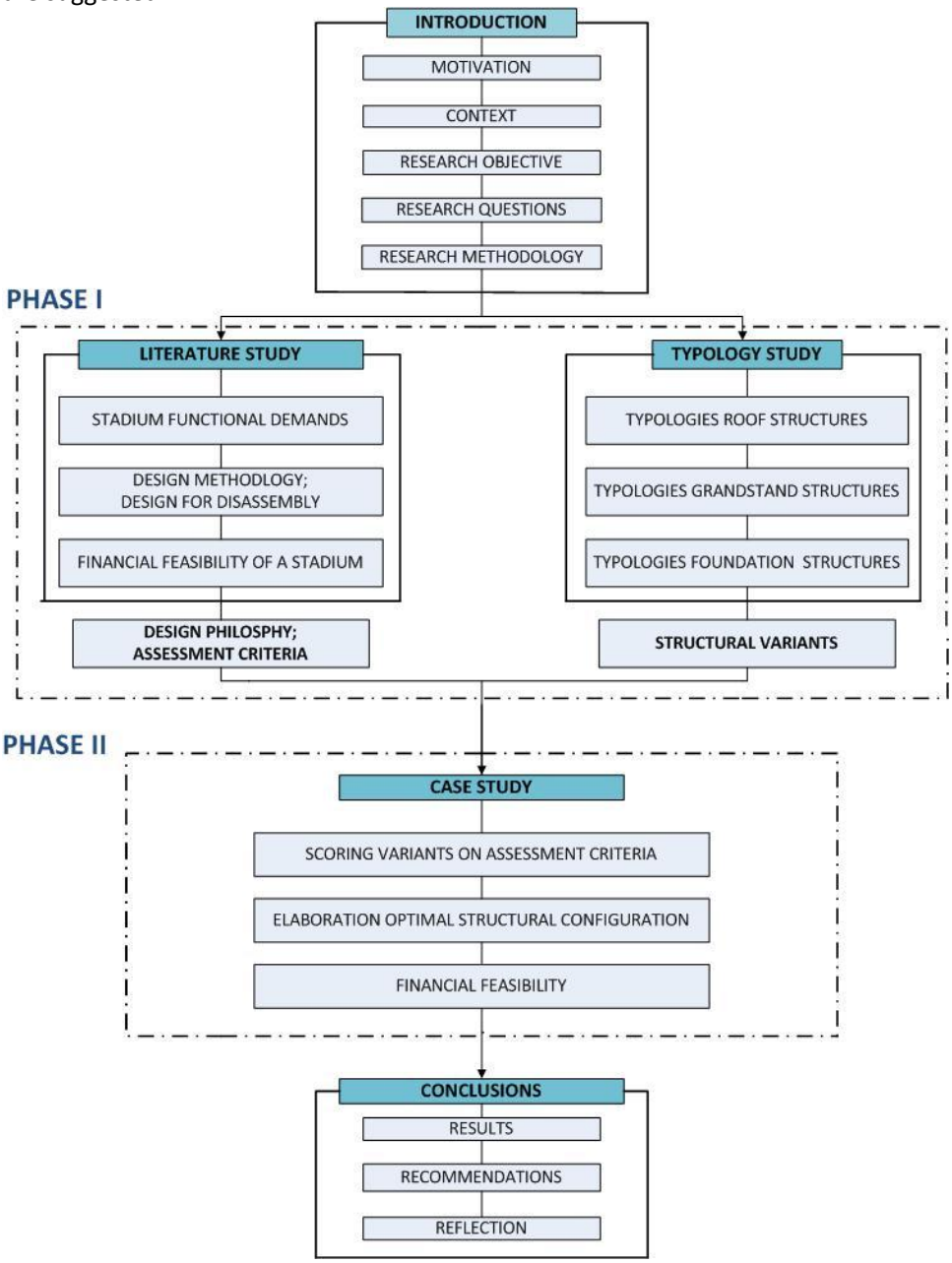


Figure 1-3 Research methodology

2 Literature study

This graduation research discusses three main topics. The design methodology of a transportable structure, the structural components within stadium design and the financial feasibility of a transportable stadium. This chapter summarizes the main frameworks and observations applicable to these three topics.

Design methodology

Over the last decades a trend to minimize the embodied energy of the build environment is noticeable (Crawford, 2012). The embodied energy can be reduced with several measures.

- Reduce the amount of material. Innovation in the building industry results in materials with improved loadbearing characteristics reducing the amount of required material.
- Reduce the amount of energy required for production. Innovation in the building industry results in a reduction of the amount of energy required to produce building materials out of recycled components or raw materials.
- Minimize disassembly efforts. This concept is known as Design for Disassembly (DfD).

The last concept, DfD, is vital for the design of an economically feasible transportable stadium. The definition of DfD is: *"DfD is the design of buildings to facilitate future change and the eventual dismantlement (in part or whole) for recovery of systems, components and materials"* (Ciarimboli, 2005).DfD changes the life cycle of the built environment as visualized in Figure 2-1. In the case of a transportable stadium, the relocation of the whole building is applicable.

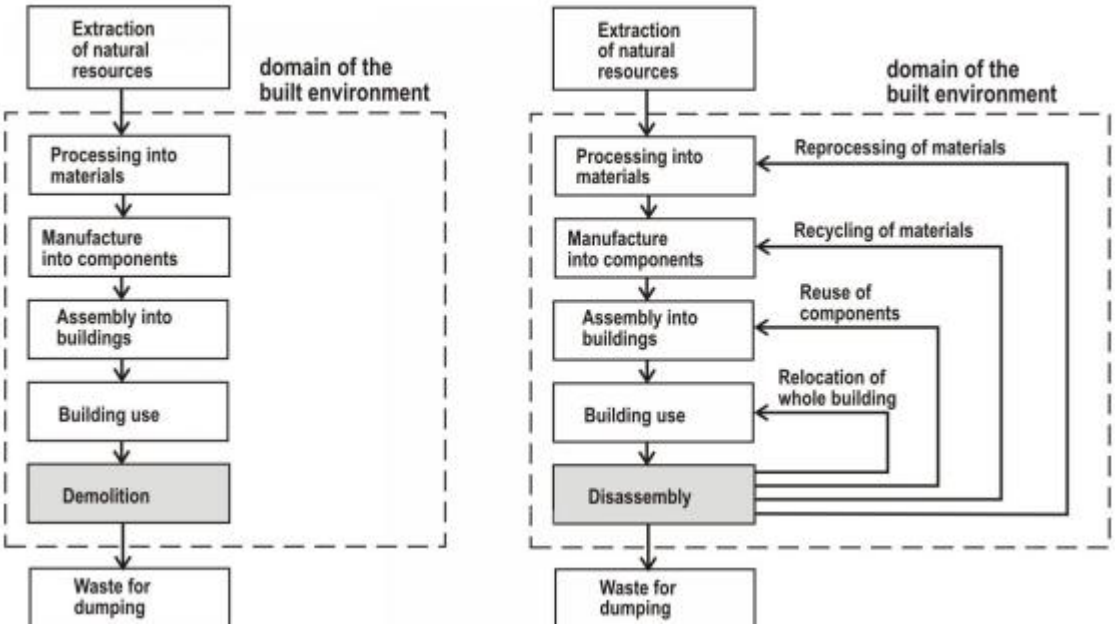


Figure 2-1 Left: Conventional life cycle of a structure. Right: DfD life cycle of a structure. Source: (Crowther, Design for Disassembly - Themes and Principle, 2005) #4

Crowther described many principles and guidelines regarding DfD (Crowter, 1999; 2005). The key guidelines are listed below:

- Minimize the number of different types of components.
- Design a modular design.
- Apply construction technologies that are compatible with standard, simple, and 'low-tech' building practice.
- Separate the structure from the cladding, internal walls, and services.
- Use a minimum number of fasteners and connectors.
- Allow for parallel disassembly rather than sequential disassembly.
- Minimize the number of different types of materials.

This research aims to design a transportable stadium which adheres to these guidelines. Moreover, two other guidelines will also have a substantial impact on the design considerations.

- The structure should be designed in accordance with its transportation means.
- The efforts required for the assembly and disassembly process of the structure should be minimized. For instance, a large temporary scaffolding structure, is undesired.

This research aims to adhere to the DfD themes and specifically intents to reduce efforts required for the transportation and (dis)assembly process.

Stadium design

Up to this point little or none examples of transportable stadiums of a scale of +/- 50.000 spectators exists. The London Arena, built to host the basketball Olympic Games in 2012, is the first example of a truly transportable stadium of substantial scale; 12.000 spectators. Nussli, a Swiss supplier of temporary structures, is the only company encountered which offers large scale transportable structures. However, Nussli commonly opts for a scaffolding structure as structural system which is undesired for the following reason. A scaffolding structure provides little flexibility underneath the grandstand to allocate functional areas such as catering activities and dressing rooms. Locating these functions outside the stadium makes the stadium substantially less attractive to be used as a substitute for a permanent stadium.

In order to obtain knowledge on stadium design in general, three different sources are consulted. Literature regarding stadium design is assessed, numerous stadiums are reviewed and stadium design guidelines, provided by sport associations, are considered.

A stadium is made out of the following five main components. Roof, horizontal grandstand, grandstand loadbearing frame, foundation and the playing field. A wide variety of roof structures exists. All options have different pro's and con's[4] and the preference of architect and owner plays a dominant role. The horizontal grandstand, grandstand loadbearing frame and foundation for a permanent stadium is predominantly constructed with concrete. Concrete has good loadbearing characteristics and is a cheap option. However, when designing a transportable stadium the large weight, increasing the transportation demands, makes concrete less ideal. The playing field dimensions depend on the type of event. In order to allocate multiple functions, a stadium should be adaptable to provide spectators with perfect viewing conditions regardless of the event type.

Hence, this research aims to design a transportable stadium in which the roof, grandstand and foundation is considered. Currently, temporary stadiums are characterized by an undesired scaffolding structure. Therefore, different structural configurations are assessed in this research.

Financial feasibility

For a large sport event multiple stadiums are required. Often, the local demand is insufficient to create sufficient revenues after the event throughout the lifetime of the stadium. South-Africa hosted the Football World Cup 2010 and is in 2012 already struggling to create sufficient revenues to cover exploitation costs.[5] Therefore, a transportable stadium can provide a solution by offering a temporary stadium at far lower costs while similar revenues are created.

Furthermore, a cost breakdown of stadium structures is only available on a conceptual level; A segmentation is created between different stadium components but a cost breakdown between labor costs and material costs is not encountered. Finally, a shift is noticeable in the stadium cost break down on a conceptual level; With increased HVAC, video and catering demands, the cost percentage of the structural components is decreasing and the costs percentage of electrical equipment is increasing. Where a 80% – 20 % ratio was applicable 50 years ago, the current ratio is roughly in the 60% – 40% region (ArenaAdvisory, 2013). This research aims to determine if a transportable stadium is an economically attractive alternative to a permanent stadium.

[4] A slender roof structure transferring solely normal forces often requires a temporary scaffolding structure during the assembly and disassembly process. Whereas a material intensive roof structure which transfer the forces via bending does not necessary require a temporary structure.

[5] www.telegraph.co.uk/news/worldnews/southafrica/South-Africas-white-elephant-stadium

3 Design approach

This chapter discusses both the design philosophy as well as the design methodology. The design philosophy discusses the aspects which are considered in the design process. The design methodology describes both the design order, in which order the stadium structures (roof, grandstand and foundation) are designed, and the decision tool to determine the optimal design.

3.1 Design philosophy

In order to design a financially feasible transportable stadium the design optimization study should adhere to the following three principles:

- Minimize recurring costs
- Minimize initial costs
- Improve the value[6] and revenue sources of the stadium

In order to align the design with above described principles, seven design aspects are taken into consideration. These aspects are discussed below.

1. Load spread

Load spread is considered to be the ability to spread the loads evenly over a large (ground) surface. An even load spread will spread the occurring loads over multiple supports. This results in relative low and balanced support reactions. Therefore, slender piles can be used and even the possibility of Stelcon plates arises. Thus, the stadium should strive for an even load spread.

2. Stability during erection

When direct in- and out of plane stability is created, temporary scaffolding structures are not necessary during construction and deconstruction. When the usage of such a temporary scaffolding structure can be prevented, the recurring costs are far lower. Thus, the loadbearing structure of the stadium should have direct stability during erection.

3. Modular design

In this research the definition of a modular design is: “A structure which consists of similar segments”. A modular structure has multiple advantages. Firstly, because the structure consists of similar modules, the construction and deconstruction process is quick and easy due to repetition of (de)construction technologies. Secondly, because the structure consists of similar segments, the segments do not require a specific location which improves the building organization process. Thus, the stadium ought to have a modular design.

4. Adaptable design

When a stadium can respond to different functional demands the stadium can be used for multiple purposes. The potential revenue sources, and therefore the value of the stadium, is increased if a stadium can be used for a soccer tournament with a capacity of 50.000 people as well as a field hockey tournament with a capacity of 30.000 people.
The stadium is considered to be perfectly adaptable when it can perform the following two alterations. Adjust the amount of segments and adjust the capacity per segment.

[6] The value of the stadium expresses itself in many ways. For instance, a larger center to center distance of the loadbearing structure provides more flexibility thus adding value to the stadium. Furthermore, a stadium with excellent sightlines has more value than a stadium with poor sightlines.

5. Amount of material

The load transferring mechanism (e.g. normal forces versus bending) determines the amount of material required in the stadium. Because the required amount of material to transfer normal forces is far less compared to bending this results in a lower volume of the loadbearing structure. When less weight and volume has to be transported less effort is required. (e.g. less containers, less hoisting activities etc.) Thus, the load should be transferred via normal forces instead of bending.

6. Optimize transportation means

The transport costs are influenced by the transportation method and the amount of containers in which the structure is transported.

Transportation method

A stadium can be transported either via road on a truck or in containers which can be mounted on both a truck or ship. In Table 1 and Table 2 the characteristics of transportation via containers and road transport is displayed.

		20 foot container	40 foot container	45 foot container
Inside measures	Length [m]	5,87	12,03	13,56
	Width [m]	2,35	2,35	2,35
	Height [m]	2,39	2,39	2,70
Volume [m^3]		33,10	67,50	86,10
Max weight [tonnes]		24,00	30,50	30,50

Table 1 Dimensions sea containers. Source: www.searates.com

	No permit needed	Long term permit	Corridor
Width [m]	3,00	3,50	4,50
Overall length [m]	24,00	30,00	40,00
Overall height [m]	3,50	4,20	4,40
Weight [tonnes]	50,00	80,00	100,00
			Axle Load:
Beam axle [tonnes]	Directive 96/53/EC	12,00	12,00
Pendulum axle [tonnes]	12,00	15,00	15,00

Table 2 Framework for abnormal road transport permits. Source: European commission, 2006

Although transportation via trucks leads to larger possible elements, which lowers assembly costs, the employability of the stadium is limited when only road transport is possible. Furthermore, transport over road is more expensive compared to transport via containers over water (Hollandia H. , 2013). Thus, road transport for special elements should be minimized and the stadium should be transported with sea containers. Hence, the stadium structural elements ought to be optimized regarding the sea container dimensions.

Amount of containers

The amount of containers is influenced by the amount of material and the degree of filling of the container. The amount and thus volume of material is determined by the type of load transfer and is already considered. The degree of filling is limited by either the load capacity of 30,5 tonnes or volume restrictions. This research will illustrate that in most cases the weight, and not the volume, is governing.

7. Minimize assembly and disassembly procedures

The assembly and disassembly costs are influenced by different aspects. Some of these aspects are already discussed as separate design philosophy aspects.

- Larger and thus fewer elements: With fewer elements less hoisting activities are necessary to erect and disassemble the structure. The downside is that larger elements are more difficult to handle and require heavier lifting machinery.
- Light elements: The lighter the element the easier they become to handle and they require lighter lifting machinery.
- Connection methods: The connection should require minimal efforts and should be easily disassembled.
- Standardization and thus repetition speeds up the erection process.

3.2 Design methodology

The design methodology consists of two parts. Respectively, the design order and the design approach, which are discussed below.

Design order

In this research a conceptual design of roof, roof truss, horizontal grandstand, grandstand loadbearing frame and foundation is considered. Since all topics influence each other the following design order is applied.

The roof truss and the grandstand loadbearing frame can only be designed when the spans, and thus resulting loads, are defined. Therefore, the horizontal roof and grandstand structure are designed first.

To limit the amount of building elements while enabling an even load spread the roof truss will transfer the forces via the grandstand loadbearing frame. Therefore, the spans of the roof and the grandstand should be identical.

Since the loads on the grandstand exceed the roof loads they will require more material and make up a dominant part of the entire stadium structural volume. Therefore, first the horizontal grandstand is designed in accordance to the design philosophy. When the optimal span for the grandstand is determined, the roof is designed to adhere to the span predefined by the grandstand.

Once the span and loadbearing structure of the roof and the horizontal grandstand elements are known, the roof supporting truss, the grandstand loadbearing frame and foundation can be designed.

Of course, the design process will have an iterative character and will not be as linear as suggested above.

Thus, first the horizontal grandstand is designed and the span is determined. Successively, the roof is designed with its span defined by the grandstand. Once the horizontal elements are designed the roof, grandstand loadbearing frame and foundation can be designed.

Design approach

For every structural system a similar design approach is adhered to. The design approach is visualized in Figure 3-2.

Firstly, variants of the considered stadium components, derived from the typology study, are discussed and designed to adhere to both functional demands as well as the demountable and transportable desires. Subsequently, the structural demands are incorporated in the variant.

Once the variants are designed, they are assessed on their financial feasibility. The initial, maintenance and transportation costs are determined per variant. When these are known, the

variants can be compared to each other via a graph. In this graph, depicted in Figure 3-1, the vertical axis illustrates the costs and the horizontal axis the amount of venues.
The number of venues depends on both the design life of the stadium as well as the desired return of investment time. In the case of Figure 3-1, if the stadium will be used between 10 to 20 venues, roof skin variant 1 is the most cost efficient. However, if the owner thinks that the stadium will be used at least 20 times variant 3 becomes more attractive.
Furthermore, besides initial, maintenance and transportation costs other cost drivers are incorporated in the determination of the optimal variant. These cost drivers are the demountable and transportable desires depicted in Figure 3-2.

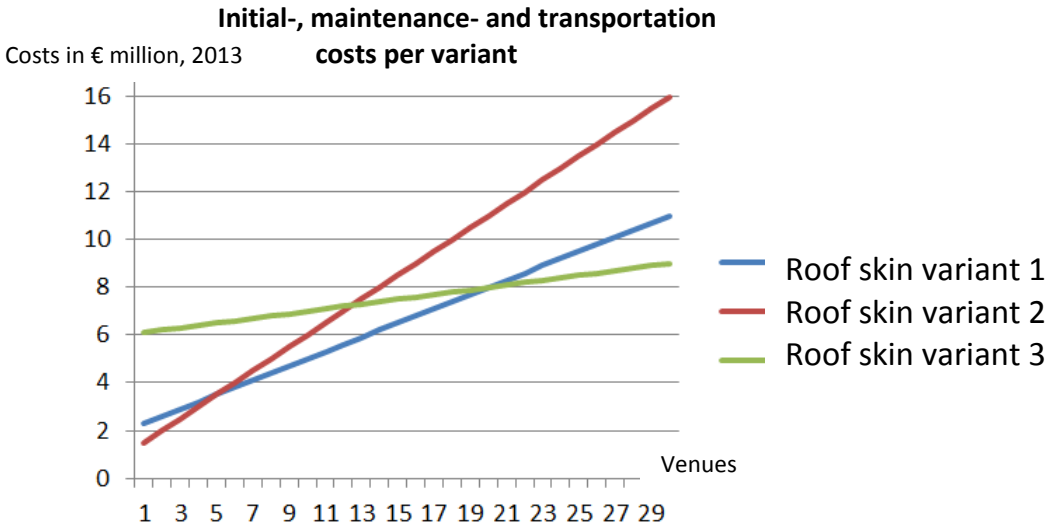


Figure 3-1 Graph design methodology

To summarize, the design approach can also be visualized in a flowchart as depicted in Figure 3-2.

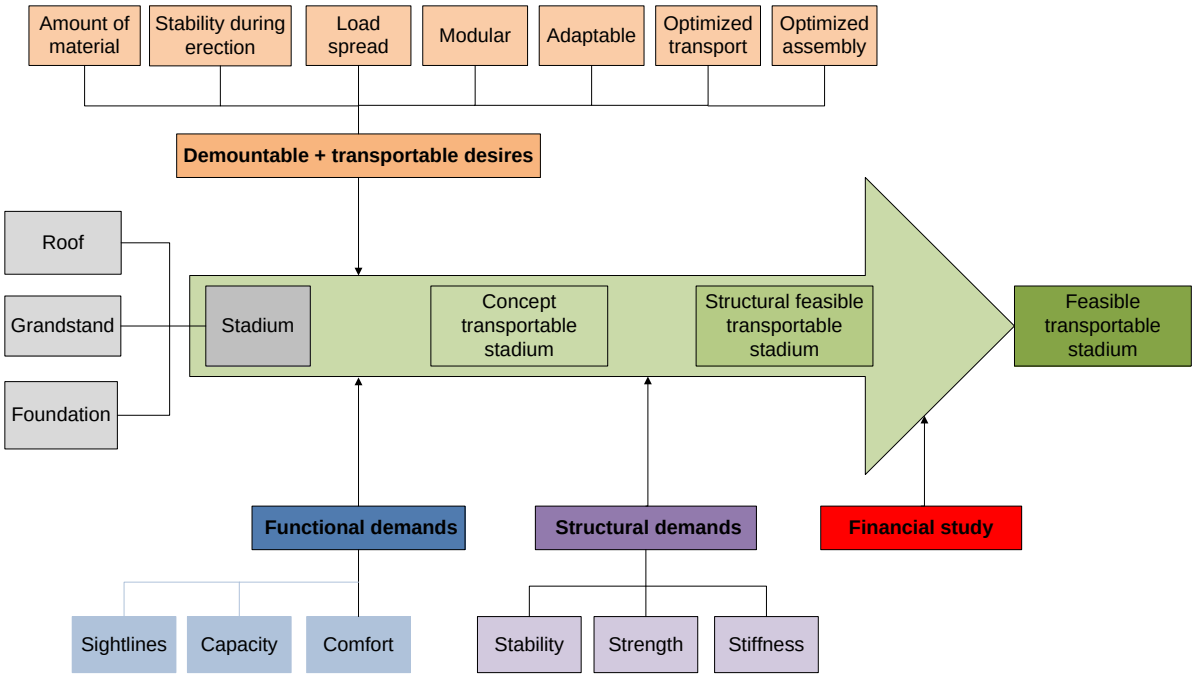


Figure 3-2 Visualization design approach.

4 Stadium architectural design

This chapter discusses the stadium architectural design in which the following topics are considered:

- Pitch dimensions
- Lay-out types
- Grandstand dimensions
- Roof

4.1 Pitch dimensions

The stadium should be adaptable to different pitch dimensions as well as different crowd capacities. The pitch dimensions of a soccer stadium are used to get a first insight in the architectural design of the stadium. Other popular sports such as American Football and field hockey all have dimensions similar or smaller than a soccer pitch. Therefore, the chosen starting point is valid.

National soccer authorities, such as KNVB (Royal Dutch Football Association), provide guidelines on minimum and maximum pitch dimensions. However, when hosting a premium international sporting event, the FIFA (International Federation of Association Football) imposes predefined pitch dimensions. The length should be precisely 105 m and the width of the playing field 65 m. Moreover, the FIFA demands a grandstand free area surrounding the pitch of 10 meters. Therefore, the stadium will have a grandstand free surface of 125 m * 85 m as displayed in Figure 4-1

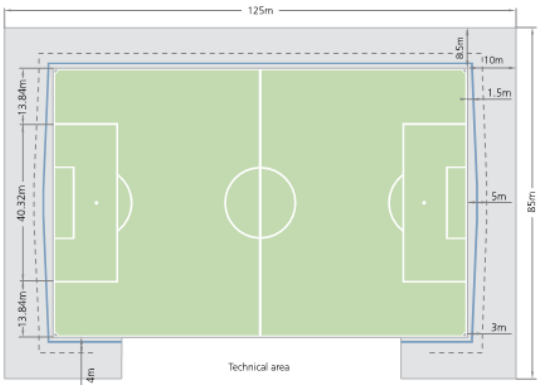


Figure 4-1 FIFA imposed pitch dimensions Source: (FIFA & Brown, 2007) #61

4.2 Lay out types

Nine different layout types of the grandstand are derived from literature (Nixdorf, StadiumATLAS). They are displayed In Figure 4-2.

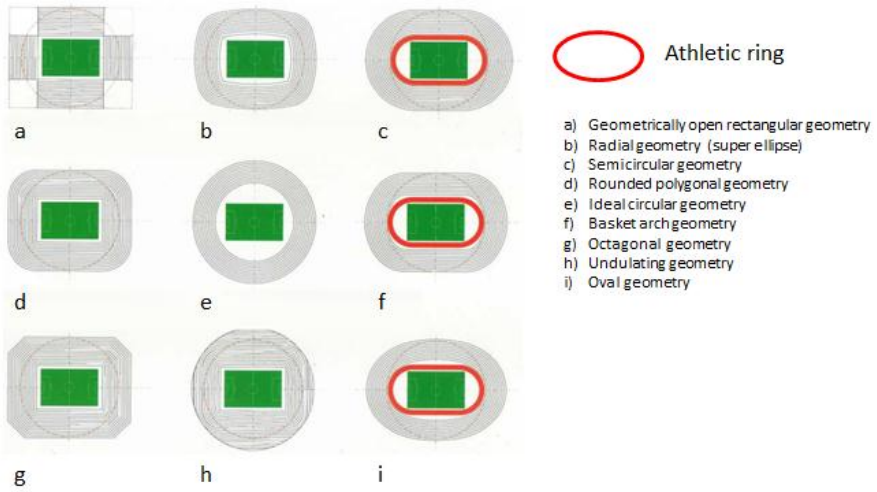


Figure 4-2 Grandstand lay out types Source: (Nixdorf, StadiumATLAS) #143

It is noted that these nine lay-out types act as a starting point for the lay out configuration. The lay outs applied in practice commonly approximates a lay out configuration but may alter slightly due to crowd routing or other practical implications.

Of the layout types in Figure 4-2 several systems can be ruled out in this research due to the following disadvantages:

- c,f and I are not considered because a stadium with an athletic ring is undesired by FIFA, spectators and players due to the distance between pitch and grandstand. However, the stadiums employability does increase if the stadium can host multiple sporting venues such as athletics. This is considered in Chapter 4.2.4.
- a is ruled out because UEFA (Union of European Football Associations) and FIFA consider solely bowl shaped lay outs as A-venue stadiums.
- e is undesired. Although the circular form creates equal viewing conditions among the crowd, the capacity is limited because the spectators are situated too far away from the pitch.

Of the design criteria described in the design philosophy, discussed in Chapter 3.1, only modularity differs for the four remaining lay out types (b,d,g and h). Furthermore, spectator's viewing angle on the pitch differs between lay out configurations and should be considered. The remaining lay outs are assessed on their modular performance, both horizontal elements as well as vertical elements and on their viewing angles performance.

4.2.1 Modular horizontal grandstand structure

When grandstands elements have a modular design at least three advantageous occur.

1. Onsite logistics: The building organization process speeds up because all elements are similar and it does not matter where each grandstand element is placed.
2. Transport: A modular design has many similar elements. This makes it easier to design elements to reduce the transportation volume as much as possible.
3. Assembly speed: Because all elements are identical the assembly procedure is similar which speeds up the erection and deconstruction process.

An ellipse lay out is not a modular structure because in an ellipse each grandstand segment will connect to each other in a different angle. Therefore, each horizontal element requires a specific location slowing down the building organization process. In order to improve the modularity the ellipse should be constructed as a circle. On a circle each segment has a similar angle creating a modular structure. This is visualized in Figure 4-3. Furthermore, when the radius of the grandstand on the short side and long side is identical, the angles are similar and all horizontal grandstand elements, except corners, are equal.

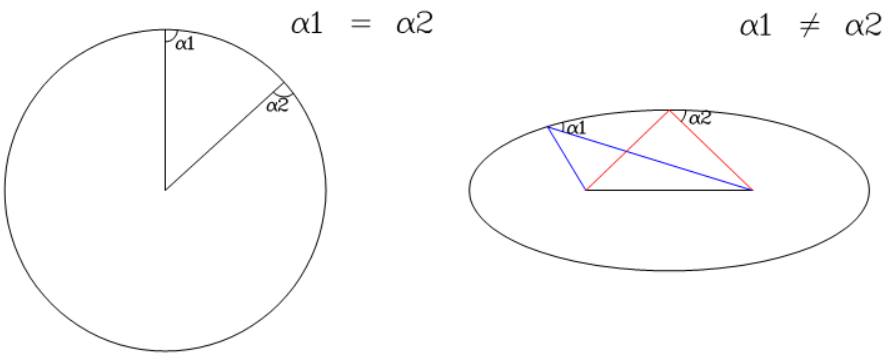


Figure 4-3 Angle differences between circle, depicted left, and ellipse, depicted right, along the perimeter.

Below the remaining lay-out types are assessed. In Figure 4-4 the areas which have identical horizontal grandstand structure have a similar color.

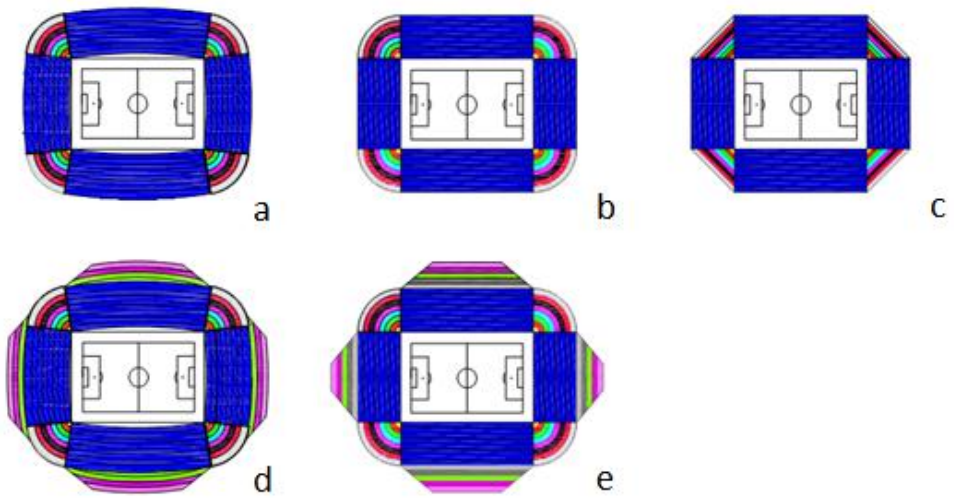


Figure 4-4 Modular horizontal grandstand comparison

The corners make it impossible to create a completely modular stadium. However, this argument holds for all considered lay out types.
The undulating oval shaped lay-out, figure d and e in Figure 4-4, extends its grandstand with rows on the centerline of the grandstand. This extension contains unique element which makes the undulating lay out slightly disadvantageous.

Conclusion
The modularity of the horizontal grandstand elements are similar. All configurations, except the undulating shape, have similar elements for the short and long grandstand. In each lay out type the corners will require a different segment.

N.B. Due to the sightline elevation the riser height is not constant. Therefore, the modular design only holds for specific vertical height. Not for the entire structure. This is discussed in chapter 4.3.

4.2.2 Modular vertical grandstand loadbearing structure

The advantages for a modular vertical grandstand loadbearing structure is identical to the horizontal grandstand structure discussed above. Three conclusion are drawn when judging the remaining five lay-out types.
Firstly, the determination of the location of the vertical elements is slightly easier in the lay-out orientation where the grandstand is parallel to the pitch compared to the super ellipse as depicted in Figure 4-5.

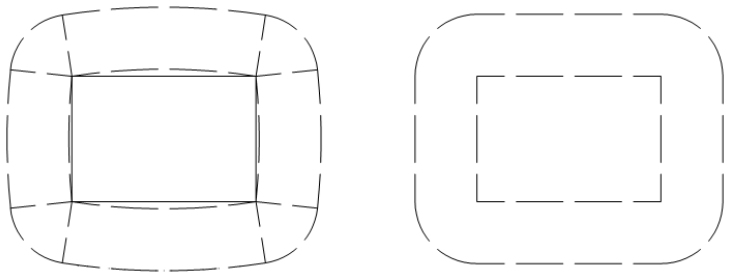


Figure 4-5 Modular vertical grandstand comparison 1

Secondly, the lay-out orientation has no impact on the modularity of the vertical supporting structure. Both in the super ellipse as in a lay-out orientation perpendicular to the pitch.

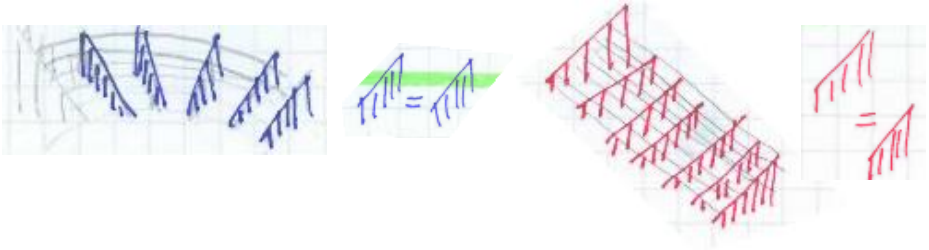


Figure 4-6 Modular vertical grandstand comparison 2

Thirdly, the undulating shapes, figure d and e in Figure 4-4, have less modular identical supporting structures compared to a straight orientation. It requires extension pieces which can be fitted to the frames used throughout the stadium. However, if the stadium roof is connected to the grandstand vertical frame this does increase the complexity of the extension pieces.

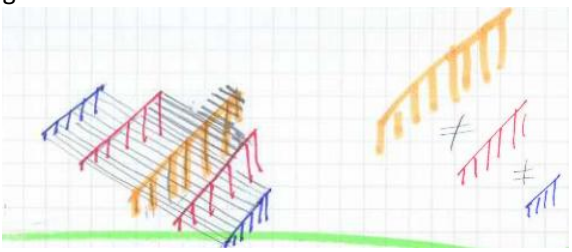


Figure 4-7 Modular vertical grandstand comparison 3

Conclusion

Once again, no striking differences occur for the considered lay out types on the modularity of the vertical supporting frame. However, again the undulating shape is slightly disadvantageous due to the necessary extension pieces.

4.2.3 Spectator's viewing angle

The lay out should assist in realizing good viewing conditions for all spectators. There are two important aspects which determine a good viewing angle:

- Whether or not a person can look over the head of the person in front.
- The angle required to view the entire pitch (necessity to tilt the head).

The first aspect depends on the riser height and is independent of lay out configuration. This is discussed in Chapter 4.3. The second aspect is influenced by the lay out configuration. Due to the fact that spectators in the super ellipse, figure a in Figure 4-4, are orientated towards the center, the sight lines are advantageous compared to an orientation parallel to the field. This means, that they will tilt their head and entire body less compared to the grandstand lay-out configuration parallel to the pitch. This is depicted in Figure 4-8.

$$\text{Max } \alpha_{1L}\,;\,\alpha_{1R} < \text{Max } \alpha_{2L}\,;\,\alpha_{2R}$$

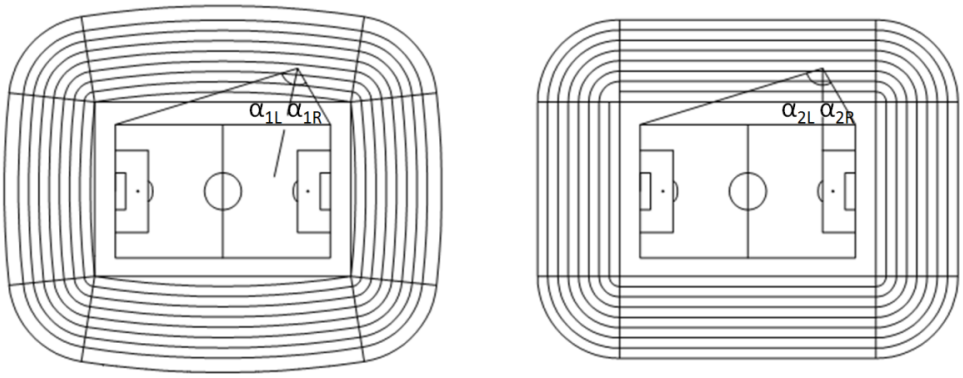


Figure 4-8Viewing angle for different lay-out configurations

4.2.4 Conclusion

The horizontal and vertical modularity is similar for all lay out configurations except the undulating lay out. Furthermore, the spectators viewing angle is better in the ellipse shaped configurations because the seats are orientated towards the center which requires less turning of spectator's head and body to view the entire pitch. Moreover, the ellipse shaped configuration are more bowl like shaped configurations which improves the atmosphere and is desired by both UEFA and FIFA.

Thus, the super ellipse, constructed out of a circle, is considered as optimal. The undulating variants are disadvantageous because they require extension segments to facilitate the additional rows. The remaining lay out configurations, figure b and c in Figure 4-4, are undesired because the grandstand orientation parallel to the pitch leads to poor viewing angles.

Another beneficial feature of the chosen lay-out is its adaptability. Segments can either be added or removed to adapt to the desired pitch dimensions. This makes the stadium both suitable for small playing fields such as tennis courts or large playing fields such as an Olympic ring.

4.3 Grandstand dimensions

In order to have a clear line of sight a spectator must be able to look over the head of the person in front of them. As displayed in Figure 4-9, when the riser height (R_i) is kept constant, the visible pitch area will decrease for the people on the higher rows. In order to still have the same point of focus, the riser height will have to be enlarged.

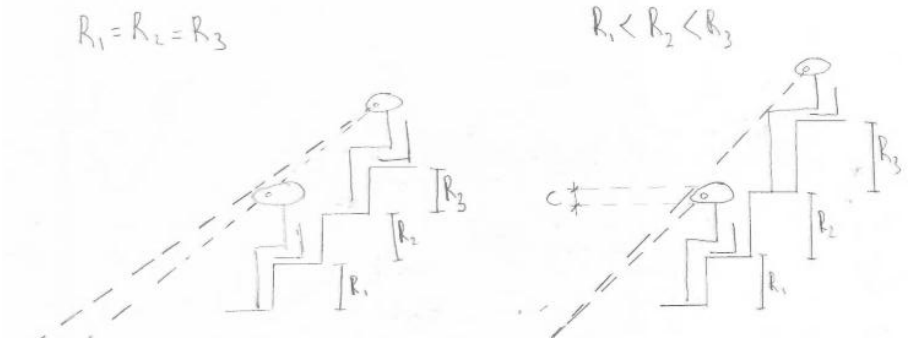


Figure 4-9 Line of sight sketch

The riser height difference is known as the C-value and is taken as a qualitative indicator for spectator's viewing conditions. The viewing conditions and the parameters which influence them are discussed below.

The following parameters influence the viewing conditions:

- P = point of focus. The chosen point of focus is the side line of the pitch. Therefore, the viewing conditions are independent of the type of sport or its pitch dimensions. And thus the stadium can be used to host a wide variety of sporting events.
- A = vertical distance to spectator located on first row.
- B = Stair row depth.
- C = 'C'-value, height difference indicating the possibility to look over head of person in front.
- D = horizontal distance to spectator located on first row.
- X = distance to specific spectator.
- R_h = Riser height.

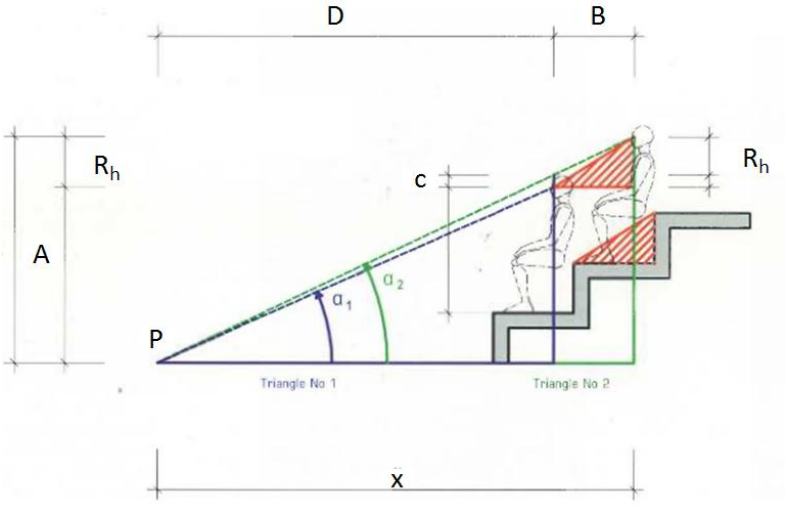


Figure 4-10 line of sight trigonometry Source: (Nixdorf, StadiumATLAS) #153

With trigonometry the relation between the parameters can be determined. (Nixdorf, StadiumATLAS) The purple triangle No. 1 is formed by the viewing conditions of the first spectator determined by its distance from the point of focus (side line) and the height on which he is located.

$$\text{Step 1: } \frac{A}{D} = tan(\alpha_1) \qquad (4.1)$$

In step two and three the triangle for the spectator on the second row is determined. This will introduce the tread width (B) and the sightline elevation C-value. In order to determine the angle of the green triangle No 2, the height of the triangle is determined by the height of the person in front and the desired C-value to look over the head of that person.

$$\textit{Step 2: } \frac{(A+C)}{D} = tan(\alpha_2) \tag{4.2}$$

When α_2 angle is known, the term S_a is introduced which is the vertical sightline distance of the eye-point height difference between two adjacent rows. The tread depth can be incorporated in the equation and trigonometry can be applied.

$$\textit{Step 3: } \frac{S_a}{B} = tan(\alpha_3) \tag{4.3}$$

With the vertical eye-point height difference known, the riser height of the row can be determined.

$$\textit{Step 4 } R_H = \frac{(A+C)}{D} * B + C \tag{4.4}$$

With this last step the riser height is determined as a function of A, B, C and D.

Different riser heights are realized when above parameters are altered. The riser height influences the design because it affects the height of the stadium and thus the design of the supporting structure. Furthermore, the riser height influences the steepness of the slope (α_r) which much be kept < 35° for spectators comfort. In the images below, the impact is displayed on the riser height and thus the slope of the stadium. Either parameter A, B, C or D is altered while the other parameters remain constant.

A

Green: First row height = 0,0 m
Yellow: First row height = 1,0 m
Red: First row height = 1,6 m

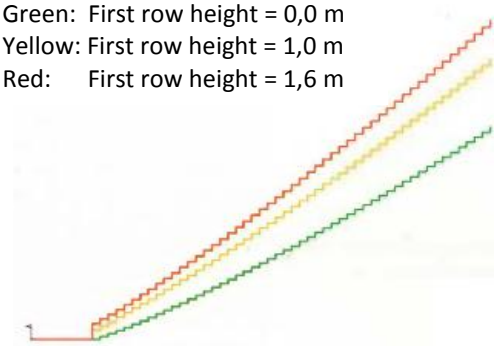


Figure 4-11 Line of sight, A-value (Nixdorf, 2007) #156

B

Green: Tread width = 0,8 m
Yellow: Tread width = 0,9 m
Red: Tread width = 1,0 m

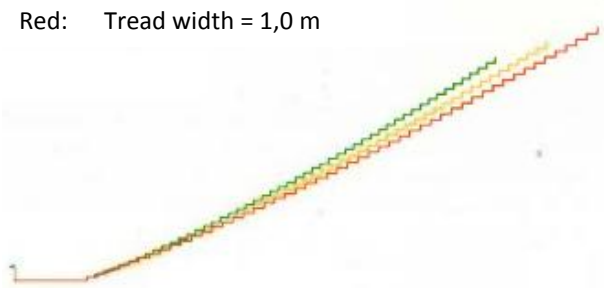


Figure 4-12 Line of sight, B-value (Nixdorf, 2007) #158

A: The height of the first spectator's row influences the slope. With a higher first row a steeper grandstand is required to maintain good viewing conditions
B: The deeper the tread width, the more shallow the slope (red line has a deeper tread width)

C Blue: C value = 15 cm
Green: C value = 12 cm
Yellow: C value = 9 cm
Red: C value = 6 cm

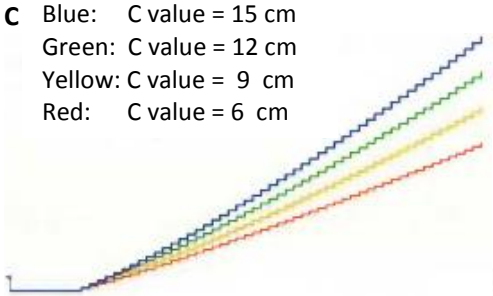


Figure 4-13 Line of sight, C-value (Nixdorf, 2007) #160

D Green: D = 6,0 m
Yellow: D = 7,5 m
Red: D = 21,0 m
Blue: D = 38,0 m

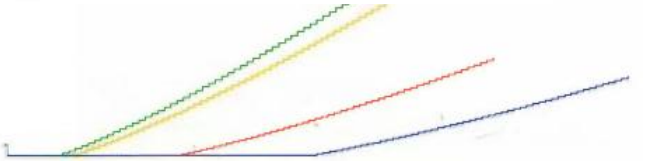


Figure 4-14 Line of sight, D-value (Nixdorf, 2007) #162

C: The higher the 'C' value of sightline elevation, the steeper the stand ascends
D: The further away the spectator is positioned from the point of focus, the shallower the slope

These parameters have the following conditions set by FIFA.

Parameter	Definition	Criteria
A	Vertical distance to spectator located on first row	- At least 0,8 m for viewing conditions first row - For safety measures 2 m is advised
B	Stair row depth	- At least 0,8 m for crowd circulation
C	C-value, sightline elevation	C < 0,06 m = unacceptable
		C = 0,09 m = acceptable
		C > 0,12 m = ideal
D	Horizontal distance to spectator located on first row	At least 10 m
α_r	Angle of radial gangway	< 35°

Table 3 FIFA imposed line of sight criteria

In this research only A is altered and the other criteria remain constant for the following reasons:

- B is kept constant. In order to reach the seats a minimal free space of 0,4 m is required. With seating depths of 0,4 m a minimal stairway depth is 0,8 meter is required. Enlarging the stairway depth will provide more comfort to reach a seat but will lead to spectators sitting further away from the pitch. This greater distance leads to larger dimensions which is undesired.
- C is kept constant. High quality sightlines are essential to be competitive in the stadium design business. Therefore, the design is chosen to have C value of 12 cm. To go above optimal is undesired because this will lead to unnecessary large dimensions.
- D is kept constant. In order to have a good connection with the game, it is desired to be as close as possible. The restriction posed by the FIFA of 10 m is adhered to, but to place the first row further away is undesired.

For safety reasons the maximum amount of rows is 30 before a large horizontal circulation ring is required (FIFA & Brown, 2007). With estimations on the seating width and space required for gangways the estimation is made that +/- 1000 spectators will sit on a row. To have a stadium suitable for high quality tournaments a capacity of +/- 50 000 is desired. Therefore, it is required to have two tiers. Furthermore, to be competitive in the stadium business, also a decent amount of VIP boxes should be provided. Therefore, a VIP area is placed between the two tiers. To create an estimation on the amount of rows required to create this capacity it is chosen to have a two tier configuration with in total 53 rows.
The formula of the riser height derived in *step 4* is applied to define the riser height.
Two calculations are performed to determine the dimensions of the grandstand when the height of the first row, parameter A, is altered.

The length of the supporting beam and its height and the angles of the tiers are determined in Appendix A6 which led to the following insights.

A constant c value will lead to a parabolic ascending riser height. However, an ascending riser height for a 2 tier grandstand with 53 rows will lead to 53 unique grandstand elements. The higher the number of unique elements, the more complex the building organization process becomes and the higher the investment costs become, this is undesired. Several measures can be taken to prevent the number of unique elements.
To provide all the rows with good viewing conditions a single riser height can be proposed. However, this is not an intelligent solution. This will result in a great part of the stadium having far larger riser heights than necessary increasing the height of the stadium unnecessary. In order to create an economical feasible stadium the number of unique elements should be minimized. Furthermore, the production costs will drop substantially if widely available standardized elements are used.

An iterative optimization process is conducted to design the riser heights with the following four requirements:

- Minimize the number of unique riser heights.
- Maintain good to excellent viewing conditions.
- Limit the total height of the grandstand.
- Choose the riser heights in accordance to widely available profile dimensions.

Result

The riser height study resulted in a grandstand design with only 3 unique elements with a riser height of respectively 360, 450 and 550 mm. 85% of the grandstand has excellent viewing conditions and the remaining 15 % have very good viewing conditions with a minimal C value of 89 mm. Furthermore, the entire height of the grandstand is only increased with 7% compared to a grandstand with fixed c-value and parabolic riser height. Thus, the optimization substantially increased the modularity of the grandstand while it had a limited impact on the viewing conditions.

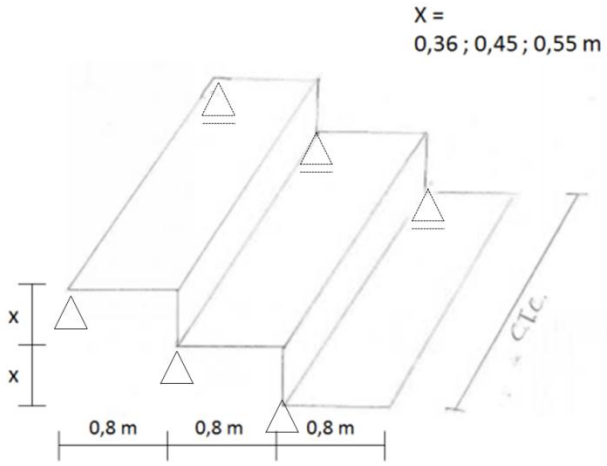


Figure 4-15 Grandstand outline

A =1,0m , B= 0,8m , C = variable, D = 10 m

Tier 1			
Row	Riser height	C – value range	
1 – 15	0,36 m	180– 91 mm	
16 - 24	0,45 m	175 – 168 mm	
Vip box height 4 meters			
Tier 2			
Row	Riser height	C – value range	
25 - 54	0,55 m	140 – 89 mm	
Radial gangway angle lower tier		25,7°	OK
Radial gangway angle upper tier		34,5°	OK

Table 4 Grandstand characteristics for optimized grandstand profile

4.3.1 Grandstand perimeter optimized in respect to span

In order to have identical frames the grandstand should be designed as a circle. In this manner, the angle along the grandstand is identical (being part of a circle) and thus each grandstand loadbearing frame is interchangeable speeding up the erection speed.
When the grandstand on both the long and short side of the pitch have a similar radius the frames and the horizontal grandstand elements are identical. Furthermore, the perimeter of the short- and long side should both consist of an exact multiplication of the span (10,8 m) to ensure that all grandstand elements are identical.
Later on in this research arguments are presented for the optimal center to center distance of the grandstand loadbearing frames of 10,8 m

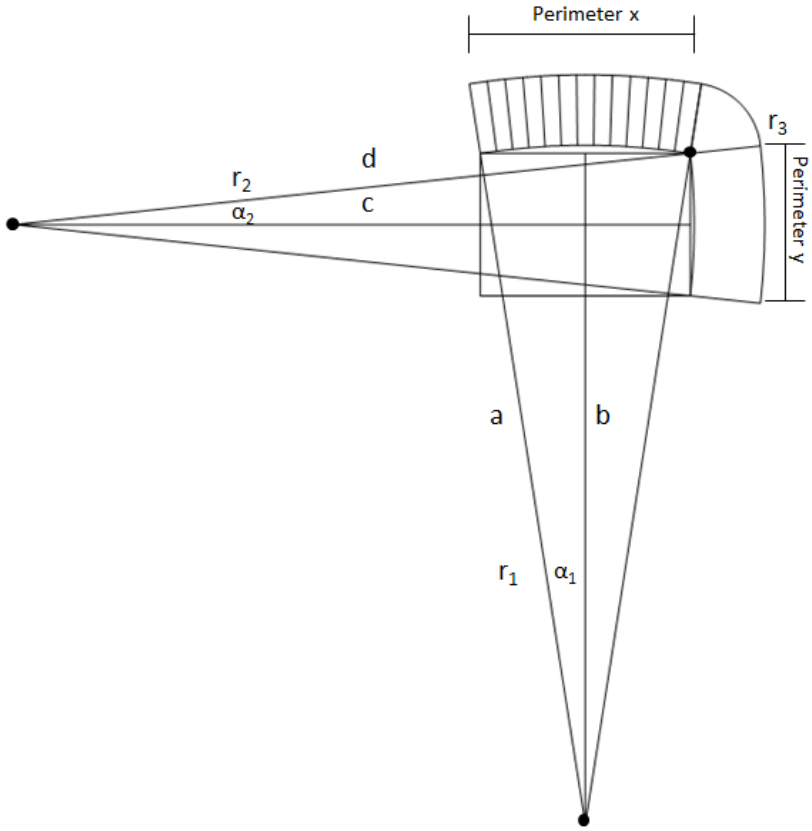


Figure 4-16 Grandstand perimeter optimization trigonometry

Below the optimization study to create identical segments with a perimeter exactly dividable by an even (whole) number of spans is discussed.
By making $r_1 = r_2$ the grandstand on both long and short side are identical. R_3 should be located on the corner of the pitch making all the frames throughout the stadium identical. If this is not the case frames in the corner will cross with the frames of the $r_1 = r_2$.
The curvature of the perimeter is influenced by $r_1 = r_2$ as follows:

- The smaller r_1, the bigger the curvature and more unused space is created close to the pitch in the center.
- The smaller r_1, the bigger the curvature which will result in spectators being more aimed towards the center improving the viewing angles for the spectators.
- The smaller r_1, the larger the perimeter.

In order to ensure that the perimeter can be exactly divided in the span of 10,8 m a trigonometry and optimization process has been developed and performed. Regarding Figure 4-16:

1. $a^2 = b^2 + 62,5$
2. $d^2 = c^2 + 42,5$ m
3. $a = d \rightarrow a^2 = d^2$
    a. $b^2 = a^2 - 62.5^2 \rightarrow b = \sqrt{(a^2 - 62,5^2)}$
    b. $c^2 = a^2 - 42.5^2 \rightarrow c = \sqrt{(a^2 - 42,5^2)}$
4. $\alpha_1 = \tan^{-1}\frac{62,5}{b}$
5. $\alpha_2 = \tan^{-1}\frac{42,5}{c}$

    Now both α_1 and α_1 can be expressed as value of a
6. Perimeter X : $2\pi(a+42,5)$

    $2\alpha_1$: 360

    This can be written as: Perimeter X = $\frac{2\alpha_1 * 2\pi(a+42,5)}{360}$
7. Perimeter Y : $2\pi(d+42,5)$

    $2\alpha_2$: 360

    With d= a, This can be written as: Perimeter Y = $\frac{2\alpha_2 * 2\pi(a+42,5)}{360}$

Now both Perimeter X and Perimeter Y are values of a.
In order to divide both perimeters in an exact number of spans both perimeters, which are determined by a, both perimeters should be exactly dividable by 10,8 m.

Conclusion
An optimization process is conducted to determine the circle radius to create an perimeter X and Y which is dividable by 10,8m. When a = d = 348 m, and thus $r_1 = r_2 = 348 + 42 = 380$, the perimeter X is made up out of 13 segments and perimeter Y is made up out of 9 segments. Leading to total of 44 segments for the long and short side of the stadium.

4.4 Roof

FIFA prescribes that all spectators are sheltered from both rain and sunshine with a roof. Stadiums can be designed with roofs which either cover only the spectators or the entire pitch. Furthermore, the roof which covers the entire pitch can either be permanent or temporary. A roof with the ability to cover the entire pitch has the following disadvantages.

- The playing field should be a column free area. Therefore, variable loads such as snow and wind load will require a substantial structure to transfer the forces.
- Sunlight is partly or entirely deprived from the playing field with a permanent pitch covering roof. This is harmful for the grass conditions.

A roof which can cover the entire playing field has the advantage that both the crowd as well as athletes are sheltered from harsh outside conditions (either sun or snow) and thus increasing the employability of the stadium.

The countless events of large sports tournament held all over the world without playing field covering roofs demonstrate that a pitch covered roof is not vital to host sporting events.

Figure 4-17 Left: Permanent playing field roof cover (Silverdome stadium) Right: Temporary playing field roof cover (Amsterdam Arena). Source: www.stadiumdb.com

Conclusion

A roof with the ability to cover the entire playing field has some advantage but requires a substantially larger loadbearing structure. This larger loadbearing structure will vastly increase both the initial- as well as the recurring costs of the stadium. Therefore, a stadium is designed with a roof covering only the spectators and leaving the athletes vulnerable to outside conditions to reduce both initial and recurring costs.

4.5 Conclusion

In this chapter the following conclusions are drawn:

- Pitch dimensions of 125 * 85 m are used as a starting point for the grandstand design.
- The grandstand consists of 2 tiers with a VIP area in between. Two tiers are necessary due to routing demands and the VIP area generates additional revenues.
- The grandstand consists of 3 different riser heights of respectively 360, 450 and 550 mm. Hence, the amount of unique elements is reduced while providing excellent viewing conditions.
- A super ellipse, constructed as a circle, is used for the bowl shaped stadium layout. This is a modular and adaptable lay-out and creates an involved atmosphere due to the bowl like appearance.
- The radius of the circular layout is 380 m resulting in 11 identical segments on the grandstand long side and 9 identical segments on the short side. The frames have a center to center distance of 10,8 m. No half span segments are necessary.
- No pitch covering roof is applied. This requires substantial supplementary loadbearing material. To date, the additional value does not outweigh the additional costs.

5 Building design classifications and list of requirements

In this chapter the building characteristics are determined. These characteristics are considered in the Euro Code[7] and will lead to different demands.

Reader guide

Firstly, the considered building code is discussed. Subsequently, the design- and consequence class of the stadium is determined. Furthermore, the load combinations with safety factors prescribed by the building code is discussed together with the possibility of a load reduction factor. Finally, the list of requirements is discussed.

5.1 Building code

In order to transform the structural system into a conceptual design building codes should be adhered to. The Dutch building codes have recently been replaced by the Euro Code. Because the stadium can be located anywhere in the world, the Euro Code is considered to be an adequate building code and this is used throughout this research.

5.2 Design class

Design working life category	Indicative design working life (years)	Examples
1	10	Temporary structures (1)
2	10 till 25	Replaceable structural parts, e.g. gantry girders
3	15 till 30	Agricultural and similar structures
4	50	Building structures and other common structures
5	100	Monumental building structures, bridges, and other civil engineering structures
(1) Structures or part of structures that can be dismantled with a view to being re-used should not be considered as temporary.		

Table 5 Design working life Source: NEN-EN 1990

The design life time of the structure should match the duration which the owner desires to exploit the structure. The foot node in the table states that the transportable stadium can not be considered as a temporary structure. Furthermore, the function of the stadium leads to an indicative design lifetime of 50 years. If a design lifetime of 30 years is chosen, as considered in the business case, the live loads defined in the Euro Code may be slightly reduced as discussed in Chapter 5.5. However, because this reduction is only 5,4 % a lifetime of 50 years is assumed. This adds value to the stadium because it can be used for a longer time period than initially assumed by the owner.

5.3 Consequence class

Consequences Class	Description	Examples of buildings and civil engineering works
CC3	**High** consequence for loss of human life, or economic, social or environmental consequences **very great**	Grandstands, public buildings where consequences of failure are high (e.g. a concert hall)
CC2	**Medium** consequence for loss of human life, economic, social or environmental consequences	Residential and office buildings, public buildings where consequences of failure are

[7] The Euro Code is a governing European building code introduced to create alignment throughout Europe regarding structural calculations. This enables both contractors and engineers to easily operate across borders without adjusting to local regulations.

	considerable	medium (e.g. an office building)
CC1	**Low consequence** for loss of human life, and economic, social or environmental consequences **small or negligible**	Agricultural buildings where people do not normally enter (e.g. storage buildings), greenhouses

Table 6 Consequence class Source: NEN-EN 1990

In the Euro Code it is clearly described that a stadium belongs to consequence class 3. Because, consequents of structural failure are catastrophic with 500 persons in the same location.

5.4 Load combinations and impact of Euro Code's National appendix

In order to design a structure which can resist the occurring loads, the Euro Code prescribes that different load combinations have to be considered. The structure should resist the forces resulting from the highest, thus governing, load combination.
In Table 7 the load combinations, applicable to consequence class 3, are presented for both the Euro Code as well as the Dutch national appendix and the old NEN. The variables ψ_0 are listed in Table 9. Below Table 7 the main differences are listed.

When the Euro Code and the Dutch National Appendix was introduced a transformation from 'safety classes' to 'consequence classes' was introduced. Compared to the NEN, the Euro Code introduced consequence class 3 for which higher load factors are governing compared to the old NEN. Because a stadium can be occupied by large crowds it should adhere to the load factors of the newly introduced consequence class 3.

The Euro Code currently makes no differentiation between consequence classes for load combinations. It only states that National Appendix should be considered. Therefore, the assumption is made that the depicted values of the Euro Code are applicable to buildings of consequence class II. In the Dutch National Appendix these values are increased with 10% when consequence class III is considered. If the 10% increase is applied to the safety factors listed in the Euro Code, the safety factors will match the values found in the National Appendix.

Permanent and temporary design situations	**Permanent load**		**Governing live load**	**Live load * simultaneous with governing load**	
	Unfavourable	Favourable		Important (when present)	Others
Euro Code					
Equation 6.10	$1,35 * G_{kj,sup}$	$1,00 * G_{kj,inf}$	$1,50 * Q_{k,1}$		$1,50\ \psi_{0,i}Q_{k,i}$
Equation 6.10a	$1,35 * G_{kj,sup}$	$1,00 * G_{kj,inf}$		$1,50\ \psi_0 * Q_{k,1} = 1,05 * Q_{k,1}$	$1,50\ \psi_{0,i}Q_{k,i}$ i > 1
Equation 6.10b	$1,15 * G_{kj,sup}$	$1,00 * G_{kj,inf}$	$1,50 * Q_{k,1}$		$1,50\ \psi_{0,i}Q_{k,i}$ i > 1
Dutch National Appendix					
Equation 6.10a	$1,50 * G_{kj,sup}$	$0,90* G_{k,j,inf}$		$1,65\ \psi_0 * Q_{k,1} = 0,99 * Q_{k,1}$	$1,50\ \psi_{0,i}Q_{k,i}$ (i >1)
Equation 6.10b	$1,30\ G_{k,j,sup}$	$0,90* G_{k,j,inf}$	$1,65 * Q_{k,1}$		$1,65\ \psi_{0,i}$ $Q_{k,i}$ (i >1)
Old Nen					
Equation 6.10a	$1,35 * G_{kj,sup}$	$0,90* G_{k,j,inf}$			
Equation 6.10b	$1,20 * G_{kj,sup}$	$0,90* G_{k,j,inf}$	$1,50 * Q_{k,1}$		

Table 7 Load combinations Source: NEN-EN 1990

The designer can choose whether equation 6.10, or the least favorite value of equation 6.10a and 6.10 b holds. The governing value of 6.10a or 6.10b will never be less favorable than 6.10.

Therefore, it is always advantageous to apply the least favorite of 6.10a or 6.10b instead of 6.10. Therefore, in this research equation 6.10 will not be considered.

The $\psi_{0,1}$ values differentiate both between the Euro Code and the National Appendix and are based upon the consequence class.
Comparing the old NEN with the new National Appendix the following is noticed:

- The Dutch national appendix 6.10b will lead to higher resulting forces than the old NEN
- The permanent load will be reduced as much as possible in a transportable stadium. Therefore, the contribution of the live load gains importance. In the new Dutch National appendix the safety factor of the live load is increased with 10% compared to the old NEN which is disadvantages

When the transportable stadium will be erected in The Netherlands, Dutch law (Bouwbesluit) prescribes that the Euro Code's Dutch National Appendix should be adhered to. Therefore, the Dutch National Appendix of the Euro Code is applied throughout this research.

Earthquakes
When the structural safety is studied in respect to earthquakes. The safety factors and load combinations should adhere to Table 8.

Permanent and temporary design situations	Permanent load		Governing live load	Live load * simultaneous with governing load	
	Unfavorable	Favorable		Important (when present)	Others
Euro Code					
Extraordinary 6.11a/b	1,00 * $G_{kj,sup}$	1,00 * $G_{kj,inf}$	1,00 A_d	$\Psi_{1,1}$ * $Q_{k,1}$	$\Psi_{2,i}Q_{k,i}$ i > 1
Earthquake Equation 6.12b	1,00 * $G_{kj,sup}$	1,00 * $G_{kj,inf}$	1,00 A_d	$\Psi_{2,i}Q_{k,1}$	$\Psi_{2,i}Q_{k,i}$ i > 1

Table 8 Earthquake safety factor and load combinations Source: NEN-EN 1990 : Table NB.7 A1.3

5.5 Reduction live load conditions

The safety factors applied in the Euro Code assume that the structure has a design life time of 50 years. However, when the design life time differentiates from 50 years a reduction factor can be applied. In the NEN-EN 1990 the following live load reduction formula is presented.

$$\text{The load reduction factor: } F_t = F_{t0}\left(1 + \frac{1-\Psi_0}{9}\ln\left(\frac{t}{t_0}\right)\right) \quad (5.1)$$

The value Ψ_o depends on the structures function. Furthermore, the Euro Code and the Dutch national appendix prescribe different Ψ_o values for similar functions.

Code	Function	Ψ_o value	Reduction factor
Dutch national appendix	Gathering places, also used as escape routes	0.6	0.946
Dutch national appendix	Gathering places, no escape routes	0.4	0.920
Euro Code	Gathering places	0.7	0.960

Table 9 Live load reduction factors Source: NEN-EN 1990

Since the formula is presented in the Dutch national appendix, the Ψ_o values of the Dutch national appendix is adhered to. The escape routes form an integral part of a stadium. Therefore, the entire stadium is considered as a gathering place which also functions as an escape route. If the design life time would be reduced to 30 years, the live load can be reduced by 0.946, which is 5.4%. However, the live load reduction of 5,4% does not outweigh the shortened life time of 50 to 30 years. Thus, the live loads acting on the stadium will not be reduced as explained in Chapter 5.2.

5.6 List of requirements

The stadium has to meet requirements which are posed by building code, sport organizations and owner's preference. The requirements are listed below. The requirements are numbered to ease the evaluation in Chapter 14.1 of the performance of the final design on the listed requirements.

Functionality

1. The stadium should adhere to the seven design criteria derived in the design philosophy discussed in Chapter 3.1.
2. The stadium should be adaptable to desired pitch dimensions imposed by different sports.
3. The stadium should provide sufficient flexibility to allocate functional areas underneath the grandstand.
4. The stadium should be designed with fire compartments to prevent fire spread.
5. The stadium is designed to be adaptable. However, the starting points desires a capacity of roughly 50.000 spectators.

Safety and comfort

6. Undesired vibrations imposed by the dynamic live load should be prevented. Therefore, the natural frequency of the stadium should be larger than 5 Hz.
7. The stadium components should be within the deformation limitations posed in the Euro Code. Because the requirements differ per stadium component. They are separately discussed in each chapter.
8. The spectators should be evacuated in a limited time span in the occurrence of an emergency and have multiple escape routes to prevent being trapped by a possible fire.
9. The spectators should have a good and unobstructed view on the playing field.
10. The spectators should be sheltered from direct sunlight and rain.
11. The grandstand steepness should be smaller than 35°.

Structural aspects

12. The stadium should adhere to demands regarding stability, strength and stiffness defined in the Euro Code.
13. The stadium should cope with moderate earthquakes and severe wind conditions.
14. The structural components should perform their function for a defined amount of time in the case of a fire.
15. Progressive collapse should be prevented.

Financial

16. The transportable stadium should be an attractive alternative for a permanent stadium if the owner is aware that the demand after the event is minimal.

5.7 Conclusion

In this chapter the following conclusion are drawn.

- The stadium is designed in accordance to design class 4 with an indicative life time of 50 years.
- Consequence class 3 is applicable to the transportable stadium.
- The safety factors, also applicable to earthquake load combination, are determined in accordance with Euro Code's Dutch national appendix .
- The live load will not be reduced. The amount of allowable reduction does not outweigh the reduced design life time.
- Multiple requirements are listed regarding safety, comfort, functionality, structural and financial aspects.

6 Horizontal grandstand system

The horizontal grandstand system makes up an essential part of the stadium. It plays a dominant role in both the (dis)assembly time of the stadium as well as the amount of material which will be transported.
With the grandstand outline defined in Chapter 4, the horizontal grandstand system can be designed. In this chapter different loadbearing horizontal grandstand systems with different compatible materials are investigated.

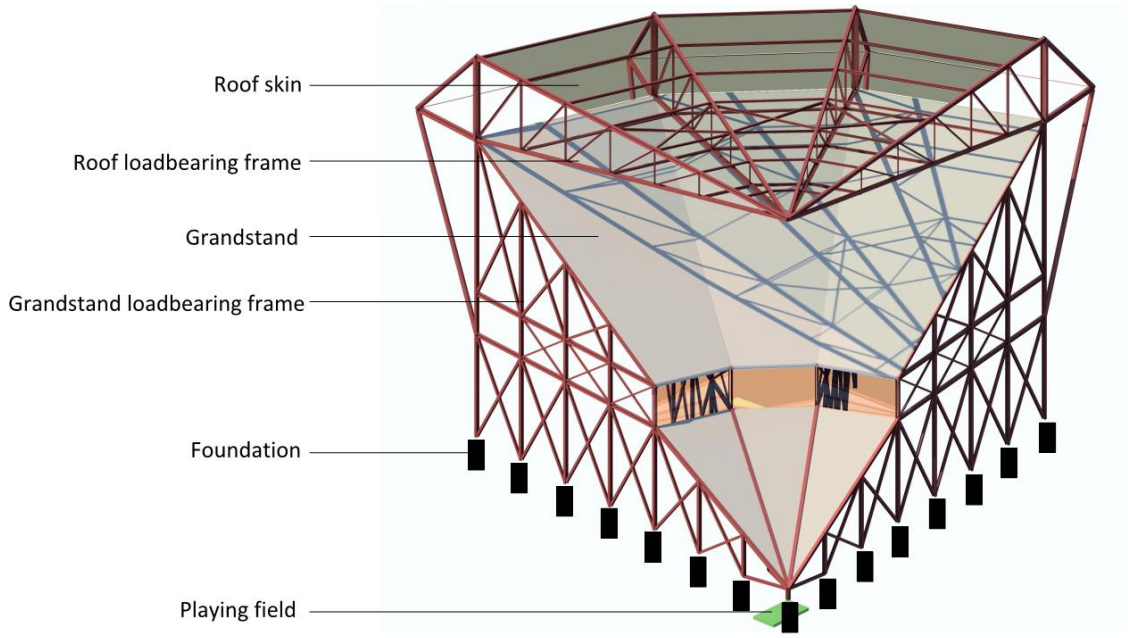


Figure 6-1 Overview of the structural components considered in this research

Reader guide
This chapter is structured as follows. Firstly, occurring loads are discussed. This is followed with an overview of grandstand systems derived from theory as well as systems applied in practice. Once the different possible systems are defined, the design criteria are listed. Furthermore, the consequence of different span distances is discussed. With all the boundary conditions defined. The actual design process can commence. Different materials are analyzed and for each material an optimum grandstand system is designed. Finally, a comparison between the different loadbearing systems and materials is presented. The system which is most in line with the design philosophy is recommended.

6.1 Grandstand loads

The occurring grandstand loads are depicted in Table 10 and determined in Appendix A1.

Load type	Calculation	Value
PG Grandstand structure	Depends on material	t.b.d.
PG Seating	Depends on seating type	Neglected
PQ Crowd	Defined in Euro Code	4 kN/m^2
PG Roof	Both the load from roof and wind are taken up by vertical grandstand loadbearing structure and are considered later in this research	
PQ Wind		

Table 10 Grandstand loads

6.2 Systems derived from theory

The horizontal grandstand system is made up from horizontal steps and vertical risers which are supported by a vertical grandstand loadbearing frame which transfers the forces to the foundation. Because this is a rather straightforward system, the differences between various grandstand designs are minor. Three different loadbearing systems are discussed.

In loadbearing systems 1, displayed in Figure 6-2, the grandstand outline defines the loadbearing structure. The outline prescribes the height of the vertical components. With the height limited, the amount of stiffness and thus span is also limited. The grandstand elements consists of several vertical and horizontal components creating one element. The amount of horizontal and vertical components which make up a single element is restricted by transportation and assembly means.

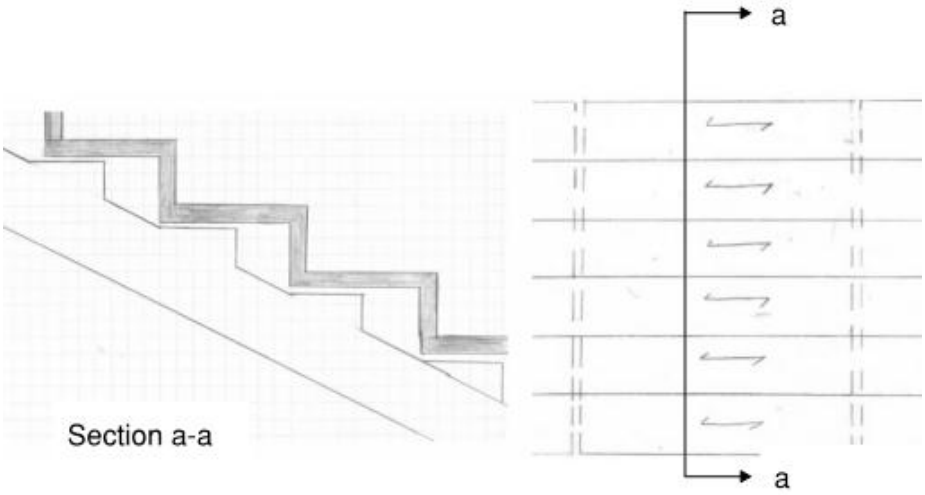


Figure 6-2 Loadbearing system 1. Left: section, Right: top view

Loadbearing system 2 is displayed in Figure 6-3 and is constructed out of beams, depicted as I profiles, which span between the two vertical grandstand loadbearing frames. Floors are placed on the top flange of the lower beam and on the bottom flange of the higher beam. It is also possible to remove a beam and create a stepped floor element. The height of the beam is limited because the floor elements span between top- and bottom flange. Therefore, the beam height is prescribed by the riser height. This loadbearing systems appears unattractive because the riser height prescribes the profile height limiting the possible span. The advantage is that this flat floor element can be extremely lightweight resulting in a small number of containers required for transport. Moreover, the same floor is applied in the entire stadium improving the erection and building organization process.

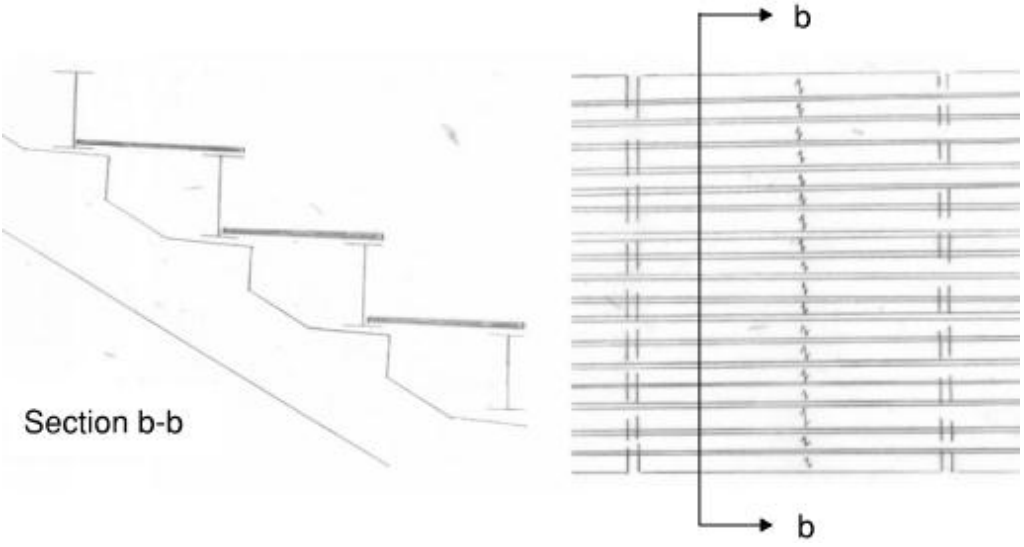


Figure 6-3 Loadbearing system 2. Left: section, Right: top view

Loadbearing system 3 is displayed in Figure 6-4. The grandstand is constructed out of beams spanning the two vertical grandstand loadbearing frames. In contrast to system 2, the riser height does not prescribe the beam height because the floors rest on the top flange on both sides. Furthermore, with stepped floor elements less beams can be applied. Similar to system 1 the number of horizontal and vertical components making up one floor element is restricted by transportation and assembly means.

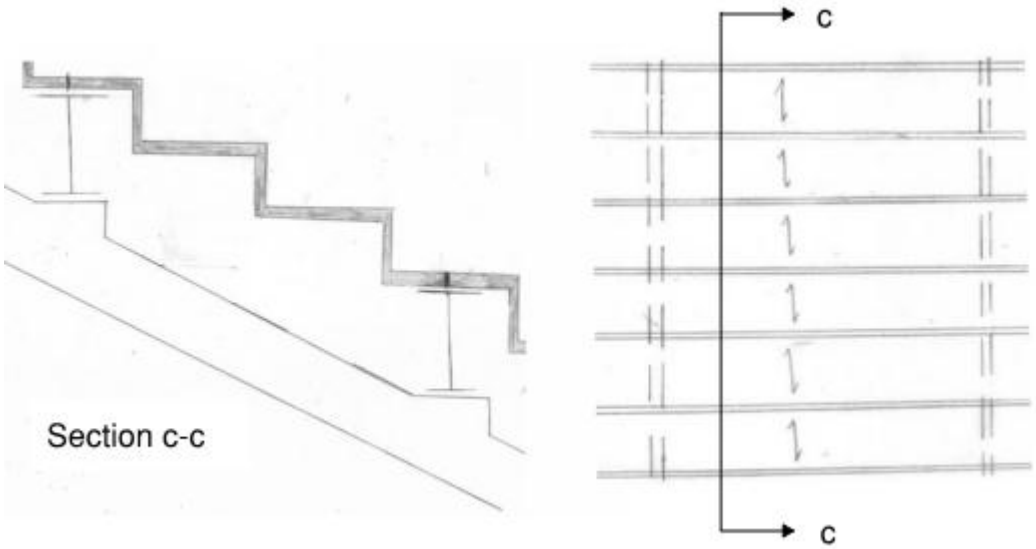


Figure 6-4 Loadbearing system 3. Left: section, Right: top view

6.3 Systems applied in practice

The first grandstand systems known to civilization date back to ancient Greece. The Greeks would have grandstand for sporting events as well as theatre gatherings. Ideally, the playing field would be located close to a hill to create a grandstand using the natural slope of the ground.

In modern stadium design several loadbearing systems can be identified. Loadbearing systems 1 can be constructed as z-elements or tilted t-elements. Both have been applied in practice as displayed in Figure 6-5.

Figure 6-5 Left: Tilted t-profile , Right: Z-profile Dortmund Energie stadion Cologne Source: (Nixdorf, 2007)

Loadbearing system 2 is applied in temporary grandstands as displayed in Figure 6-6.

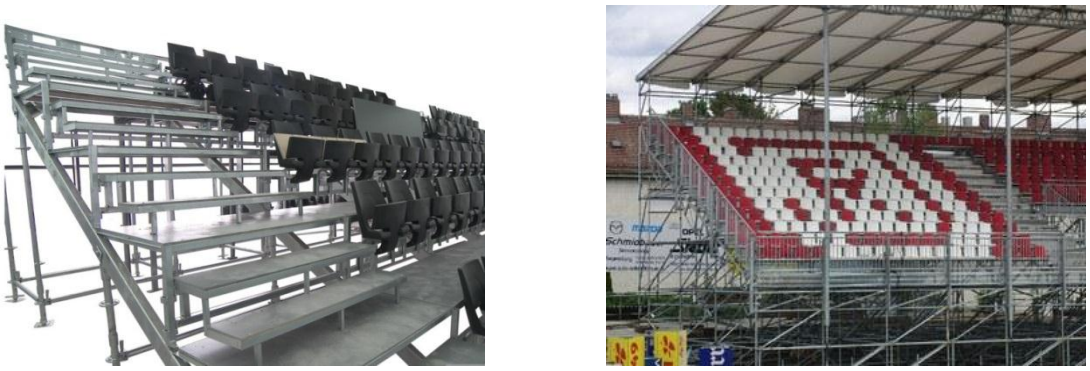


Figure 6-6 Temporary grandstand structures. Left: www.sportbleacher.com/ right: SSV Jahn Regensburgs stadium Source: www.nussli.com

No examples have been found of loadbearing system 3.

There is only a very limited number of transportable stadiums built in practice. They all use a scaffolding structure and none have the capacity aimed for in this research. A scaffolding structure is applied because the assembly process is straightforward and the scaffolding material is widely available. However, the scaffolding structure consists of slender profiles which result in a small span. Hence, there is no space available underneath the structure to allocate functions. Therefore, a scaffolding structure is undesired when designing an A-venue stadium. Thus, it will not be further considered. Almost all the permanent stadiums studied in the literature study are designed with concrete grandstands. Concrete has the advantage of being cheap and perfectly capable of handling the dynamic behavior enforced by jumping spectators due to its damping capacity. Loadbearing system 1 is most suitable when designing a concrete grandstand because the assembly and production methods are quick and cheap.

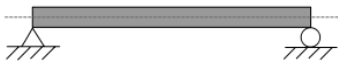
6.4 Design criteria

Each grandstand loadbearing system discussed in the previous paragraphs consists of vertical components (beams) spanning between the vertical loadbearing frames and the horizontal components (floors) spanning between the vertical components (beams). Both can be regarded as simply supported beams[8] with a different length.
The loadbearing systems are designed adhering to the design philosophy, described in Chapter 3.1. Furthermore, the conceptual designs of the grandstand loadbearing system are determined with assistance of the following nine design criteria:

1. Stability
2. Dynamic behavior
3. Stiffness
4. Strength
5. Lateral torsional buckling
6. Fatigue
7. Building sequence
8. Transportation demands
9. Fire resistance

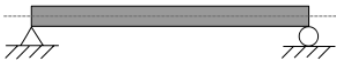
1. Stability
Stability is required to create a safe and reliable structure.

2. Dynamic behavior
Dynamic behavior concerns the natural frequency of the grandstand. The grandstand is considered to be simply-supported and the natural frequency is determined with equation 6.1. The μ represents both the own weight of the truss as well as the occurring live load in the Serviceability Limit State. The natural frequency of the system should be >5 Hz.



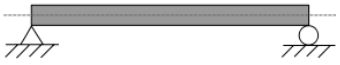
$$f = \frac{2}{\pi}\sqrt{\frac{3\,EI}{0{,}49\,\Psi_2\,\mu\,l^4}}\;Hz \tag{6.1}$$

3. Stiffness
The deflection of the grandstand element should not be more than 1/250 of the span in the Serviceability Limit State. The grandstand element is considered as simply supported and the deflection equation 6.2 applies.



$$w = \frac{5\,q\,l^4}{384\,EI} < \frac{l}{250} \tag{6.2}$$

4. Strength
The strength of the grandstand element is determined with the maximum occurring moment in the Ultimate Limit State. The occurring tension stresses should be below the Yield stress of the material.



$$M_{max} = \frac{1}{8}\,\gamma_q q\,l^2 \tag{6.3}$$

$$\sigma = \frac{M_{max}}{W} < f_y \tag{6.4}$$

[8] Simply supported beams are desired above continuous beams for two reasons. Simply supported beams are less sensitive for progressive collapse. Furthermore, a hinged connections between successive beams is less intensive to realize compared to a fixed connection.

However, above equations only hold for symmetric profiles. With asymmetric profiles the 'Momentvlakstelling' should be considered .

5. Lateral torsional buckling

With the downward directed load, compression forces will occur at the top flange. The profile becomes sensitive to lateral torsional buckling. The lateral torsional buckling can be checked as follows:

$$\lambda_{rel} = \zeta\sqrt{\frac{l*h*f_\gamma}{b*t_f*E}} \quad (6.5)$$

$$\frac{M_{y;s;d}}{\omega_{kip}*M_{y;el;d}} < 1 \quad (6.6)$$

6. Fatigue

Fatigue concerns the gradual degradation and eventual failure due to cyclic tension and compression loading of an element. (Abspoel, 2008) Since a grandstand will have many alternating cycles of being loaded and unloaded, fatigue should be considered.

Fatigue starts as a small crack on the profile's surface which gradually increases due to the fluctuating stress levels. The fatigue behavior can be influenced in three ways:

- Decrease the load and thus lower the stress differences.
- Influence the geometry to be without sharp thin edges. Thin edges have high localized peak stresses due to their small surface.
- Choose material with advantageous fatigue behavior.

Fatigue is determined with the assistance of an S - N curve as displayed in Figure 6-7.

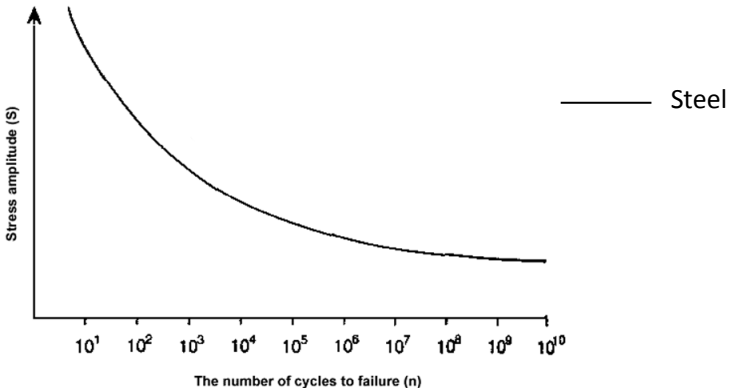


Figure 6-7 Fatigue S-N curve. Vertical axis is the stress difference, horizontal axis is number of cycles. The line illustrates steel's fatigue behavior. Source: www.lisgermany.com

Fatigue behavior is determined by the number of cycles and the difference in stresses. The occurring stresses can be determined when the profile and occurring loads are defined. However, the number of cycles is difficult to estimate. When we assume a stadium which will last for 30 years with an employability of 1 event per year, 10 matches per event, 5 hours per event and one load cycle every minute, $9*10^4$ cycles occur in the lifetime of the stadium. But the assumptions concerning the usage and occurring loads per hour is highly unpredictable. It is nearly impossible to determine the potential future events and its crowd characteristics. Therefore, efforts should be paid to minimize the stress differences.

The location where the highest stress difference occurs for a simply supported beam is at mid span. With the highest stresses occurring at mid span, it is not the connection but the profile which is

governing from a fatigue point of view.[9] With a continuous beam the highest occurring stresses are lower which is beneficial. However, the assembly efforts required to create a continuous beam are more costly than an intelligent design in which fatigue is considered.

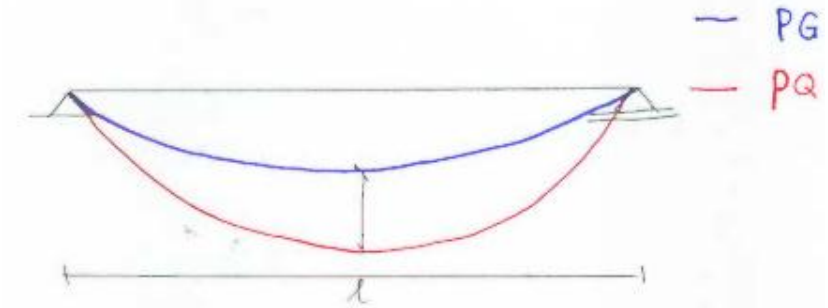


Figure 6-8 PG and PQ stress line for simply supported beam. The highest stress difference occurs at mid-span. Dimensions are omitted because this figure aims to demonstrate the concept of the highest stress location.

Since the material type and profile section have a substantial influence on the system's fatigue characteristics, the fatigue characteristics of each material type are discussed separately.

7. Building sequence
All grandstand elements will rest on grandstand loadbearing frames. The assumption is made that these vertical frames are not influenced by the material of the horizontal grandstand element. Therefore, to compare grandstand systems, the supporting frame is considered as defined and solely the assembly procedure to mount horizontal grandstand elements including seating is considered.

8. Transportation
Transportation plays a dominant role in the recurring costs of the stadium. The transportation capacity of a single container can be limited by either the maximum allowable weight or by volume restrictions. As already discussed in Chapter 3.1, a 40 foot sea container is chosen with dimensions of (l*B*H) of 12,0 * 2,4 * 2,7m and a weight restriction of 30.500 Kg.

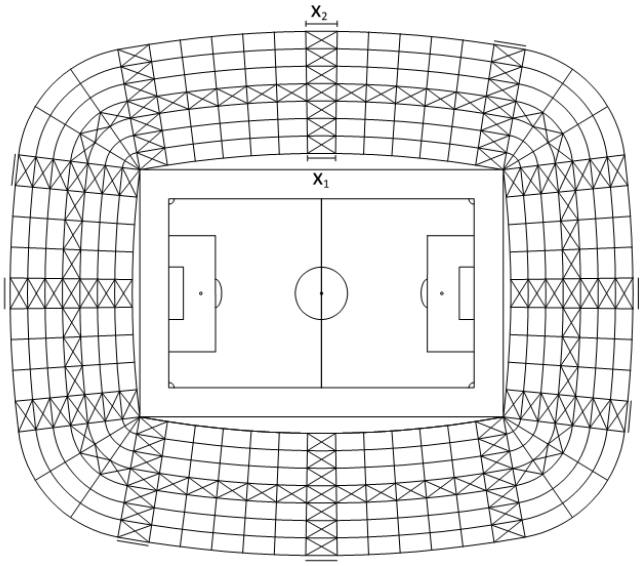
In the design process multiple transportation configurations are designed to identify the maximum number of elements which can be transported per container. With this knowledge the number of containers necessary to transport the entire grandstand can be determined.

The container loading configurations assumed in this research are possible in theory but further investigations are required whether certain configurations can be achieved onsite. This will demand specific hoisting machinery and supporting structure installed in the container.

Furthermore, investigations are conducted to identify the maximum capacity of a sea container if there are no weight restrictions. This is performed to demonstrate what happens when boundary conditions change.

Amount of elements for transportation
As discussed in Chapter 4, the stadium, except corners, is made up from 44 identical segments. Therefore, the number of steps is a multiplication of the number of rows which have the identical riser height multiplied with the number of segments, respectively 44.
Due to the circular shape of the stadium the riser height close to the pitch, thus having a smaller radius, span a smaller distance than the riser height located further away from the pitch. This is depicted in Figure 6-9.

[9] With a simply supported beam the forces at the field ends are transferred with shear forces. The connection should be capable of transferring these shear forces but this is not a governing design criterion.



$$x_1 < x_2$$

Figure 6-9 Stadium lay out. Circular shape leads to different spans between inner and outer perimeter

Therefore, each step should have a slightly different length. However, this can be partially taken up by fitting space and partially by placing blocks in the fabrication molds to ensure that each step has the appropriate length. Nonetheless, there is still enough repetition to ensure that the production costs are moderate.

Row	Number of rows	Riser height	Span	Number of steps
1 till 12	12	360 mm	9,8 m	12 * 44 = 528
13 till 30	18	450 mm	10,2 m	18 * 44 = 792
31 till 53	24	550 mm	10,8 m	24 * 44 = 1056
			Sum	**2380**

Table 11 Relation between rows, riser height, span and number of steps

In this research one step is considered to be one segment containing one riser height and one floor element. It becomes attractive to couple multiple steps for transportation, production and assembly reasons. This is considered in this research as an element, containing multiple steps.

9. Fire resistance
The grandstand should perform its function for a predefined duration while being subjected to a fire. This is discussed in Chapter 6.8.

6.5 Span grandstand elements

After identifying the possible horizontal grandstand systems and defining the design criteria, the optimal span of the horizontal grandstand element is determined.

The grandstand span is related to:

- Number of supporting frames.
- Dimensions and weight restrictions of transportation means.
- Seating section dimensions.
- Capacity hoisting machinery.
- Soil loadbearing characteristics.
- The roof trusses connect to the frames. The span of horizontal grandstand elements and roof skin should be identical.

6.5.1 Number of supporting frames

The number of frames influences:

- Amount of horizontal grandstand elements and number of hoisting activities.
- Amount of vertical grandstand loadbearing frames and number of hoisting activities.
- The concentration of forces introduced in the soil.

A balance has to be found for an appropriate span which:

- Reduces the amount of hoisting activities.
- Reduces the number of building elements and thus the transportation volume.
- Is within the limits concerning strength, stiffness and dynamic behavior.
- Limits the concentration of soil forces which require a pile foundation.

The perimeter of the stadium is approximated to be 2 * (145 + 95) = 480 m. Table 12 depicts the relation between the span of the supporting frames and the number of supporting frames.

Span supporting frames	Number of frames
5,4 m	88
7,2 m	66
10,8 m	44

Table 12 Number of spans in relation to ctc frames

Although a span of 10,8 will lead to higher concentrated loads introduced in the soil the reduction on hoisting activities and transportation volume due to lower number of frames outweighs this disadvantage. Moreover, if the soil loadbearing characteristics require also a pile foundation for a span of 5,4 m even more piles and time is required to install the piles. Another advantage is that a larger span will create less obstructions for the functional spaces situated underneath the grandstand.

6.5.2 Dimensions transportation means

Chapter 3.1 argued that transport via sea containers is considered.

		20' container	40' container	45' high-tube' container
Inside measures	Length [m]	5,87	12,03	13,56
	Width [m]	2,35	2,35	2,35
	Height [m]	2,39	2,39	2,70
Volume [m^3]		33,10	67,50	86,10
Max weight	[tonnes]	24,00	30,50	30,50

Table 13 Dimensions sea containers Sorce: www.searates.com

A grandstand element of 7,2 can not fit in a 20 foot container and makes inefficient use of a 40 foot container. When a grandstand element of 10,8 m is placed in a 40 foot container, 90% of the depth of the container is used.

6.5.3 Seating section dimensions

The seating section dimensions influence the optimal span and are determined by:

- Width of the seat.
- Allowable number of consecutive seats.
- Width of gangways.

FIFA prescribes that the minimum width of a seat to be 45 cm, 47 cm is recommended and a seat width of 50 cm is considered luxurious.

The evacuation guidelines prescribe that a maximum of 40 consecutive seats and 30 rows is allowed in one seating section followed with a gangway of at least 1,2 meter as depicted in Figure 6-10.

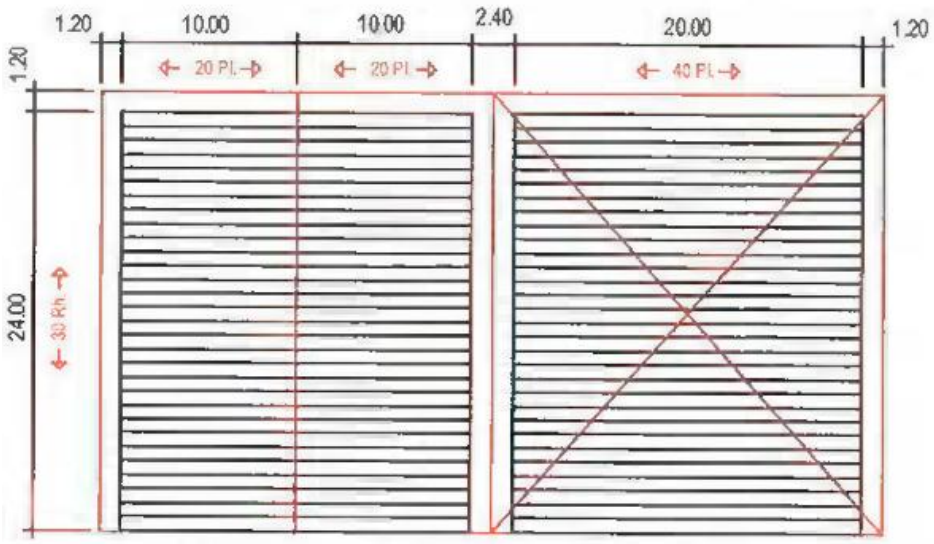


Figure 6-10 Seating section dimensions. Displayed distances in meters. Source: (Nixdorf, 2007) #117

With a seat width of 48 cm the width of two sections is 43,2 m which is equivalent to four times 10,8 m or 6 times 7,2 m. To conclude, the seating section does not prefer a particular span as long as it's a multiple of 3,6 m. This applies to all discussed grandstand loadbearing systems.

6.5.4 Capacity hoisting machinery

The span influences the dimensions and thus the weight of the elements.
The type of crane is influenced by both the load as well as the flight (horizontal distance). When the vertical grandstand support frame is entirely erected before the horizontal grandstand, the maximum fleight is 42 m. Cleaver building sequence solutions should be investigated to limit the flight, thus requiring lighter and cheaper cranes to erect the stadium.[10] In the case of an entirely erected support truss the maximum flight of 42 m prescribes a Liebherr LTM 1070 crane with a hoisting capacity ranging from 1,1 till 29 tonnes. For none of the materials the weight of a single element exceeds 29 tonnes. Therefore, the hoisting machinery does not pose any restrictions to the span. A table of possible cranes and their corresponding flight and weight restrictions is presented in Appendix A7.

6.5.5 Soil loadbearing characteristics

Bigger spans will lead to higher concentrated loads, which increases the potential demand for a pile foundation. However, when a pile foundation is required, less piles are necessary because less frames are present.

6.5.6 Conclusion

A span of 10,8 m is considered to be optimal because it minimizes assembly and transportation demands and optimizes the functional space underneath the grandstand. A smaller span leads to smaller profile dimensions. However, with a smaller span more loadbearing frames are required. The reduction on the number of loadbearing frames, and thus assembly and transportation efforts, outweighs the advantage of smaller profile dimensions. A larger span does not fit in a 40 foot container and is therefore undesired. Hence, a span of 10,8 is optimal.

[10] The width of the crane, including crane support structure, is 6,5 m and could fit between two frames lowering the flight distance.

6.6 Materialization

The grandstand can be designed with different materials. The grandstand materials which are considered in this research are chosen for their track record in the building industry as well as material costs. The following materials are considered: [11]

- Concrete
    - Standard prefabricated concrete
    - Pre-tensioned concrete
- Metal
    - Steel
    - Aluminum
- Composites
    - Glass fiber epoxy

Each material has different characteristics which should be used to their advantage. The differences between the materials expresses themselves in various ways. For instance, aluminum and composites do not have standardized production dimensions. This creates the opportunity to design an unique and optimized element.
The different E-modulus of the materials influences the design possibilities. For example, aluminum is lighter than steel but its E-modulus is 33% of steel influencing the possible spans.
The metal and composite systems are designed according to the design criteria described in paragraph 6.4. The concrete system is designed using construction manufacturing companies profiles.

[11] Timber is not considered as an attractive grandstand material due to its low E-modulus. Calculations demonstrated that large undesired profile dimensions are necessary to create moderate spans.

6.6.1 Concrete

Loadbearing system

The high compression strength of concrete combined with reinforcement, capable of transferring tensions forces, make it possible to span large distances with relative low heights. Furthermore, the production process using malts to create unique elements are not excessively higher than standardized elements when the ordered volume is substantial. Therefore, loadbearing system 1 is most suitable.

The concrete grandstand elements can either be constructed as z-elements or as tilted t-elements. The t-element has an higher profile height which make it possible to span larger distances. However, because the t-elements are easier damaged during transport and assembly, they will not be considered.

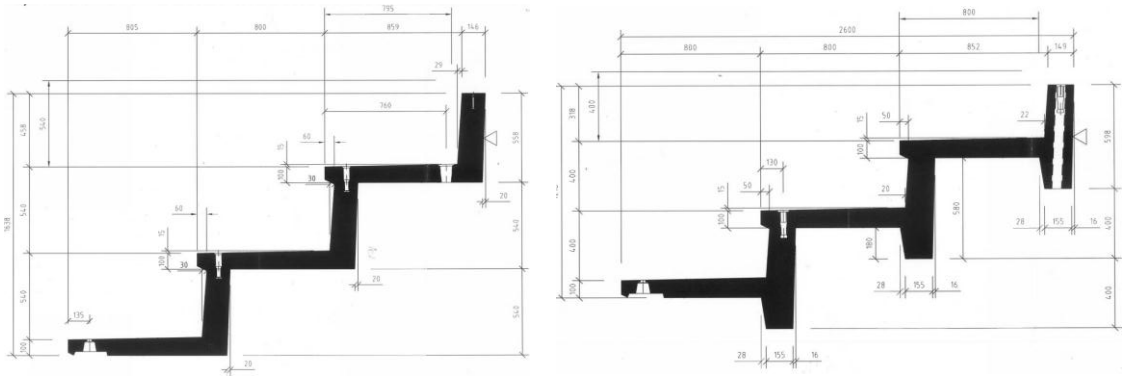


Figure 6-11 Section concrete grandstand profile. Left: z-profile, Right: t-profile Source: Haitsma Displayed dimensions are of no importance. The figure is solely presented to illustrate both configurations.

Material

The loadbearing structure follows the outline of the grandstand. The outline is defined and only the thickness of the elements can be adjusted. Concrete can be produced with pre-stressed elements. The normal prefab elements, applied in practice, have a thickness of 100 mm. The reinforcement in the concrete requires a covering of roughly 35 mm for an outside climate. When pre-tensioning is applied the stiffness is increased, but it not possible to create a more slender structure due to reinforcement cover restrictions. Another possibility is to apply ultra high strength concrete. The material can be produced with fibers. Because of the fibers the amount of additional reinforcement can be reduced or even omitted. (Walraven, 2006) Although the features of ultra high strength concrete are promising, it is not yet considered in this research.[12]

Maximum span

Concrete elements applied in practice are used to determine possible spans. Haitsma, Dutch market leader in concrete grandstand design, has none-pretensioned concrete elements spanning either 8,75 m and 10,8 m in both z- and t-shaped elements. For a z-profile spanning 8,75 m the section is 0,18 m^2/m. Thus, with a concrete density of 24 kN/m^3 the permanent load of the grandstand is 4,32 kN/m^2.[13] For a z-profile spanning 10,8 m the section is 0,19 m^2/m which leads to a permanent load of 4,56 kN/m^2.

The maximum span is also influenced by the dynamic behavior. The design of Haitsma is applied in numerous stadiums and therefore it is assumed that the prescribed possible spans adhere to the dynamic behavior requirement of a natural frequency > 5 Hz.

[12] This is partly because the research aims to provide insight in the 'standard' material comparison of common building materials. Furthermore, with slender concrete, the own weight is reduced significantly. Therefore, fatigue behavior, which is hard to predict due to ongoing research, could be a governing design criterion. Moreover, proper building code guidelines are not yet available.

[13] Concrete unit weight is 24 kN/m^3 in the NEN-EN 1991-1-1 Appendix A

Fatigue behavior

The fatigue behavior of concrete elements is influenced by both the concrete as well as the reinforcement. There is a substantial difference between pretensioned and standard reinforced concrete. Reinforced concrete is allowed to crack during the serviceability state which severely decreases the E modulus of the concrete and thus increasing the occurring stresses and decreasing the fatigue resistance. This situation will not occur for pretensioned concrete.

Attention should be paid to the fatigue resistance in a concrete grandstand design. Since the determination of concrete fatigue characteristics is rather cumbersome it will not be performed at this stage. It suffices to state that pretensioned concrete will behave better than standard reinforced concrete and that in general concrete has good fatigue characteristics.

Building sequence

1. Grandstand loadbearing vertical frame is erected containing pins on top.
2. Concrete elements with extrusions are placed on pins.
3. Seating is bolted on grandstand profiles.

(concrete is sufficient fire resistant. Hence, no additional measures are necessary)

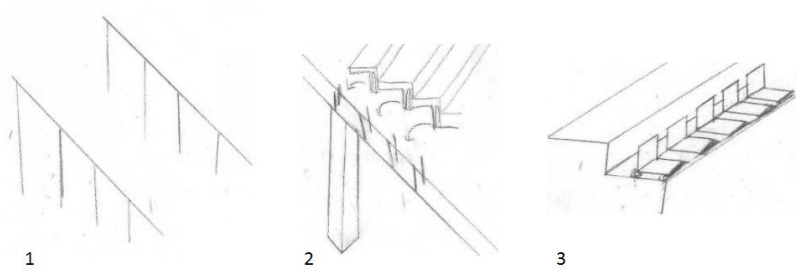


Figure 6-12 Building sequence concrete grandstand

Transportation

When concrete elements are made out of a single element with multiple steps less assembly activities are required. The number of steps influences the weight and dimensions of the profile. The maximum width of a sea container is 2,4 m and the height is 2,7. With a defined tread depth of 0,8 m it is difficult to fit multiple elements in a container. When the concrete elements are transported in sea containers the maximum number of steps can only be three when placed vertically which is undesired. So concrete grandstand elements should either have two steps or should be transported without sea containers.

Moreover, a single tree stepped concrete element weights 11 tonnes[14]. When a concrete element is transported via sea containers a maximum of 2 concrete elements contributing 6 steps and one element of 2 steps can be transported per container. So with 8 steps per container and a total of 2376 steps, 297 containers are required to transport the concrete grandstand.

Performance on design philosophy

	Concrete
Weight	8.893.651 KG
Maximum possible span	10,8 m
Building sequence	Elements with extrusions are placed on pins. Subsequently, seats are connected with bolted connection
Fatigue	Good
$€_{initial}$	Very low
# containers required	297

Table 14 Performance concrete grandstand on design philosophy

[14] Concrete element with width 2,4 m weighs 0,45 m^2 * 10,2 m *24 kN/m^3 / 9,81 = 11,2 *10^3 KG = 11,2 tonnes.

6.6.2 Steel and aluminum

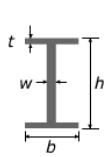
This chapter discusses the metals steel and aluminum. Firstly, the differences between the materials is discussed. Secondly, optimal grandstand designs for both materials are presented.

Material

When comparing steel to aluminum the following is stated:

- Aluminum has a lower density, respectively 2,9 times.
- Due to low E modules, $E_{steel} = 3\ E_{Alu}$, a 3 times higher I_{zz} is required to create equal EI.
- Low E Modulus makes aluminum profiles sensitive for both buckling as well as lateral torsional buckling.
- High live- dead load ratio makes aluminum sensitive to fatigue.
- The lower weight of aluminum decreases the required soil loadbearing characteristics and attracts less forces during earthquakes.
- Aluminum is more expensive to produce but creates the opportunity to design unique elements.

In Figure 6-13**,** a comparison between steel and aluminum profiles is presented from a structural point of view. In order to create similar EI values, the I value of the aluminum profile should be 3 times as high compared to a steel profile. The most efficient way to improve the stiffness while minimizing extra material is to enlarge the height of the profile. This will reduce the buckling resistance. Figure 6-13 clearly shows that, for an IPE 240 profile, when the height is restricted the required additional material to create the stiffness leads to profiles of similar weight. Thus, diminishing the lightweight advantage of aluminum.



		Steel	Al Alloy	Al Alloy
h	mm	240	240	300
b	mm	120	240	200
t	mm	9.8	18.3	12.9
w	mm	6.2	12	6
g	kg m^{-1}	30.7	30.3	18.4
Second moment of area	mm^4	38.9×10^6	116.6×10^6	116.7×10^6
EI	N mm^{-2}	8.17×10^{12}	8.16×10^{12}	8.17×10^{12}

Figure 6-13 Comparison EI characteristics steel aluminum profiles. Source: aluMATTER, 2012

When similar EI values are strived for two things can happen. The aluminum becomes higher and more slender compared to steel making it more vulnerable to buckling and fatigue. Or the aluminum profile becomes thick decreasing the lightweight advantage.

From a financial point of view, a comparison between steel and aluminum is influenced by several aspects. Both raw material prices of steel and aluminum depend on market demand and supply making it difficult to state the costs difference at any given time. Moreover, knowledge of both materials is required to design, handle and repair them. Since the knowledge concerning aluminum is less widely available the costs of an aluminum structure rises. However, aluminum has several advantages. It is a light material and is not effected by corrosion. Finally, the type of steel and aluminum is of influence. Weighing all pro's and con's, a common indicator applied in the building industry is that aluminum is in the range of 1,5 to 2 times as expensive as steel per kg. (Hollandia H. , 2013)

Conclusion comparison

The different materials are optimal for different spans and loadbearing systems. When a customized profile is desired aluminum is advantageous and a moderate span can be achieved.

With steel larger spans can be realized but the profile dimensions are predefined. Aluminum is in the range of 1,5 to 2 times as expensive as steel per kg.

Loadbearing system

For steel loadbearing system 2 and loadbearing system 3 are considered. Loadbearing system 1 is unattractive due to the customized shape which substantially increases production costs. The stepped floors of loadbearing system 2 and loadbearing system 3 should have a none-slippery rough surface and behave well in different climates. Therefore, the steps should not be constructed as steel floors.

For aluminum loadbearing system 1 is considered. The aluminum grandstand system is designed as a z-element. In this manner, usage is made of the riser height increasing the stiffness of the profile. Furthermore, the characteristic of aluminum to be produced in any shape is most advantageous in loadbearing system 1.

The aluminum grandstand design is assumed to be a z profile. But because the ends of the z-profile are connected to a consecutive z profile they are considered as symmetrical elements. The web of the element is prescribed by the riser height and the width of the flange is half the floor depth of 800mm. This is demonstrated in Figure 6-14. Due to this assumption use can be made of 'vergeet mij nietjes' when dimensioning the profiles.

Figure 6-14 Schematization aluminum grandstand step

The assumption that half of the floor depth is activated (as a flange) is supported by the fact that the highest stress will occur at mid span and that this location is sufficiently far away from the support to activate the entire half floor depth to take up the load as depicted in Figure 6-15.

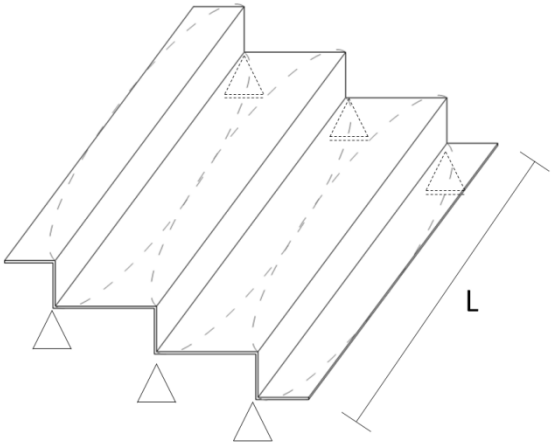


Figure 6-15 Flange activation in relation to profile location

Maximum span

The riser height of the steel structure with loadbearing systems 3 is not predefined. Considering transportation restrictions, it is assumed that a three stepped floor element is used creating a center to center distance of 2,4 m, PQ is 9,6 kN/m^1. For loadbearing system 2, the height is prescribed by the riser height. It will be investigated if the steel profiles, respectively IPE 360, 450 and 550, can span 10,8 m while having a center to center distance of 0,8 m, PQ is 3,2 kN/m^1.

Since loadbearing system 1 is chosen for aluminum the riser height steers the possible span. The riser height of 360 mm will lead to lower possible spans compared to the riser height of 450 and 550 mm. Therefore, for each riser height different profiles are designed. The center to center distance of the aluminum profile is 0,8 m, PQ is 3,2 kN/m[1].
To get a first insight in the possible maximum span the following criteria should be adhered to :

- Dynamic behavior
- Stiffness
- Strength
- Lateral torsional buckling
- Fatigue
- Building sequence

Material characteristics

Material	Profile	Weight [kN/m]	E [N/mm2]	I_y [mm^4]	W_y [mm^3]	Yield stress [N/mm^2]
Steel	IPE 360-O	0,65	210 E3	19050 E4	1047 E3	235
Steel	IPE 450	0,76	210 E3	33740 E4	1500 E3	235
Steel	IPE 550	1,03	210 E3	67120 E4	2668 E3	235
Aluminum	Height = 360 mm $t_{web} = t_{flange}$ = 18 mm	0,59	69 E3	53650 E4	2592 E3	300
Aluminum	Height = 450 mm $t_{web} = t_{flange}$ = 13 mm	0,43	69 E3	62520 E4	2340 E3	300
Aluminum	Height = 550 mm $t_{web} = t_{flange}$ = 12 mm	0,42	69 E3	89237 E4	2640 E3	300
Steel	IPE 600	1,20	210 E3	92080 E4	3069 E3	235

Table 15 Material characteristics steel and aluminum profiles

Performance on design criteria
As discussed in Chapter 4 the circular shape of the grandstand results in different spans for the three different riser heights. Thus, riser height 360 mm spans 9,8m, riser height 450 mm spans 10,2m and riser height 550 mm spans 10,8m.

Design Criteria	Frequency [Hz]				Deflection [mm]				Tension [N/mm^2]			
Span	**5,4**	**7,2**	**9,8**	**10,8**	**5,4**	**7,2**	**9,8**	**10,8**	**5,4**	**7,2**	**9,8**	**10,8**
Steel IPE 360- O	22,3	12,5	6,7	5,6	1,1	3,4	11,6	17,0	21,4	38,0	70,5	85,6
Alu 18*18*360	21,7	12,1	6,6	5,4	1,1	3,5	12,2	18,0	8,4	15,0	27,8	33,8
Allowable values	*>5,0*	*>5,0*	*>5,0*	*>5,0*	*<21,6*	*<28,8*	*<39,2*	*<43,2*	*<235*	*<235*	*<235*	*<235*
Span	**5,4**	**7,2**	**10,2**	**10,8**	**5,4**	**7,2**	**10,2**	**10,8**	**5,4**	**7,2**	**10,2**	**10,8**
Steel IPE 450	29,2	16,4	8,1	7,4	0,6	2,0	7,9	9,9	15,2	27,1	54,4	60,9
Alu 13*13*450	23,8	13,4	6,7	5,9	0,9	2,9	10,1	14,9	9,1	16,2	30,0	36,4
Allowable values	*>5,0*	*>5,0*	*>5,0*	*>5,0*	*<21,6*	*<28,8*	*<39,2*	*<43,2*	*<235*	*<235*	*<235*	*<235*
Span	**5,4**	**7,2**	**10,8**	**14,4**	**5,4**	**7,2**	**10,8**	**14,4**	**5,4**	**7,2**	**10,8**	**14,4**
Steel IPE 550	39,9	22,5	9,9	5,6	0,3	1,1	5,3	16,8	9,9	17,6	39,6	70,4
Alu 12*12*550	28,4	16,0	7,1	4,0	0,7	2,2	11,3	35,7	8,7	15,5	34,9	62,0
Steel – IPE 600	29,2	16,4	7,4	4,1	0,6	2,0	9,9	31,3	20,5	36,4	81,9	145,7
Allowable values	*>5,0*	*>5,0*	*>5,0*	*>5,0*	*<21,6*	*<28,8*	*<43,2*	*<57,6*	*<235*	*<235*	*<235*	*<235*

Table 16 Performance steel and aluminum profiles on design criteria

Lateral torsional buckling

In hindsight, it is concluded that the aluminum grandstand element is most advantageous. Therefore, only these elements are checked for their lateral torsional buckling capacity. As stated in the design criteria of this chapter, the relative slenderness is determined first with:

$\lambda_{rel} = \zeta\sqrt{\frac{l*h*f_y}{b*t_f*E}}$. Once this is determined, the following unity check should be adhered to.

$$\frac{M_{y;s;d}}{\omega_{kip} * M_{y;el;d}} < 1$$

$\zeta = 1{,}23$

$\omega_{kip} = \frac{1}{\lambda_{rel}{}^2}$

$M_{y;s;d} = \left(\frac{1}{8}\right)\gamma_q * q\ (l)^2, \qquad [\gamma_q * q = 1{,}65 * 4{,}0\ kN/m\ ]$

$M_{y;el;d} = W_y *\ f_y$

Material	Profile	E [N/mm2]	W_y [mm^3]	f_y [N/mm^2]	l [mm]	ω_{kip}	Unity check
Aluminum	Height = 360 mm $t_{web} = t_{flange}$ = 18 mm	69 E3	2592 E3	300	9800	0,31	0,36
Aluminum	Height = 450 mm $t_{web} = t_{flange}$ = 13 mm	69 E3	2340 E3	300	10200	0,17	0,72
Aluminum	Height = 550 mm $t_{web} = t_{flange}$ = 12 mm	69 E3	2640 E3	300	10800	0,11	0,89

Table 17 Lateral torsional behavior aluminum profiles

Thus, lateral torsional buckling is not a governing design criterion. The profile dimensions are steered by the natural frequency demand.

Fatigue behavior

In Figure 6-16 the fatigue curve of both steel and aluminum is displayed. Aluminum has no fatigue limit, so each load cycle contributes to the fatigue performance. Furthermore, the dead- live load ratio determines the maximum and minimum occurring stresses influencing the fatigue behavior. The maximum stress occurs when fully loaded in the Serviceability limit state, the minimum stress occurs when fully unloaded in the Serviceability Limit state. The Δσ of prescribes the number of loading cycles before fatigue failure occurs.

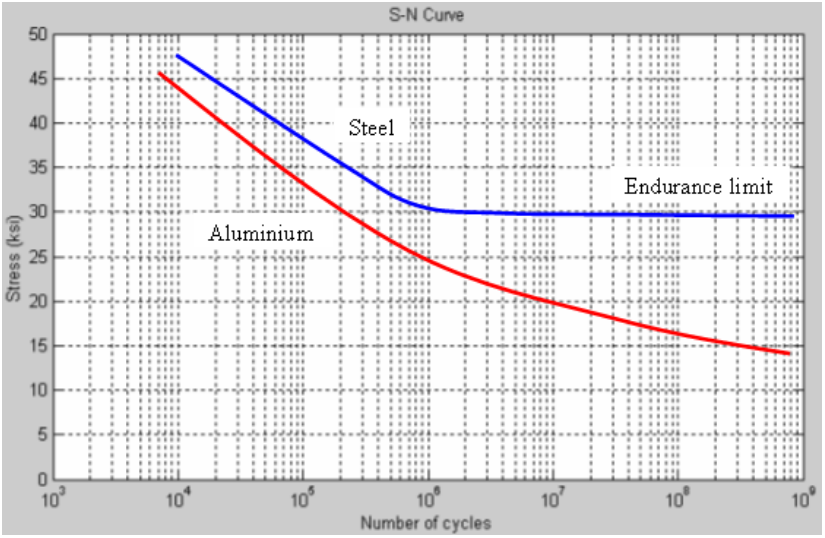


Figure 6-16 Fatigue curve steel and aluminum Source: Kalpakjian, Manufacturing Engineering and technology, 1995

Profile	Max stress [N/mm^2]	Min stress [N/mm^2]	Delta stress [N/mm^2]	Possible loading cycles	Additional measures required?
Steel IPE 360- O	42,5	7,4	35,1	$2 * 10^5$	No
Alu 18*18*360	17,6	1,7	15,9	$2 * 10^8$	No
Steel IPE 450	33,0	6,6	26,4	∞	No
Alu 13*13*450	20,2	2,4	17,8	$8 * 10^7$	No
Steel IPE 550	24,0	6,2	17,8	∞	No
Alu 11*11*550	20,0	2,3	17,7	$8 * 10^7$	No
Steel – IPE 600	50,1	5,7	44,4	∞	No

Table 18 Fatigue behavior steel and aluminum profiles

Thus, fatigue is not a governing design criterion. The profile dimensions are steered by the natural frequency demand.

Building sequence steel, both loadbearing system 2 and 3.

1. Grandstand loadbearing vertical frame is erected
2. Steel beams are bolted on diagonal beam of supporting frame
3. Composite floors are bolted onto the steel beam
4. Rails, mounted with seats, are bolted onto either the steel beam or composite floor
5. Fire proofing should be investigated

Building sequence aluminum

1. Grandstand loadbearing vertical frame is erected
2. Aluminum profiles with floor covering are bolted on diagonal beam of supporting frame
3. Rails, mounted with seats, are bolted to the aluminum profile
4. Fire proofing should be investigated

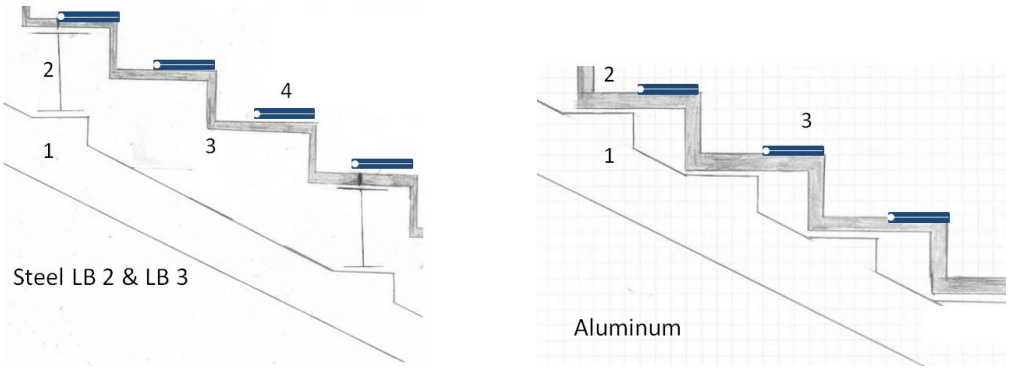


Figure 6-17 Building sequence grandstand Left: Steel loadbearing system 3. Right: Aluminum

Floors for steel structures

For the materials concrete, aluminum and composite loadbearing system 1 is preferred. This system already contains a horizontal component which acts as a flooring system. Some of these materials may require additional covering to provide a non-slippery surface and protect the material, but at this stage this is not considered.

Steel is the only material in which loadbearing system 2 or 3 is favored. The floor of loadbearing system 2 is flat and rest between the top flange of one beam and the bottom flange of the consecutive beam with a floor span of 0,8 m. The floor of loadbearing system 3 is a stepped element which spans between the beams with a center to center distance that is steered by transportation means.

Material

The floor can be designed with different materials. Considering the practical requirements (e.g. easy to handle and assemble) and earthquake design limiting the mass of the grandstand, the materials steel, aluminum and composite are considered.

The floor system is used throughout the entire stadium and contributes hugely to the total mass of the stadium. Therefore, a lightweight material such as steel, aluminum and composite is attractive. Furthermore, the grandstand should be mendable, hooligan proof and should require a rough surface providing sufficient grip to the persons walking and jumping on the grandstand. Moreover, the grandstand should require as little maintenance as possible and should behave well in all weather conditions.

Aluminum is a less precious material which will be damaged when in direct contact with steel. Therefore, an aluminum floor element should be covered with additional material to prevent direct contact with the steel beams. This makes aluminum an unattractive material as flooring material for both steel variants.

Comparing the steel and composite floor variant regarding weight, mendability, rough surface and minimal maintenance activities a composite floor is considered to be the most attractive option.

Thus, a composite flooring system is investigated for both steel variants.

Dimensioning

For loadbearing system 2 the span of the floor element is between the beams which have a center to center distance of 0,8 m. The flat floor element is considered to be one solid slab. Resulting in the I_{yy} being 1/12 bh^3 and W_y = 1/6 bh^2. The span is decreased to 0,7m due to the width of the flanges. With a thickness of 13 mm the resulting natural frequency is 12,1 Hz, stresses are 12,1 N/mm^1 and a deflection of 2,17 mm occurs where 2,8 mm is allowed. Weighing 23,4 kg/m^1.

For loadbearing system 3 a 3 stepped element is considered. Unfortunately, because the span is between the beams no advantage is made of the stiffness available in the riser height.

When the floor is designed as a solid slab, similar to loadbearing system 2, a thickness of 60 mm is required weighing 108 kg/m^1. This profile results in a natural frequency of 5,8 Hz, stresses are 20,7 N/mm^1 and a deflection of 9,48 mm occurs where 9,60 mm is allowed.

The composite floor element can also be designed with two flanges and a negligible web stiffness. The web cavity for the floor of loadbearing system 2 is 20 mm and the thickness of the flanges are 22 mm weighing 79,2 kg/m^1. This profile results in a natural frequency is 6,1 Hz, stresses are 13,1 N/mm^1 and a deflection of 8,56 mm occurs where 9,60 mm is allowed.

A sketch of the stepped profile is presented in Figure 6-18. Detailed calculations to determine the thickness and center to center distance of the web to provide the necessary stiffness to the flanges are omitted in this stage.

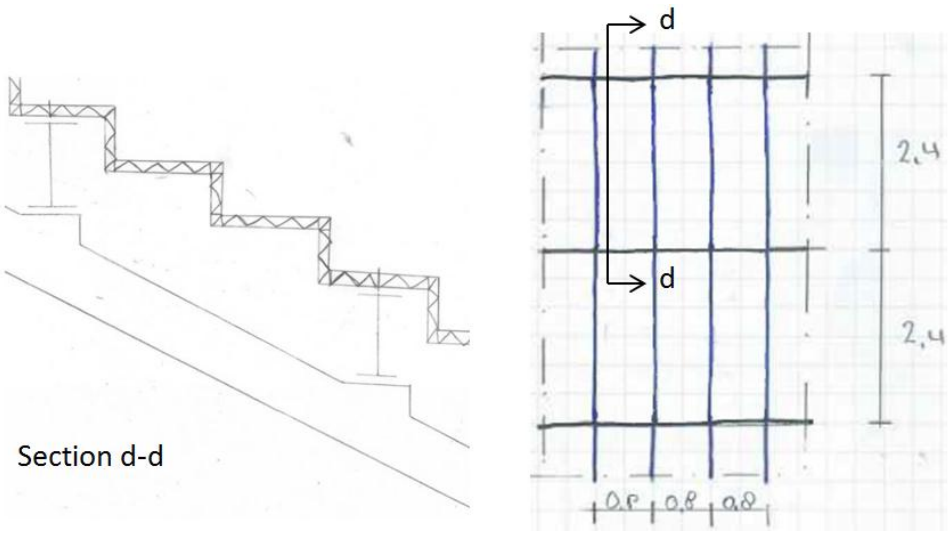


Figure 6-18 Section three stepped floor profile. Left, Section of the profile. Right top view in which the vertical lines are the crenate web location and the horizontal lines are the boundaries of a single tree stepped floor element.

Connection
Connections are designed for the stepped floor of loadbearing system 2 and 3.

Floor connection loadbearing system 2
The floor can be connected to the beams in numerous ways. Different floor designs for loadbearing system 2 have been investigated, the results are presented in Appendix A8. A focus point to compare the different connection possibilities is the ease of (dis)-assembly. The optimal floor system is considered to be the flap.

A flap system is easy to place and fix between the steel beams. It consists of a floor with two flips locking the floor between the two beams. These flaps can be pushed out sideways of the floor to enclose the flanges and prevent the floor from being lifted. When the floor is dismantled the lever can be pulled to pull the flaps inside and to remove the floor system. The lever should be designed with hooligan proof knobs so that they can only be used by the assembly workforce.

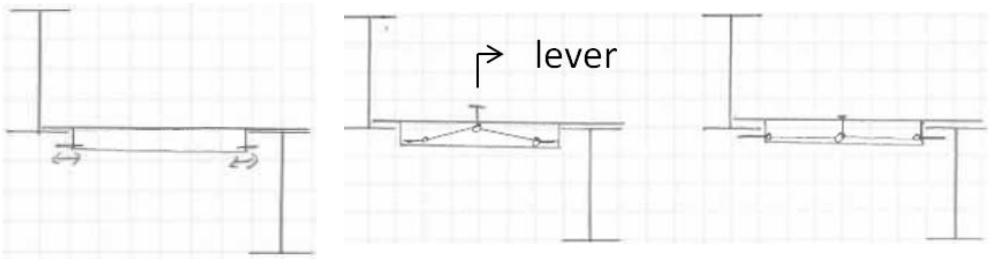


Figure 6-19 Connection composite floor to steel I profile of loadbearing system 2

Floor connection loadbearing system 3
The connection should prevent the floor element from moving in all three directions. A bolted connection is the quickest and easiest method to realize this. A sketch of the floor connection is presented in Figure 6-20.

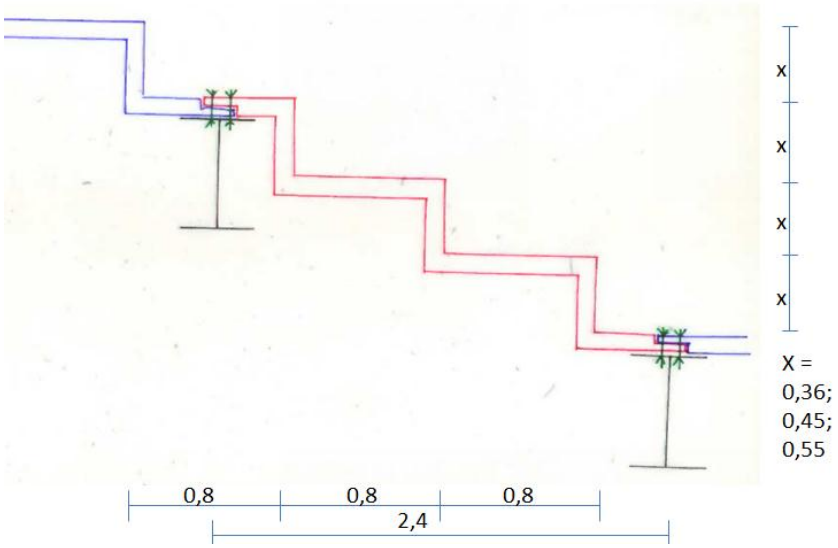


Figure 6-20 Bolted connection composite floor to steel IPE profile. Flange thickness of floor element and bolt configuration is not yet determined.

Transportation
Steel, loadbearing system 2, is assessed on the design criteria. This is summarized in Table 19.

Profile	Kg / m1	Kg / step	Max steps per container (weight)	Max steps per container (volume)	Governing number of steps per container	# of containers necessary
IPE 360-O	66,0	646,8	47	98	47	528 / 47 = 12
IPE 450	77,6	792,5	38	60	38	792 / 38 = 21
IPE 550	105,5	1139,4	26	44	26	1056 / 26 = 41
Subsum						**74**
Compo floor 360 mm	23,4	229,3	133	623	133	528 / 133 = 4
Compo floor 450 mm	23,4	238,7	127	623	127	792 / 127 = 6
Compo floor 550 mm	23,4	252,7	120	623	120	1056 / 120 = 9
					Sum	**93**

Table 19 Transportation demands steel grandstand loadbearing system 2

Weight steel = 528 * 646.8 + 792 * 792,5 + 1056 * 1139,4 = 2.173.343 KG
Weight composite floors = 528 * 229,3 + 792 * 238,7 + 1056 * 252,7 = 576.972 KG

Steel, Loadbearing system 3
For loadbearing system 3 the same beam is used throughout the entire stadium. The only minor differences is the length ranging between 9,8 and 10,8 m. Therefore, the beams are considered to all have a length of 10,8 m and the necessary amount of containers is a slightly conservative but realistic approach.

Below the different floors for steel loadbearing system 3 are designed in respect to transport configuration.
Different stacking configurations are considered for the riser height of 360 mm and displayed in Figure 6-21. The number of steps is restricted by weight to 34 steps. With different stacking configurations either 10 elements, 30 steps, or 21 elements, 42 steps, could be transported if weight was unrestricted.

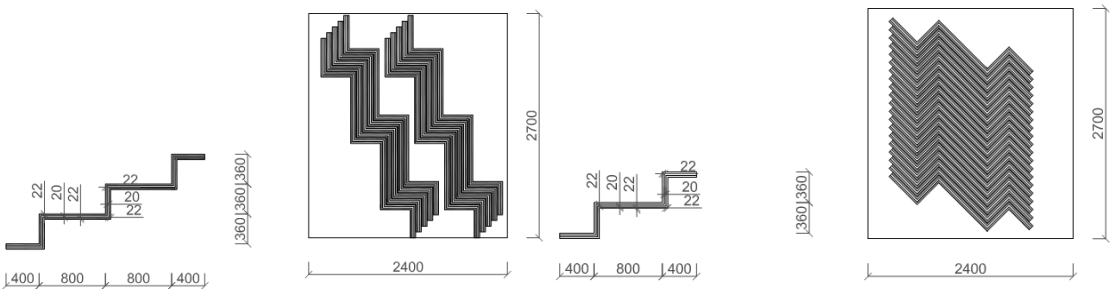


Figure 6-21 Stacking configurations composite floors riser height 360 mm

For the riser height of 450 mm a 2 steps per element configuration is considered and displayed in Figure 6-22. The number of steps is restricted by weight to 31 steps. With a 2 steps per element 42 steps could be transported if the weight was unrestricted.

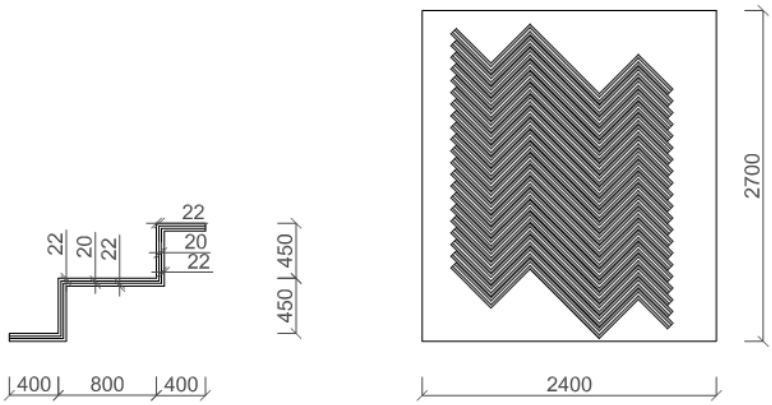


Figure 6-22 Stacking configuration composite floors riser height 450 mm

For the riser height of 550 mm a 2 steps per element configuration is considered and displayed in Figure 6-23. The number of steps is restricted by weight to 29 steps. With a 2 steps per element 40 steps could be transported if the weight was unrestricted.

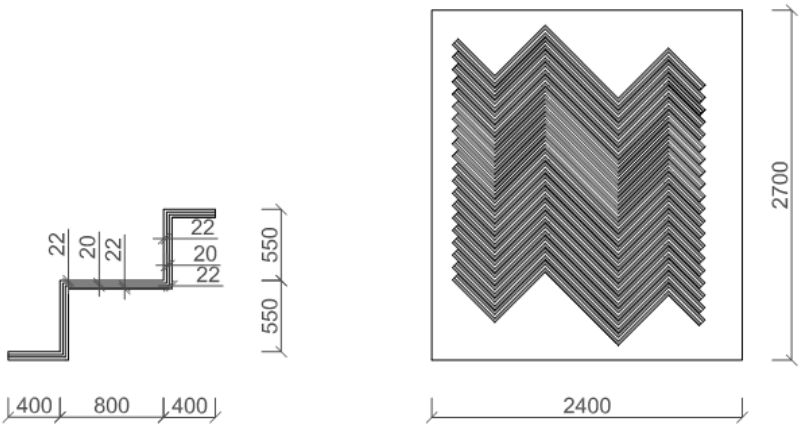


Figure 6-23 Stacking configuration composite floors riser height 550 mm

For the riser height of 450 and 550 mm a 2 stepped profile is considered. However, this is undesired because a 2 stepped profiles requires 50% more supporting beams. The three stepped profiles for the 450 mm and 550 mm riser height can also be transported in a container optimizing the degree of filling. The downside is that supporting installations are required in the container to keep the elements at the desires location during transport.

Steel, loadbearing system 3, is assessed on the design criteria. This is summarized in Table 20.

Profile	surface m^2/ m for 3 stepped element	Kg / m1	Kg / step	Max steps per container (weight)	Max steps per container (volume)	Governing number of steps per container	# of containers necessary
IPE 600	-	122,4	1321,9	23	44	23	(528+792+1056) / (3 * 23) = 35
Compo floor 360 mm	0,158	284	929	32	30 (3 steps / element) 42 (2 steps / element)	32	528 / 32 = 17
Compo floor 450 mm	0,165	297	1010	31	42 (2 steps / element)	30	792 / 30 = 27
Compo floor 550 mm	0,18	324	1166	26	40 (2 steps / element)	26	1056 / 26 = 41
						Sum	120

Table 20 Transportation demands steel grandstand loadbearing system 3

Weight steel = ((528+792+1056)/3)*1321,9 = 1.0496.945 KG
Weight composite floors = 528 * 929 + 792 * 1010 + 1056 * 1166 = 2.521.728 KG

Aluminum

Profile	Kg / m1	Kg / step	Max steps per container (weight)	Max steps per container (volume)	Governing number of steps per container	# of containers necessary
360 * 18 * 18	59,8	585	52	165	52	528 / 52 = 11
450 * 13 * 13	44,0	449	67	213	67	792 / 67 = 12
550 *11 * 11	40,2	434	70	264	70	1056 / 70 =15
					Sum	38

Table 21 Transportation demands aluminum grandstand loadbearing system

Weight aluminum = 528 * 585 + 792 * 449 + 1056 * 434 = 1.122.792 KG

Different stacking configurations are considered for the riser height of 360 mm and displayed in Figure 6-24. The number of steps is restricted by weight to 52 steps. With different stacking configurations either 32 elements, 96 steps, or 53 elements, 165 steps, could be transported if weight was unrestricted.

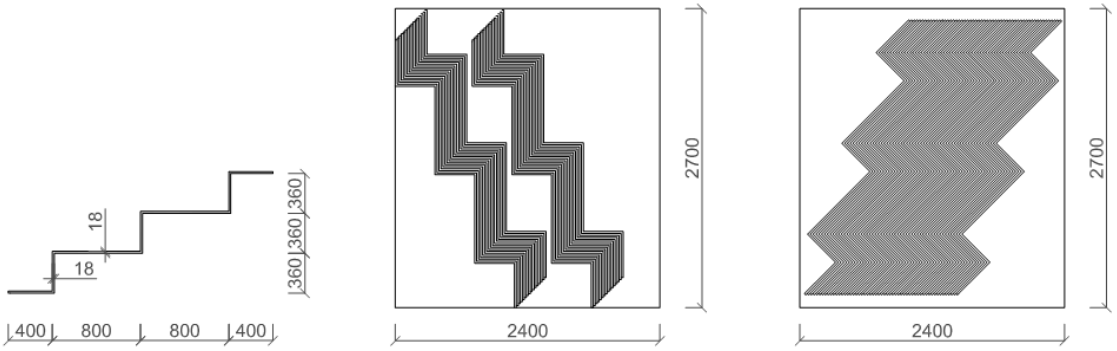


Figure 6-24 Stacking configurations aluminum grandstand riser height 360 mm

For the riser height of 450 mm different stacking configurations are considered and displayed in Figure 6-25. The number of steps is restricted by weight to 67. With different stacking configurations either 40 elements, 120 steps, 71 elements, 213 steps could be transported if weight was unrestricted.

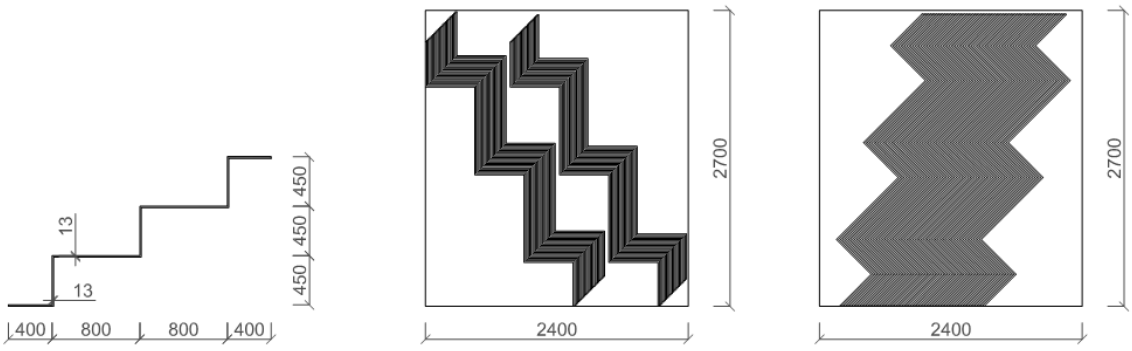


Figure 6-25 Stacking configurations aluminum grandstand riser height 450 mm

For the riser height of 550 mm different stacking configurations are considered and displayed in Figure 6-26. Because the length of the tilted configuration goes outside the boundaries of the container a different configuration is considered. Therefore, the elements are transported with only 2 steps instead of 3. In this way the element can be placed horizontally. The number of 3 stepped elements is restricted by weight to 70 steps. When transported as three stepped elements 24 elements, 72 steps, could be transported. When transported as 2 stepped element a maximum of 35 elements, 70 steps, is prescribed by weight whereas in theory 132 2-stepped elements, 264 steps could be transported.

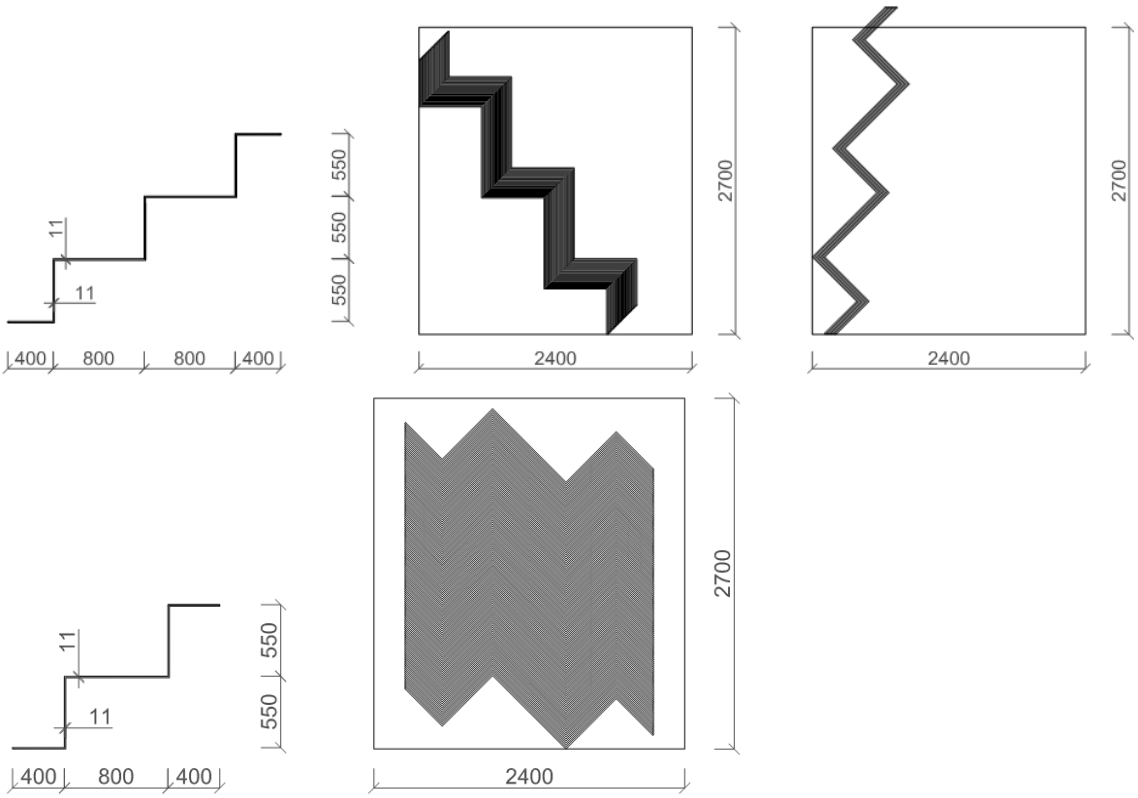


Figure 6-26 Stacking configurations aluminum grandstand riser height 550 mm

Thus, if the weight capacity of sea containers are increased more elements could be placed in a sea container lowering the amount of containers necessary.

N.B. The stacking efficiency as presented in the figures is depended on non-displayed supporting structures and the onsite equipment to place the elements on their desired location. Therefore, in reality a conservative approach is recommended towards the defined number of containers.

Performance on design philosophy

	Steel Loadbearing system 2	Steel Loadbearing system 3	Aluminum
Weight	compo floors = 576.972 KG Weight steel = 2.173.343 KG Sum: 2.750.312 KG	compo floors = 2.521.728 KG Weight steel = 1.046.945 KG Sum: 3.568.673 KG	Integrated element = 1.122.792 KG
Maximum span	10,8	10,8	10,8
Building sequence	Bolted connection beam to supporting frame, bolted connection floors to beam, fire proof sheets	Bolted connection beam to supporting frame, bolted connection floors to beam, fire proof sheets	Bolted connection beam to supporting frame, fire proof sheets
Fatigue	Good behavior	Good behavior	Good behavior
$€_{initial}$	Relatively high	Very high	Relatively low
# containers required	93	120	38

Table 22 Performance steel and aluminum grandstand on design philosophy

6.6.3 Composites

A composite is a non-homogenous profile in which different materials are combined. This combination is desired because different materials have different mechanical characteristics which can lead to a single strong element when combined. The best known composite building material is reinforced concrete. The concrete behaves will in compression whereas the steel will take up the tension forces.

In this chapter plastic composites are considered. The plastic composites are already extensively applied in the aerospace and aircraft industry and is increasingly applied in the building industry. In the building industry its main application is glass fiber epoxy composite bridges.

Composites are build up out of strengthening materials which are kept together by the matrix. In the case of reinforced concrete, the steel acts as the strengthening material and the concrete acts as matrix. In the case of plastic composites, the strengthening material can be comprised out of fibers, particulates or flakes. For the latter two options the exact location of the strengthening material is difficult to ensure during the manufacturing process which decreases the reliability of the loadbearing characteristics. Therefore, fiber composites are considered.
The binding material can be different materials ranging from polymer to ceramic to carbon. In the building industry the polymer epoxy matrix is most often applied due to its relative low initial costs. In this research a relatively cheap glass fiber epoxy composite is considered.

Loadbearing system
Composites can be designed along similar lines as aluminum. The malls can be designed in accordance to the designer preference. This creates the opportunity to integrate the seat connections or even create a single element containing beam, floor and seating minimizing the assembly process. Therefore, loadbearing system 1 is considered with a center to center distance of 0,8 m and PQ is 3,2 kN/m[1].

Material advantages
- Low weight combined with high strength.
- Good fatigue behavior.
- Long service life and minimal maintenance demands.

Material disadvantage
- Due to the low E modulus more material is required to provide sufficient EI.

Material characteristics

Material	Profile	Weight [kN/m]	E [N/mm2]	I_y [mm^4]	W_y [mm^3]	Yield stress [N/mm^2]
Composite	IPE 360 R	0,16	27 E3	20290 E4	1109 E3	240
	He 360 M	0,32	27 E3	84870 E4	4297 E3	240
	RHS 350 * 250 * 8	0,16	27 E3	15997 e4	9568 E3	240
	RHS 350 * 250 * 16	0,30	27 E3	27450 E4	1569 E3	240

Table 23 Material characteristics composite profiles

Profiles performance on design criteria

As discussed in Chapter 4 the circular shape of the grandstand results in different spans. Thus, riser height 360 mm spans 9,8m, riser height 450 mm spans 10,2m and riser height 550 mm spans 10,8m

Design Criteria	Frequency [Hz]				Deflection [mm]				Tension [N/mm^2]			
Span	**5,4**	**7,2**	**9,8**	**10,8**	**5,4**	**7,2**	**9,8**	**10,8**	**5,4**	**7,2**	**9,8**	**10,8**
Com 50*50*360	21,3	12,0	6,5	5,3	1,2	3,7	12,6	18,6	3,3	6,0	11,0	13,4
Allowable values	*>5,0*	*>5,0*	*>5,0*	*>5,0*	*<21,6*	*<28,8*	*<39,2*	*<43,2*	*<240*	*<240*	*<240*	*<240*
Span	**5,4**	**7,2**	**10,2**	**10,8**	**5,4**	**7,2**	**10,2**	**10,8**	**5,4**	**7,2**	**10,2**	**10,8**
Com 35*35*450	23,4	13,2	6,6	5,8	1,0	3,1	12,3	15,5	3,6	6,5	13,0	14,5
Allowable values	*>5,0*	*>5,0*	*>5,0*	*>5,0*	*<21,6*	*<28,8*	*<39,2*	*<43,2*	*<240*	*<240*	*<240*	*<240*
Span	**5,4**	**7,2**	**10,8**	**14,4**	**5,4**	**7,2**	**10,8**	**14,4**	**5,4**	**7,2**	**10,8**	**14,4**
Com 28*28*550	26,3	14,8	6,6	3,7	0,8	2,4	12,2	38,5	3,6	6,5	14,6	25,9
Allowable values	*>5,0*	*>5,0*	*>5,0*	*>5,0*	*<21,6*	*<28,8*	*<43,2*	*<57,6*	*<240*	*<240*	*<240*	*<240*

Table 24 Performance composite profiles on design criteria

Fatigue behavior

In general it can be stated that composites perform very good on fatigue behavior. Proved by its current application in the blades of wind power parks.[15]

Building sequence

1. Grandstand loadbearing vertical frame is erected.
2. Composite profiles are bolted on diagonal supporting truss.
3. Rails, mounted with seats, are bolted to the aluminum profile.
4. Fire proofing should be investigated.

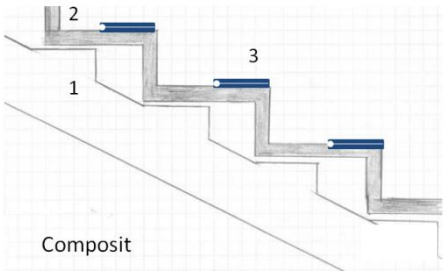


Figure 6-27 Building sequence composite grandstand

Transportation

Profile	Kg / m1	Kg / step	Max steps per container (weight)	Max steps per container (volume)	Governing number of steps per container	# of containers necessary
360 * 50 * 50	104,4	1023	29	60	29	528 / 29 = 19
450 * 35 * 35	78,8	803	37	44	37	792 / 37 = 22
550 * 28 * 28	68,0	734	41	100	41	1056 / 41 = 26
					Sum	67

Table 25 Transportation demands composite grandstand loadbearing system

Weight = 528 * 1023 + 792 * 803 + 1056 * 734 = 1.951.224 KG

For the riser height of 360 mm different stacking configurations are considered and displayed in Figure 6-28. The number of steps is restricted by weight to 29 steps. With different stacking

[15] http://www.vkcn.nl/over-composieten/construeren/kenmerken-bij-ontwikkeling

configurations either 10 elements, 30 steps, or 20 elements, 60 steps, could be transported if weight was unrestricted.

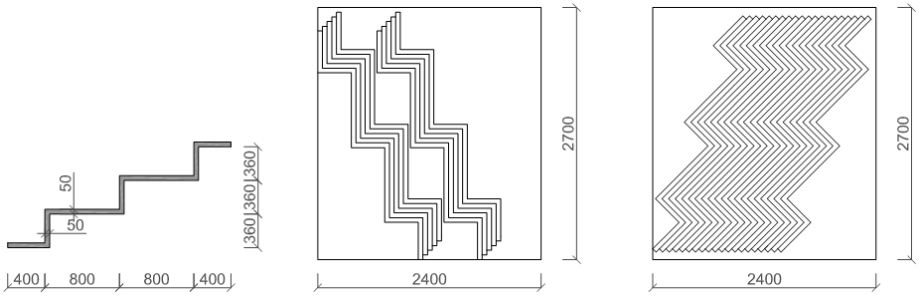


Figure 6-28 Stacking configurations composite grandstand riser height 360 mm

For the riser height of 450 mm different stacking configurations are considered and displayed in Figure 6-29. The number of elements is restricted by weight to 37 elements. With a 3 stepped element 33 steps, and tilted with 3 stepped element 66 steps could be transported if weight was unrestricted.

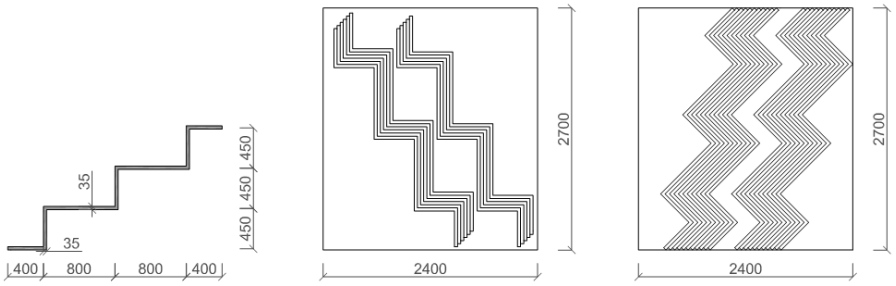


Figure 6-29 Stacking configurations composite grandstand riser height 450 mm

For the riser height of 550 mm different stacking configurations are considered and displayed in Figure 6-30. Because the length of the tilted configuration goes outside the boundaries of the container a different configuration is considered. In Figure 6-30 right the elements are transported with only 2 steps instead of 3. In this way the element can be placed horizontally. The number of steps is restricted by weight to 41 steps. When transported as three stepped elements 8 elements, 24 steps, could be transported. When transported as 2 stepped element a maximum of 50 elements, 100 steps could be transported if weight was unrestricted.

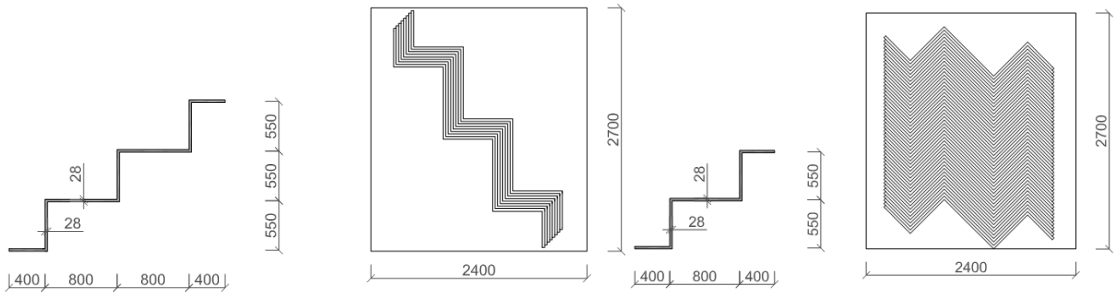


Figure 6-30 Stacking configurations composite grandstand riser height 550 mm

Performance on design philosophy

	Composite
Weight	1.951.224 KG
Maximum possible span	10,8
Building sequence	Bolted connection integrated floor element fire proof sheets
Fatigue	Good behavior
$€_{initial}$	Relatively high
# containers reqiured	67

Table 26 Performance composite grandstand on design philosophy

6.7 Seating system

The seating should be integrated with the grandstand design to improve the assembly process. In order to prevent the installation of 50.000 separate seats several measures can be taken.
Firstly, the seats can be installed on a rail. Subsequently, the rail with multiple chairs can be connected to the grandstand limiting the assembly procedures. Furthermore, an interesting option are foldable chairs. Because they take up less volume during transportation it becomes attractive to permanently mount the seats to the grandstand floor. When folded down, the chair and grandstand floor can be transported as a whole. With the seats already mounted to the grandstand the recurring (dis)assembly costs are severely decreased.

Figure 6-31 Foldable chairs. Source: www.Tradekorea.com

The foldable chairs significantly increase the thickness of the element as displayed on Figure 6-32**.** If the seats when folded have a thickness greater than 2,5 cm the transportation volume becomes dominant for all considered stacking configurations, which increases the amount of containers. Therefore, additional research is required if a separate transportation of steps and seats is more efficient than an integrated seating solution. Furthermore, the weight of the above lying elements could crush the seats. Therefore, spacers should be placed which are slightly higher than the seats to transfer the loads of the elements above without loading the seats.

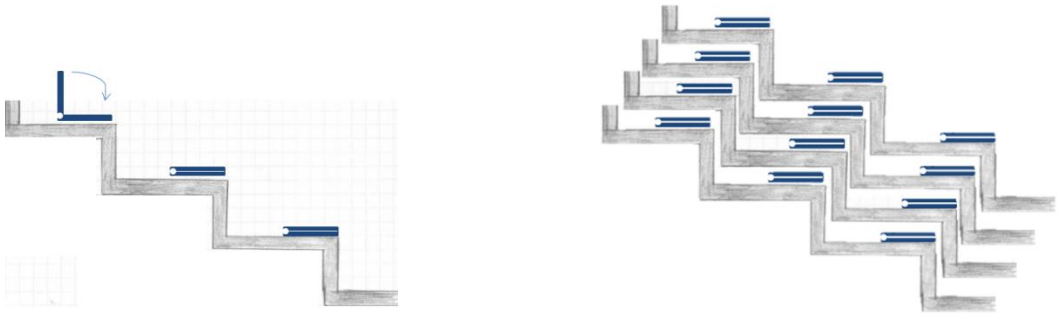


Figure 6-32 Tree stepped floor element stacking configuration Left: Single element Right: Stacked configuration Spacers should be applied between the elements to prevent crushing of the seats

6.8 Fire safety engineering

In this chapter the fire safety of the grandstand is briefly discussed. The requirements of the building code is presented as well as important aspects regarding fire safety engineering.

The requirements concerning the fire duration resistance of a structure is described in Dutch Bouwbesluit 2012 and is listed in Table 27.

Function other than residential	Fire resistance duration before failure
With no floor located higher than 5 m	60 minutes
With floors located higher than 5 m but lower than 13 m	90 minutes
Floors located higher than 13 m	120 minutes
Duration can be shortened by 30 minutes if permanent combustible material <500 MJ/m^2	

Table 27 Fire proof duration Source: Bouwbesluit 2012 Article 2:10.

Therefore, with floors above 13 meter the fire resistance duration should be 120 minutes. However, for non-combustible materials with a fire fuel capacity < 500 MJ/m^2, the fire resistance duration can be decreased with 30 minutes to 90 minutes. However, English Building Regulations 1991 :Part b of schedule 1 states: "T*he building shall be designed and constructed so that, in the event of fire, its stability will be maintained for a reasonable period."*
When the evacuation time is determined. Valid arguments could be presented to shorten the fire resistance duration.

Important aspects of fire safety engineering (FSE) are (Breunese, 2011):

- Fire occurrence. A fire will occur if the following three aspects are present: Oxygen, heat and combustible material.
- Fire development. The development is influenced on the availability of both oxygen and combustible material.
- Means of escape. The spectators should be able to leave the stadium quickly and in multiple directions to prevent being trapped by a fire.
- Suppression. The fire should be suppressed by eliminating one or multiple of the aspects oxygen, heat and combustible material.
- Propagation of smoke and fire. The smoke should be guided away from the spectators. Furthermore, the fire should be retained. Hence, not set fire to enclosed compartments.
- Progressive collapse. If the fire provokes structural failure. The loadbearing structure should be designed to prevent collapse of structural components outside the fire area.

Active and passive measures can be applied to improve the structure regarding fire safety:

- Active measures are: Fire detection sensors, sprinklers, smoke screens etc.
- Passive measures are: Over dimensioning of structural components, board covering the structure of sprays protecting the structural components.

In this research, emphasis is placed on the prevention of progressive collapse. The other aspects are of importance but are outside the scope of this project.
The grandstand elements are simply supported. Hence, if a fire occurs and a structural element fails, it will not influence the enclosed frames. Therefore, structural collapse is prevent. Another important aspect is the segregation in multiple fire compartments to prevent spread of the fire.

The fire resistance performance differs per material. For instance, concrete will perform its structural function for a longer period during a fire compared to aluminum. Therefore, the structural materials should be enclosed by fire resistant materials to limit the impact of the fire on the structural function of structural components. A commonly applied and cheap method is the application of board, covering the structural elements.
Further investigations are required to thoroughly assess the optimal measures required to design a structure which adheres to the demands listed in the building code regarding fire safety.

6.9 Comparison optimal grandstand variant

The grandstand variants perform similar on the design aspects: Load spread, stability during assembly and modular design. The variants are compared on the remaining aspects of the design philosophy as well as the design criteria applicable to grandstands.

	Concrete	Steel		Aluminum	Composites
		Loadbearing system 2	Loadbearing system 3		
Weight	8.893 tonnes	compo floors; 576 tonnes steel;2.174 tonnes Sum: 2.750 tonnes	compo floors; 2 522 tonnes steel; 1.047 tonnes Sum: 3.569 tonnes	1.123 tonnes	1.951 tonnes
Max. span	10,8 m	10,8 m	10,8 m	10,8 m	10,8 m
Fatigue	Good	Good	Good	Good	Good
# containers	297	93	120	38	67
$€_{initial}$	€ 0,5 million	€ 9,7 million	€ 45,4 million	€ 4,4 million	€ 10,7 million
$€_{transportation}$	€ 0,45 million	€ 0,14 million	€ 0,18 million	€ 0,06 million	€ 0,10 million
Assembly efforts + Building organization	Bad, many containers thus effort intensive	Average, small # containers, but 1 step floor element	Average, medium # containers, but 3 stepped floor element	Excellent, small # cont., 3 stepped floor element	Good, low # cont., 3 stepped floor element
Maintenance activities	None	After thermal sinking none	After thermal sinking none	None	None

Table 28 Comparison optimal grandstand variant

The comparison demonstrates that aluminum outperforms steel and composites. It has substantial lower initial costs, requires less containers and has an effortless assembly process.

In order to get insight in the (recurring) costs of the variants. The initial and transportation costs are defined and presented in Figure 6-33. The cost indicators are listed in Table 29.

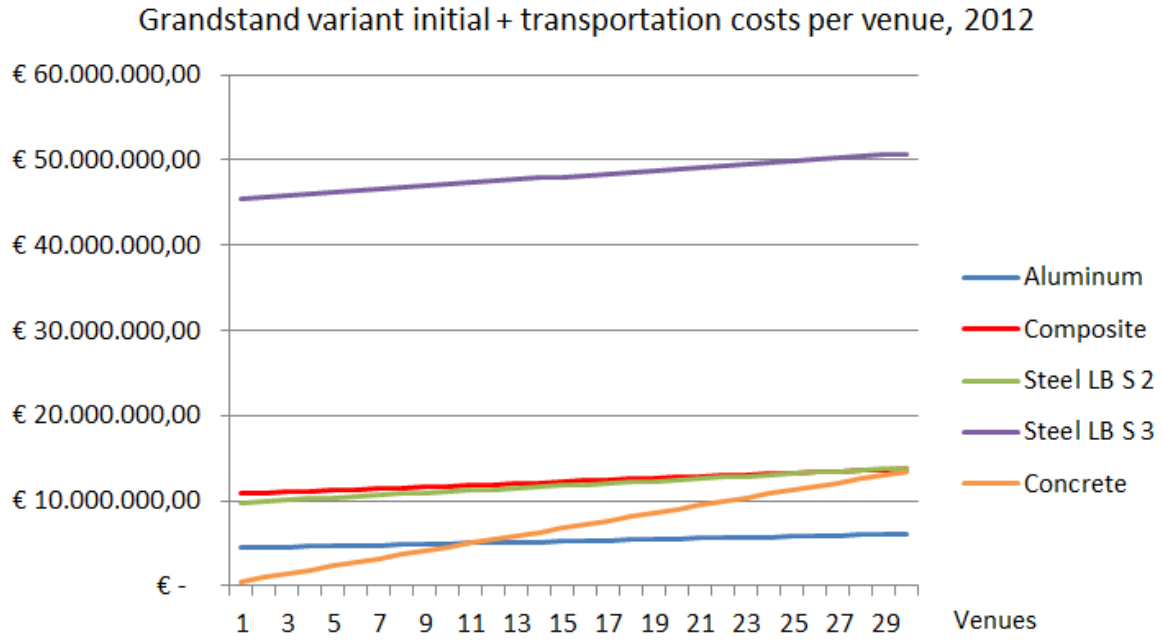


Figure 6-33 Grandstand variant initial + transportation cost comparison

The following cost indicators are considered.

Material	Value	Source
Steel	€ 3,0 / kg	Hollandia, 2012
Aluminum	€5,4 / kg	Hollandia, 2012
Composite	€5,5 / kg	Bijl Composieten, 2013
Concrete (C45/55)	€200,0 /m^3 = €0,08 /kg	Heildelberg cement, 2012
€ / container	€1.500,- / container	CBS – Wereldbank[16], 2011

Table 29 Cost indicators grandstand

Figure 6-33 clearly demonstrates that from a cost point of view both the concrete and aluminum variants are more attractive than the others. The significant disadvantage of the concrete variant is the required number of containers. This will dramatically increase the costs involved with the building organization process. Therefore, the aluminum variant, with its low weight and low number of containers, is the most advantageous grandstand configuration.

6.10 Conclusion optimal grandstand system

Grandstand variants, all adhering the design philosophy criteria of Chapter 3.1 and spanning 10,8 meters, are designed and compared. In the grandstand chapter the following conclusions are drawn:

- The initial costs of a concrete grandstand is far lower compared to other materials. Therefore, if a permanent stadium is build, concrete is an ideal material. However, if the stadium is designed to be transported, the high weight of the concrete grandstand components, requiring many containers, make concrete a less ideal grandstand material.
- The grandstand span has to find a balance which:
  - Reduces the amount of hoisting activities.
  - Reduces the number of building elements and thus the transportation volume.
  - Is within the limits concerning strength, stiffness and dynamic behavior.
  - Limits the concentration of soil forces which require a pile foundation.

  Hence, a span of 10,8 m is considered to be optimal.
- The number of elements which can be transported with a container is limited by the weight restrictions of the container, rather than the physical dimensions.
- The seats should be foldable and permanently mounted on a rail to improve the transportation and (dis)assembly efforts.
- Both active and passive measures are required to improve the fire safety behavior of the grandstand structure.
- The concrete and aluminum variants outperform the other variants when the initial and transportation costs are considered.
- The aluminum variant has a far more advantageous building organization process, reducing the recurring costs, due to its small number of containers required to transport the grandstand elements.

To conclude, an aluminum grandstand is recommended due to:

- Low weight.
- Small number of containers which improves the building organization process.
- Three stepped floor system minimizing assembly efforts.
- Moderate initial costs.

[16] www.doingbusiness.org

7 Roof skin system

Different roof skin systems have different loadbearing characteristics and can be suitable for different spans. In this chapter the roof skin systems which are commonly applied in practice are presented and compared.

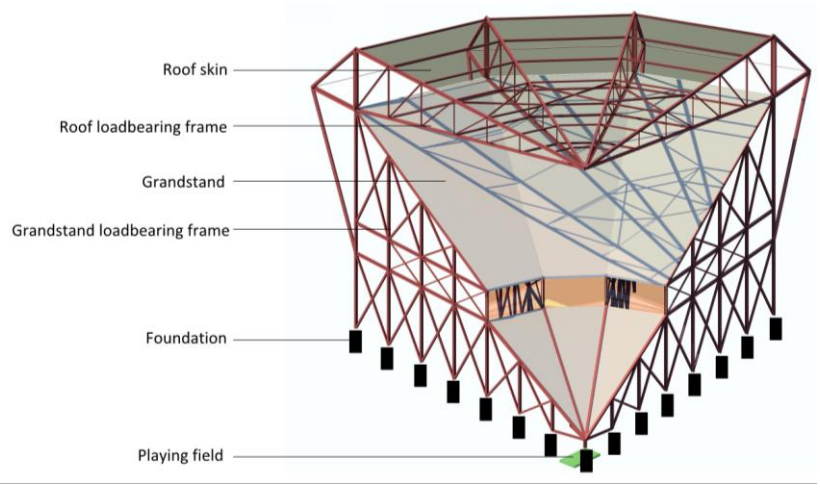


Figure 7-1 Overview of the structural components considered in this research

Roof skins are the horizontal roof parts which transfer the forces acting on the roof to the roof loadbearing structure. There is a wide variety in possible roof loadbearing structures and this is extensively discussed in Chapter 8. Furthermore, the roof skin has a very close relation to the desired roof loadbearing structure which is discussed in Chapter 8.

In the design plan of approach of Chapter 3 it is discussed that the roof trusses connects to the grandstand frame to improve the load spread. Therefore, the span of roof skin system is identical to the grandstand frame. Due to the fact that the grandstand takes up a far larger portion of the assembly efforts and transported volume, the optimized span for roof skin is steered by the optimal grandstand span. Thus, the roof should be optimized in respect to the desired span of 10,8 m and a roof depth of +/- 42 m.

Reader guide

This chapter is structured as follows. Firstly, the roof loads, defined in Appendix A1, are summarized. Subsequently, an overview of different roof skin variants is presented. Successively, the designed criteria are defined and a conceptual design for each variant is presented. Finally, the roof skin which is most in line with the design criteria is recommended.

7.1 Roof loads

Load type	Load direction	Calculation	Value
PG Roof skin	Downward	Depends on material	t.b.d.
PG Girder	Downward	Depends on roof skin	t.b.d.
PQ Repair work	Downward	Eurocode prescribes 1 kN every 10 m^2	This value is negligible compared to occurring wind forces and will not be considered
PQ Snow load	Downward	Defined in Appendix A1	0,56 kN/m^2
PQ Wind load vertical	Upwards	Defined in Appendix A1	1,96 kN/m^2
PQ Wind load horizontal	-	The wind load will be transferred from the roof skin to the roof truss. Emphasis is placed on the roof truss and grandstand truss to take up the loads rather than the roof skin.	

Table 30 Roof loads

7.2 Roof skin systems applied in practice

Although there is a wide variety in roof loadbearing structures the choices for roof skins are limited. The three considered roof skin variants are chosen for their track record in stadium roof skin systems. The roof skin systems are:

- Roof plates
- Single layer membrane cover
- Multi-layer membrane cushion

Figure 7-2 Roof skins system: Left to right: De Kuip (Netherlands), King Fahd stadium (Saudi Arabia) , BC Place stadium (Canada) Source: www.stadiumdb.com

7.3 Design criteria

The three variants are designed adhering the design philosophy described in chapter 3.1 as well as their performance on the focus points. The focus points for roof skin systems are:

- Weight
- Easy to (dis)assemble
- Transportation demands
- Stability
- Strength
- Stiffness

7.4 System variants

In this chapter, the three different roof skin systems are designed in accordance to the design criteria.

7.4.1 Roof plates

Configuration

All plates have a similar sheet pile like configurations. The plates can span the roof structure either in transverse (radial) or longitudinal direction. Usually the plates are configured in the transverse direction with a tapered roof. The tapered roof enables water drainage.

Material

The roof plates can be either constructed in steel or aluminum. The lightweight aluminum initial costs are higher compared to steel. Furthermore, the higher weight of the steel is not necessarily disadvantageous since the roof skin has to withstand wind forces trying to lift the roof skin.

Maximum span

The roof plates can either span between the trusses or span between girders. Practice shows that spans up to 7,2 m are possible without girder. Figure 7-3 depicts a possible lay out of the roof plates. The roof girders span 10,8 m between the frames and the girders have a ctc of 5,4. The plates rest on the girders and span in transverse direction. When the roof trusses are tilted rain drainage is created to the back side of the stadium.

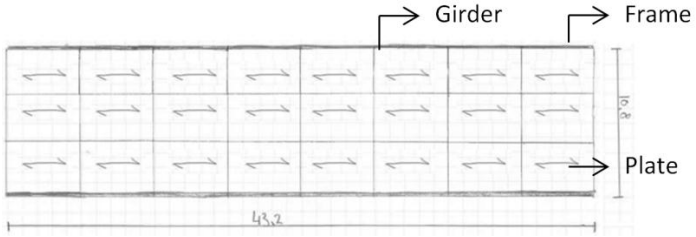


Figure 7-3 Spanning direction roof plates

Connection

A snap system will decrease the assembly time and severely reduces the assembly efforts. Furthermore, the snap system can be designed to be reusable.[17]

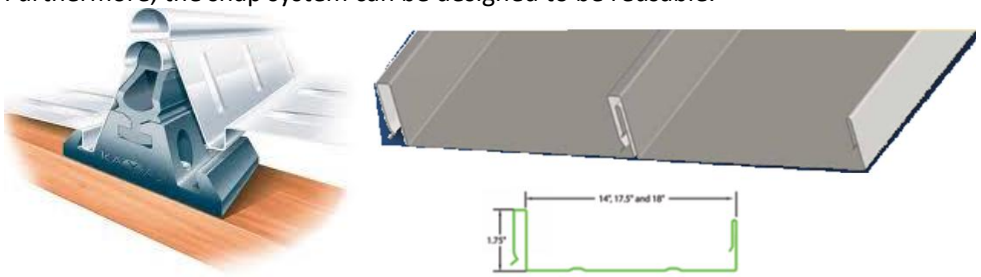


Figure 7-4 Different snap systems Source: www.drexmet.com

Dimensioning roof plates

System characteristics

The roof plates span in the radial direction of the roof with a total length of 43,2 m. The plates are supported by girders every 5,4 m. The length of the roof plates are optimized in respect to the required span and the depth of a container leading to a plate length of 10,8 m. This means that in practice the plates span 2 fields and are statically underdetermined with supports at the ends and one in the middle. The width of each plate is restrained by the sea container width being 2,4 m.

Because the plate is statically undetermined and spans two fields it is a cumbersome process to optimize the design of the plates. The maximum deflection and maximum stresses can be derived

[17] Confirmed by Zipline, Dutch roof sheeting company

by extensive calculations or the use of a computer program. For simplicity, the plates are considered to span only 1 field and are statically determined. This creates the opportunity to optimize the design of the plates easily with excel. The dimensions designed in this manner are a conservative approach, the maximum occurring deflections and stresses are lower in the actual system.

Governing load combination

With the roof loads listed in Table 30 the following governing load combinations are determined for both Serviceability Limit State (SLS) and Ultimate Limit State (ULS).

Governing upwards

SLS: PQ wind – PG dead load plate = 1,96 – PG plate (7.1)

ULS: γ_q * PQ wind –γ_g * PG dead load plate = 1,65 * 1,96 – 0,9 * PG Plate (7.2)

Governing downwards

SLS: PG Dead load plate + PQ Snow (7.3)

ULS: γ_g PG Dead load plate + γ_q * PQ Snow = 1,3 * PG plate + 1,65 * 0,56 (7.4)

Dimensioning

For the design of the steel roof plate use is made of predefined profiles in (Staalprofielen, 1998). In which the E, I and own weight values are given. A tapered sheet pile like configuration is assumed for the aluminum roof plates. Due to the trapezium shape of the web the flanges are not present over the entire width. Therefore, the I and W values of the aluminum plates are reduced with 20% . To determine the profiles excel is used and the following formulas are applied.

Strength: $M_{max} = 1/8\ q\ l^2$ (7.5)

$$\sigma = \frac{M}{W} \quad (7.6)$$

Stiffness: $$w = \frac{5ql^4}{384\ EI} < 0{,}004\ l \quad (7.7)$$

Steel 153/280 t =0,75	Value	Unit	Aluminium	h=200, t = 1,8 mm
Span	5,4	m	5,4	m
Fields	1	-	1	-
W	4,10E+04	mm^3	14,4 E+04	mm^3
E	210000	N/mm^2	69000	N/mm^2
I	3,77E+06	mm^4	14,40E+06	mm^4
Width plate and load	0,75	m	1,00	m
Permanent	0,08	kN/m^1	0,05	kN/m^1
Wind	1,47	kN/m^1	1,96	kN/m^1
Snow	0,42	kN/m^1	0,56	kN/m^1
SLS				
governing upward	1,39	kN/m^1	1,91	kN/m^1
governing downward	0,50	kN/m^1	0,61	kN/m^1
ULS				
governing upward	2,35	kN/m^1	3,19	kN/m^1
governing downward	0,80	kN/m^1	0,99	kN/m^1
Strenght				
LC 1	2,35	kN/m^1	3,19	kN/m^1
Moment (1/8)ql^2	8,58	kNm	11,63	kNm

Tension	209,28	N/mm^2	80,77	N/mm^2
Stiffness				
LC 1	1,39	kN/m^1	1,91	kN/m^1
w allowed	21,60	mm	21,60	mm
w occuring	19,45	mm	21,31	mm

Table 31 Dimensioning Steel and Aluminum roof plate

With the weight of the plates known the girders can be defined in a similar manner. The calculations are presented in Appendix A9**.** for both materials an IPE 400 girder is required to span 10,8 m with a ctc of 5,4 m.

Transportation

Each container is filled with plates with a width of 2,4 m and a depth of 10,8 m. Each segment is 10,8 m wide and (4*10,8) 43,2 m deep. With 44 segments a total of (10,8 / 2,4) * 4 * 44 = 792 plates are required

Steel

The plate has a weight of 10,51 kg/m^2. So the weight of one plate is 2,4 * 10,8 * 10,51 = 272 kg/plate. Weight restrictions of 30,5 tonnes prescribe a maximum of 111 plates per container. From a volume point of view this can be easily achieved since the plates can be stacked. 792 plates are required resulting in 8 containers for steel plates.

Aluminum

The plate has a weight of 4,88 kg/m^2. The weight of one plate is 2,4 * 10,8 * 4,88 = 126 kg/plate. Weight restrictions of 30,5 tonnes prescribe a maximum of 241 plates per container. From a volume point of view this can be easily achieved since the plates can be stacked.[18] 792 plates are required resulting in 4 containers for aluminum plates.

Girders

IPE 400 are used as girders which span 10,8 m between the segments. For each segment 9 girders are required thus in total 396 girders.

One girder weighs 66,3 kg/m^1 * 10,8 = 716 kg. Therefore, one container can carry 42 girders. From a volume point of view (2,4 / 0,18) * 6 (max fit in height) 66 girders can fit. Thus, the weight is the limiting factor and 396 / 42 = 9 containers are necessary for the girders of both the aluminum and steel plates.

Performance on focus points

	Steel plates	Aluminum plates
Weight	0,08 kN/m^2 215.424 KG plates 252.032 KG girders	0,05 kN/m^2 99.792 KG plates 252.032 KG girders
Assembly procedure	Girders , click plates	Girders , click plates
Initial costs	Low	Medium
# containers	Plates : 8 Girders: 9 Sum: 17	Plates : 4 Girders: 9 Sum: 17

Table 32 Performance steel and aluminum roof plates on focus points

[18] The necessary height is determined by multiplying the thickness of a plate with the number of plates per container. (241 * 1,8) + 200 = 0,7 m. The actual height is 2,7 m. So even with 2 mm between each plate the height is still not restrictive.

7.4.2 Single layer membrane roof cover

Membrane roof covers are increasingly applied in stadium roofs. Membrane structures transfer the load as tension forces. Furthermore, elegant shapes and substantial spans can be created and membrane is a durable material, unaffected by weather or climate conditions. This makes membrane an attractive, durable, lightweight and flexible building material. The downside of membrane structures are the high initial costs and the required post tensioning to create the desired stiffness.

Configuration

The single layer membrane roof cover can be designed in many different configurations. The three most common configurations are discussed below. Respectively, double curvature membranes, straight post-tensioned membranes and single curved membranes. Their performance on the design criteria is assessed and the best performing variant is recommended.

Double curvature high point - low point post-tensioned tent structures

Figure 7-5 Single layer double curvature roof structures. Left: King Fahd stadium Right: Kiev Olympic stadium (Source: www.stadiumdb.com)

The double curvature structures require pylons to create high points and require post-tensioning. The double curvature provides good loadbearing characteristics and enables large spans. The span depends on the amount of curvature which is influenced by the height difference between high and low point.

Straight post-tensioned roof structures

Figure 7-6 Single straight post-tensioned roof structures. London Olympic stadium (Source: www.stadiumdb.com)

Straight post-tensioned roof structures require intensive post-tensioning to create sufficient stiffness in the flat cloth. A limited span can be achieved

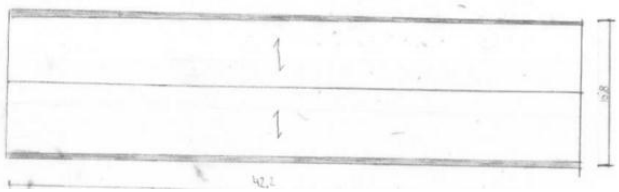


Figure 7-7 Loadbearing direction straight post-tensioned roof structures. Span is 5.4 m.

Single curved post-tensioned roof

Figure 7-8 Single curved post-tensioned roof structure Metricon stadium (Source: www.stadiumdb.com)

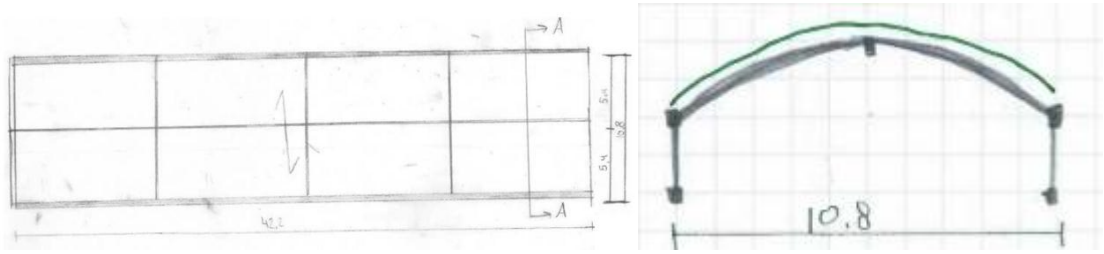


Figure 7-9 Left: Loadbearing direction single curved post-tensioned roof structures Right: Section A-A span 10,8m

The curved roof structure is relatively easy to post-tension. Figure 7-9 assumes a span of the roof which is similar to the roof ctc. A high point is required to create the curve. When the high point is between two roof trusses, curved girders are required. Subsequently, a horizontal beam is placed on the top of each curved girder over which the membrane is pulled. Thus, this system requires many curved girders with a horizontal girder spanning from the back to the front side of the roof similar to Figure 7-8.

The single curved system depicted in Figure 7-10 requires far less supporting structures due to high point being situated above a roof truss. Nonetheless, (smaller) curved girders are required to obtain the desired shape. But the length of the girder does not have to span from roof truss to roof truss and therefore requires less material. The dotted curved girder line represents the potential need for a 3d frame. If this variant is recommended. The girder should be further investigated to determine the need for a 3d truss and its dimensions.

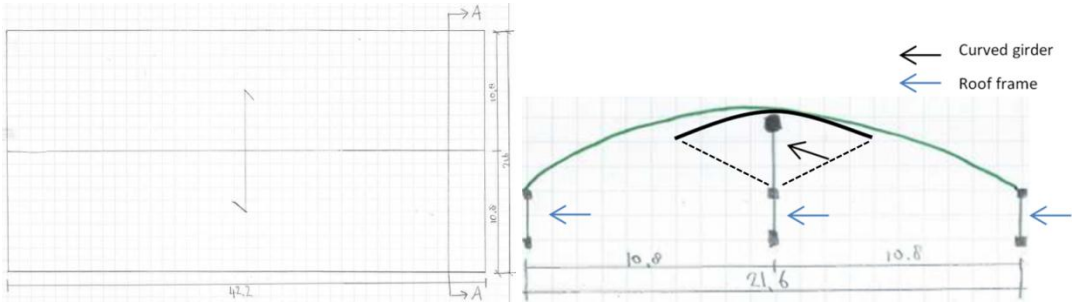


Figure 7-10 Left: Loadbearing direction single curved post-tensioned roof structures Right: Section A-A span 21,6m

Maximum span

The single curved roof structures can establish large spans depending on the angle and thus the height of the high point.

Material

The membrane cover is a relatively new material which is continuously improved and can have very good mechanical properties. The cloths with good mechanical properties usually also have a higher price.

Comparison double curvature, straight and single curved single layer membrane roof covers

	Double curvature		Straight		Single curved	
Weight	--	Thin cloth but requires much secondary structural material	++	Lightweight	+	Lightweight but requires large curved girders
Assembly procedure	-	Post-tensioning and difficult to reach high points	-	Much post-tensioning because no curvature thus no stiffness	++	Less post-tensioning, but requires small curved girders
Transportable	-	Cloth is lightweight and takes in little space, big secondary structure necessary	++	Cloth is lightweight and takes in little space, no secondary structure	+	Cloth is lightweight and takes in little space, small secondary structure
Initial costs[19]	-	High €70,- 100,- /m^2	-	High €70,- 100,- /m^2	-	High €70,- 100,- /m^2
Span	+	Large spans depending on high low point difference	-	Small spans of 5,4	+	Large spans up to 21,6 m

Figure 7-11 Performance single layer membrane roof cover on focus points

The single curved roof structure is the most advantageous structure. It requires little secondary supporting material (girders). Due to the curvature a stiff structure is realized. Further investigations are required to determine the exact amount of post-tensioning and the assembly process and girder dimensions. Double curved structures require much additional material to create the high points and have an effort intensive assembly process. Therefore, they will not be further investigated. Straight roof structures have a small span resulting in an effort intensive assembly process and possibly additional girders and are therefore undesired.

The actual properties of both cloth and girder dimensions of the single curved membrane variant will be determined if the comparison with the other variants provides sufficient motives to further investigate this option. However, the number of containers can be estimated and combined with an indicative price /m^2 cloth. Hence, this variant can still be considered in the variant comparison.

Transportation demands single curved membrane

Every other roof truss requires additional girders with a height of approximately 8 m. With 44 segments 22 girders are required. If the girders are CHS 323 mm with a thickness of 8 mm the weight for 10,8 m is 63,32 kg/m^1 * 10,8 = 683 kg. Allowing, 44 pipes per container. In total 22 girders of 4 * 10,8 require 88 girders. With 44 girders per container, 2 container are required.[20]
For the amount of containers for the membrane the assumption is made that the container height will be filled efficiently with 20%. So: volume available is 10,8 * 2,4 * (2,7 * 0,2). If we now assume that the thickness of the cloth is 3 mm, the amount of surface which can be transported per container is(10,8 * 2,4 *(((2,7 * 0,2)*1000)/3)= 4665 m^2. With a total roof surface of 20529 m^2, 4 containers are required to transport the membrane cloth totaling at 6 containers.

[19] Source: Spon's Architects' and Builders' Price, Book 2011 (http://tinyurl.com/arxuvav)
[20] It could be that 3d trusses are necessary as girders. If this option is recommended, further investigations are recommend.

Performance on focus points

	Single curved membrane
Weight	0,08 kN/m^2 - KG membrane, 60.104KG girders
Assembly procedure	Girders , post tension membrane
Initial costs	High
# containers	6

Table 33 Performance steel roof plates on focus points

7.4.3 Multi-layer membrane cover (ETFE)

Multi-layer membrane covers consists between 2 up to 5 different layers. The concept is that the curvature, improving the stiffness, is created due to cushion shaped segments which are pneumatically (air powered) pre-stressed. The amount of layers influences characteristics such as heat insulation, sound insulation, light penetration and so on. The cushions can be designed into practically any shape.

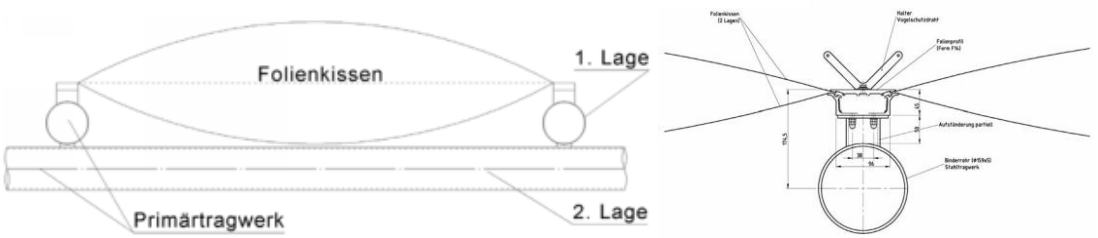


Figure 7-12 Multi-layer membrane cover Left: section Right: detail Source: vector foiltec

In Figure 7-13, a two layered air cushion is presented. The cushions are mounted between two continuous CHS profiles. The pipes can be placed maximally 4 meters apart and the length in the longitudinal direction is practically unlimited and restrained by the length of the pipe. The pipes usually rest on either the main loadbearing structure or secondary structures (girders). In Figure 7-12 right, a detail is presented on connection between cloth and CHS profile.

Configuration

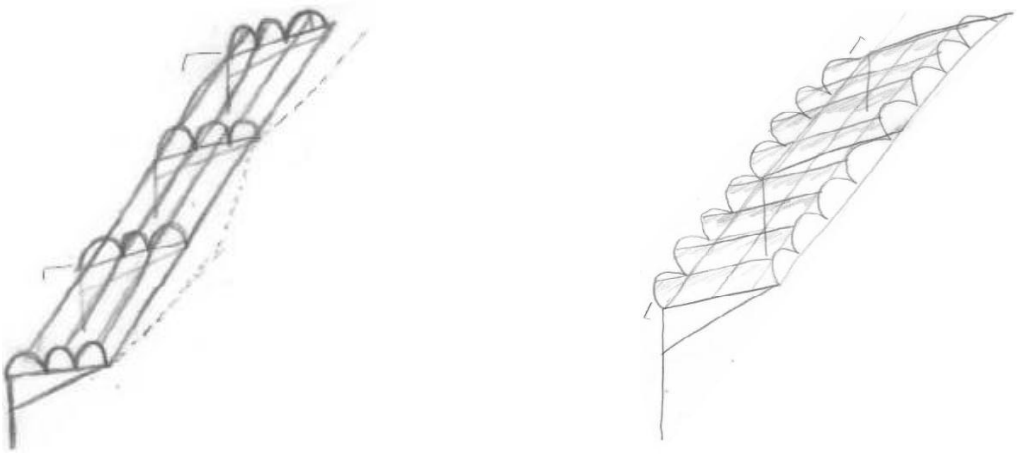


Figure 7-13 Multi-layer membrane cover Left, span in longitudinal direction Right, span in transverse direction

Figure 7-13 depicts the span is in the longitudinal direction. To ensure water drainage the roof trusses should have an altering high and low point to transport the water to one point from which it can be transported to the gutter. All trusses have to have a slight angle to transport the water into the gutter. With the span in the transverse direction a tapered roof truss is sufficient to transfer the water to the gutter. In the span in transverse direction girders are necessary to support the CHS profiles. In the span in longitudinal direction the CHS profiles could be dimensioned to span from roof truss to roof truss without girders.

Maximum span
The width of the cushion is restricted to 4 m and the length of the cushion is virtually unlimited and solely restricted by the CHS profiles length. These are restricted by transportation methods.

Material
The membrane cover is a relatively new material which is continuously improved and can have very good mechanical properties. The cloths with better mechanical properties usually also have a higher price.

Performance on focus points

	Span in longitudinal direction		Span in transverse direction	
Weight	+/-	Lightweight ETFE but CHS with ctc of 4,0 m	+/-	Lightweight ETFE but CHS with ctc of 4,0 m and girders are required
Assembly procedure	+	Placement of CHS profiles and air compressor	+	Placement of CHS profiles and air compressor
Transportable	+/-	Clough is foldable and CHS profiles should be optimized with length of transport	+/-	Clough is foldable and CHS profiles should be optimized with length of transport
Initial costs	-	High €70,- 100,- /m^2	-	High €70,- 100,- /m^2
Span	+	10,8 m between roof trusses	-	10,8 m between girders
Water drainage	-	Tilting roof truss and alternating height difference between roof trusses	+	Tilting roof truss

Table 34 Performance multi-layer membrane roof cover on focus points

Thus, a span in transverse direction is recommended because the girders outweigh the building organization disruption by alternating truss heights.

7.5 Comparison optimal roof skin system

The roof skin variants perform similar on the design aspects: Load spread, stability during assembly and modular design. The variants are compared on the remaining aspects of the design philosophy as well as the design criteria applicable to roof skins.

	Steel plates	Aluminum plates	Single curved membrane	Multi-layer transverse direction
Weight	0,08 kN/m^2 215.424 KG plates 252.032 KG girders	0,05 kN/m^2 99.792 KG plates 252.032 KG girders	0,08 kN/m^2 - KG membrane 60.104KG girders	Lightweight ETFE but CHS with ctc of 4,0 m
Assembly procedure	Girders Snap system	Girders Snap system	Girder above roof truss Post tensioning	Placement of CHS profiles and air compressor
Initial costs	Low and widely available €30 / m^2	Low and widely available €25/ m^2	High €70,- 100,- /m^2	High €70,- 100,- /m^2
Span	5,4 m Girders are required	5,4 Girders are required	10,8, high girder above truss	10,8 m between girders
# containers	17	13	6	Not determined

Table 35 Comparison performance of different roof structures on focus points

The multi-layer air cushion is undesired and will not be further considered. It requires CHS profiles with a ctc of 4 meter. Therefore, this systems has an effort intensive assembly procedure and takes up a rather large transportation volume.

Material	Value	Source
Steel	€ 3,0 / kg	Hollandia, 2012
Aluminum	€5,4 / kg	Hollandia, 2012
Membrane	€70 / m^2	Spon's Architects' and Builders' Price, Book 2011 [21]
€ / container	€1.500,- / container	CBS – Wereldbank[22], 2011

Table 36 Cost indicators roof skin

In order to get insight in the (recurring) costs of the variants. The initial and transportation costs are defined and presented in Figure 7-14.

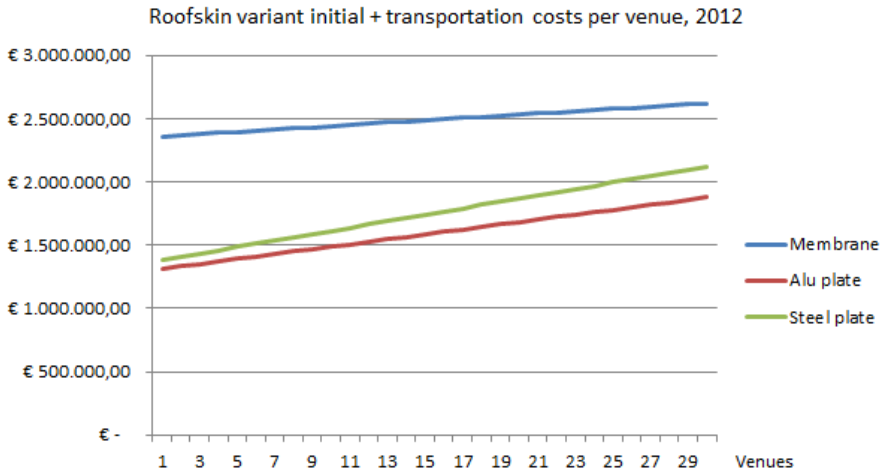


Figure 7-14 Roof skin variant initial + transportation cost comparison

[21] (http://tinyurl.com/arxuvav)
[22] www.doingbusiness.org

When solely the initial and transportation costs are considered the plates are advantageous compared to the membrane. The membrane has one other downside which makes it unattractive. During the disassembly, transport and re-assembly process it is likely, although not desired, that the roof skin is damaged. When a plate is damaged it can easily be replaced. However, if a membrane is damaged, the cloth, which is a fairly large part (several hundred square meters), has to be sawn or entirely replaced which is a costly endeavor. Therefore, membrane is undesired and will not be further investigated.

The aluminum plate is advantageous compared to the steel plate. Due to the design freedom an aluminum roof plate is designed which has a slightly larger height, thus more stiffness, than the standard available steel plates. With this increased height and thus stiffness an aluminum plate is designed which is so much lighter per m^2, that is also becomes cheaper than the steel plate. Furthermore, the aluminum plate will not require treatment to prevent corrosion. Moreover, the lightweight aluminum plates are easier to handle for the workforce, thus severely reducing the assembly efforts. Hence, the aluminum roof plate is considered to be the optimal roof skin variant.

7.6 Conclusion optimal roof skin system

In this chapter, the following conclusions are drawn.

- Between the membrane variants, the single curved membranes is most attractive because it requires the least amount of secondary structures while still having a decent span.
- The membrane structures have high initial costs.
- If the roof skin is damaged during (dis)assembly or transport, the replacement costs of membrane are far higher compared to steel or aluminum plates.
- The aluminum roof plates are lightweight making them mendable for the assembly workforce.
- The aluminum roof plates is most advantageous from both a cost as well as assembly point of view.

Hence, an aluminum roof plate spanning 5,4 m, resting on IPE 400 girders is recommended. It is lightweight, relatively cheap, requires little assembly efforts with its click connection and is mendable for the assembly workforce.

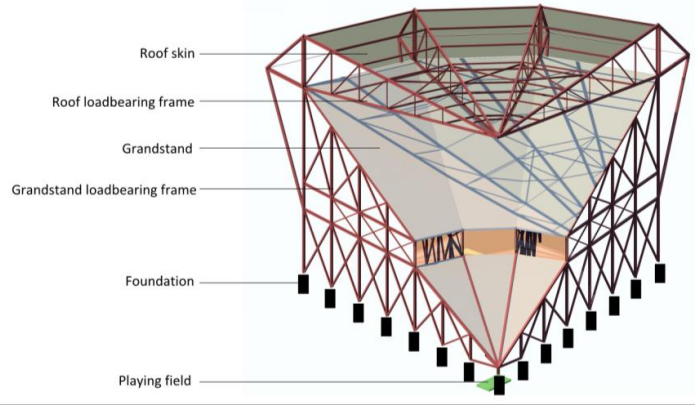
8 Roof loadbearing structure

Stadium roofs appear in numerous shapes and structural systems. Each structural system has a different configuration and different loadbearing characteristics. For example, to create a small span a beam is the most economical solution. Whereas application of a spaceframe is too labor intensive and possesses too much material. But when the span increases the required dimensions of the beam become too large and a spaceframe becomes economically attractive.
Furthermore, each design may possess different boundary conditions concerning the locations to transfer the forces to the foundation (e.g. a roof supporting column can be undesired when located in front of or on the grandstand). This results in different roof systems with different loadbearing directions. Therefore, the variety in stadium shapes exists (partly) because each stadium has a different capacity, function and different demands concerning the load transfer, which requires a different optimal roof structure. Furthermore, the roof plays a dominant role in the appearance of stadium. Hence, the owner's and architect's preference also influence the roof design.

Plan of approach

In this thesis the designer's preference to minimize recurring costs steers the decision process. A design choice is made by judging possible roof structures on their demountable and transportable performance influencing the recurring costs. The approach to determine the optimal roof structure which minimizes recurring costs can be summarized in the following seven steps:

1. Determine the cost drivers of a transportable roof structure, use them as assessment criteria and assign weight factors to each assessment criterion.
2. Perform a literature study on possible stadium roof structures.
3. Perform a study to identify which roof structures are applied in build stadiums.
4. Assess the roof structures performance on the cost drivers.
5. Validate the results with experienced (IMd) engineers.
6. Examine the roof structures with the highest score on the assessment criteria more closely.
7. Recommend the optimal roof structure that is most in line with the design philosophy.



Reader guide

This chapter is structured as follows. Firstly, the design criteria are presented and their importance is discussed. Secondly, an overview on structural stadium roof systems derived from literature is presented. Thirdly, a typology study is performed on stadium roofs encountered in practice. Arguments are presented on the absence of roofs derived from literature in practice. Subsequently, the roof structures encountered in practice are assessed on their performance on each design criterion. Successively, a survey is performed to validate the scores assigned to the roof structure's performance as well as the design criteria weight factors.[23] Finally, the two top performing roof structures are further examined and a roof structure is recommended which is further elaborated in this research.

[23] There is a high diversity between different roof systems. Therefore, assessing the system variants without weight factors, as performed in the previous chapters, could provide an incorrect outcome on the desired roof system.

8.1 Design criteria

The research goal is to design a transportable stadium with a focus on minimizing recurring costs. Five criteria are used to determine the performance of a roof system on minimizing recurring costs. These five criteria are: Load spread, stability during erection and deconstruction, modular design, adaptable design and amount of material.
In this chapter arguments are presented on the importance of each criterion on the recurring costs. (This will have similarities to the design philosophy of Chapter 3. Furthermore, a diagram is presented to demonstrate the possible performances. Each criterion, cost driver, has a different impact on the recurring costs. In Chapter 8.4 weight factors are assigned to the cost drivers and the performance of different roof systems is determined.

Load spread

Load spread is considered to be the ability to spread the loads evenly over a large (ground) surface. Load spread has a substantial impact on the recurring costs due to the following argument: With an even load spread relative cheap Stelcon plates can be applied instead of an expensive pile foundation. This statements is only valid when the following two assumptions are met. Firstly, the soil underneath the stadium should be sufficient to carry the occurring loads. Secondly, the application of a Stelcon plate should be cheaper than a pile foundation. Furthermore, when Stelcon plates are applied, there will be no pile foundation left behind after each venue. This is in line with the design philosophy to reuse all the materials in the highest possible state and prevent material degradation.

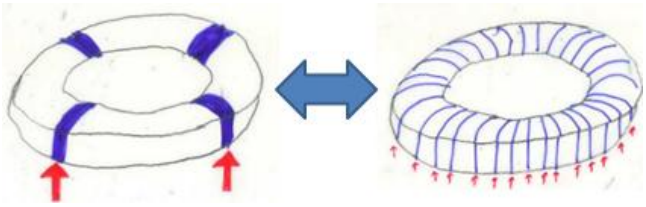


Figure 8-1 Load spread diagram

To check the first assumption stating that the soil could carry the occurring loads an estimation is made on the occurring stadium loads and the required soil characteristics. The calculation, displayed in Chapter 8.4.1.1, showed that soil characteristics of ≈ 115 kN/m^2 are required. Moist clay has similar loadbearing characteristics so the first assumption is validated.
The second assumption states that a Stelcon plate costs less than a pile foundation. Stelcon plates require a well prepared soil surface and lifting machinery. Furthermore, to truly create an even load introduction the thickness of the Stelcon plates could be substantial. Nonetheless, a pile foundation requires an effort intensive process to drive the piles into the ground and remove them when the stadium is transported. Furthermore, if poor soil loadbearing characteristics require a pile foundation, an even load spread will lower the pile loads thus creating the opportunity to apply a more slender pile foundation. Therefore, in this research the assumption is made that an even load spread is beneficial.

Stability during erection and deconstruction

When direct in- and out of plane stability is created, temporary scaffolding structures are not necessary during construction and deconstruction. Because the stadium roof will hover at a height of roughly 30 meter and have a depth of 40 meter, the temporary scaffolding structure will be a substantial structure. When the usage of such a temporary scaffolding structure can be prevented, the recurring costs are far lower.

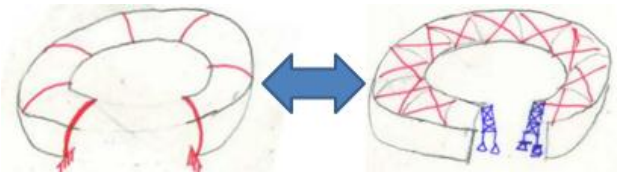


Figure 8-2 Stability during erection diagram

Modular design

In this research the definition of a modular design is: “A structure which consists of similar segments.” A modular structure has multiple advantages. Firstly, because the structure consists of similar modules, the construction and deconstruction process is quick and easy due to repetition of (de)construction technologies. Secondly, because the structure consists of similar segments, segments do not require a specific location which improves the building organization process. (e.g. With a portal roof structure, portals can be interchanged and thus not require an exact location).

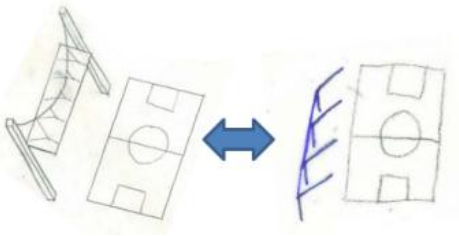


Figure 8-3 Modular design diagram

Adaptable design

When a stadium can respond to different functional demands, the stadium can be used for multiple purposes. The potential revenue sources and therefore the value of the stadium is increased if a stadium can be used for a soccer tournament with a capacity of 50.000 people as well as a field hockey tournament with a capacity of 30.000 people.

The stadium is considered to be perfectly adaptable when it can perform two functions, as displayed in Figure 8-4: Adjust the amount of segments, top of diagram. And adjust the depth of the roof, bottom of diagram.

Although the link between an adaptable design and the recurring costs is rather thin, this criterion does influence the employability of the stadium. Therefore, the potential revenue sources are increased and therefore this criterion is considered.

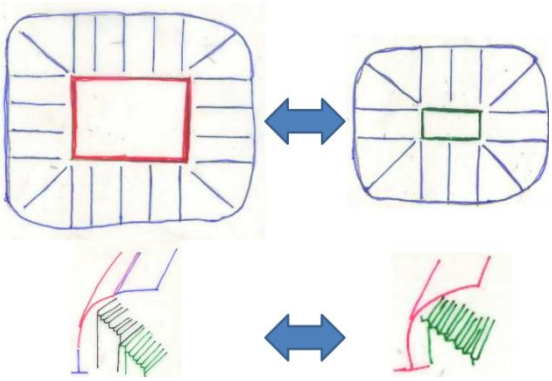


Figure 8-4 Adaptable design diagram

Amount of material (load transfer mechanism)

The load transferring mechanism (e.g. normal forces versus bending) determines the amount of material required in the roof structure. The required amount of material to transfer normal forces is far less compared to bending. This will result in a lower volume of the loadbearing structure. When less weight and volume has to be transported less effort is required. (e.g. less containers, less hoisting activities etc.)

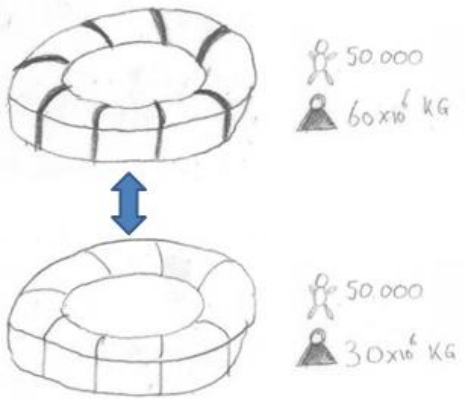


Figure 8-5 Amount of material diagram

8.1.1 Absence of transportation- and assembly demand design criteria

The optimal stadium roof was initially determined with assistance of these five design criteria. However, during the course of this research two other criteria were added. Respectively, to optimize the structure regarding transportation means and to minimize the assembly and disassembly procedure.
Firstly, the influencing factors of both criteria are discussed. This is followed by a discussion if these aspects should also be taken into account in the roof type assessment. Luckily, the aspects influencing these two criteria are either already considered as one of the 5 design criteria or are independent of the type of roof structure. Hence, the initial research remains valid.

Optimize roof structure regarding transportation means

The transport costs are influenced by the transportation method and the amount of containers in which the structure is transported.
The transportation method is discussed in the design philosophy of Chapter 3.1, dictating transportation via sea containers.
The amount of containers is influenced by the amount of material and the degree of filling of the container. The type of load transfer determines the amount of material and is already considered as a separate criterion in the design philosophy. The degree of filling influences the number of containers. The degree of filling of the material can be limited by both the volume as well as the weight. The degree of filling of a container is an optimization process occurring at the detail engineering phase of a design. (Hollandia H. , 2013) Since this research aims to compare the different roof structures on a conceptual level, it is of little to no use to take this criteria into consideration at this stage.

Conclusion

The transportation means are influences by the type of transport and the number of containers. The type of transport is already discussed in the design philosophy and does not necessary favor any specific roof structure. The number of containers is determined by the amount of material and the filling degree of each container. The first criterion highly differs per roof type and is considered as a design criteria. The degree of filling is optimized in the detail engineering phase of a design and is independent of the roof structure. Hence, each aspects regarding the optimization of the roof structure concerning transportation means is either already considered as a separated design criterion or is independent on the type of roof structure

Minimize assembly and disassembly procedures of the roof structure

The assembly and disassembly procedures are mainly influenced by the following five aspects.
1. The dimensions of the roof structure elements, 2. the amount of elements, 3. the connection methods, 4. the need for scaffolding, and 5. the number of separate elements. Each aspect is briefly discussed.

1. The dimensions of the elements of the roof structure influence the assembly procedure as follows. With larger, and thus fewer, elements less hoisting activities are necessary to erect and disassemble the structure. However, the downside is that larger elements are more difficult to handle and require heavier lifting machinery. The dimensions of the elements are determined by the dimensions of the transportation means rather than the type of roof structure. Hence, this aspect is independent of the type of roof structure.
2. The amount of elements, thus the total weight of the structure, is determined by the type of load transfer and is already considered as a separate design criterion.
3. The connection methods is based on the connection type. A fixed connection requires more assembly procedures than a hinged connection. However, the impact of type of connection on the total costs of the assembly procedure is considered to be negligible. Furthermore, the repetition of the connection methods influences the assembly procedure. This aspect is already considered as a separate design criterion. Therefore, the connection methods will not be considered.

4. Need for scaffolding structure: When a structure achieves direct in- and out of plane stability, a temporary scaffolding structure is not required reducing the assembly procedure. This highly differs per roof type and is considered as a separate design criterion; stability during erection.
5. The number of separate elements relates to the complexity of the roof structure. For instance, a space frame truss is made up out of many small components which are normally transported as a whole. However, because the structure has to be transported via sea containers this is not possible. Hence, a space frame has to be rebuild at each location requiring an intensive assembly procedure. This aspect has not been taken into account by the other five design criteria. Therefore, the outcome of the roof study will be reconsidered to determine if the number of elements give reason to change the outcome.

Conclusion
The assembly and disassembly procedures are mainly influenced by: The dimensions of the roof structural elements, the amount of the elements, the connection methods, the need for scaffolding, and the number of separate elements. The first four aspects are either already taken into consideration by the five design criteria or are independent of the roof structure and should be considered in a later stage of this research. The number of separate elements does differ per roof type and has not been considered. Therefore, the outcome of this study should be evaluated to determine if alterations are required.

8.2 Roof systems derived from literature

The classification of structural systems for stadium roofs, depicted in Figure 8-6, is based on considerations by Prof. Dr. Udo Peil of Technical University Braunschweig. The classification is performed from a load carrying direction point of view. Below Figure 8-6 the characteristics of each system is discussed.

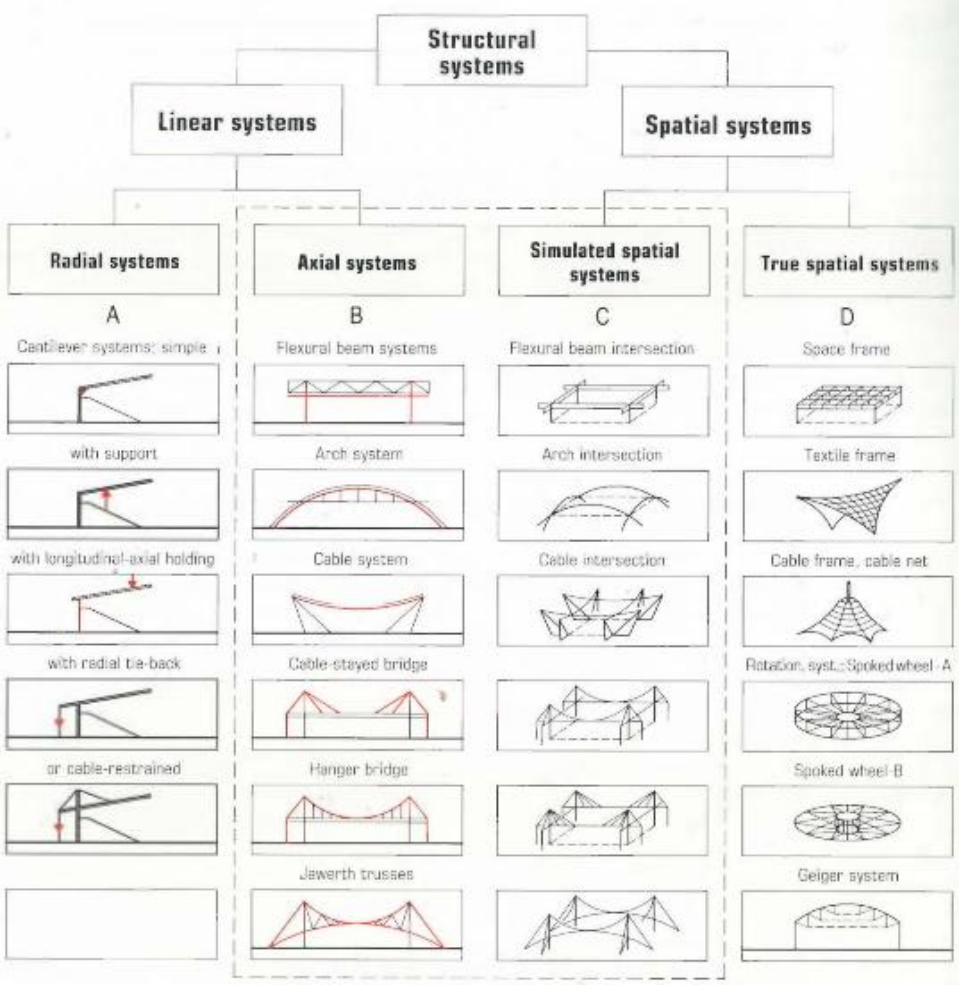


Figure 8-6 Overview of structural systems derived from theory Source: (Nixdorf, 2007) #244

- Radial systems (A) transfers loads perpendicular to the pitch. Radial systems do not have to follow a circular stadium layout. Straight portals perpendicular to the pitch, are also considered. Due to spectators' demand for an unobstructed view on the pitch the structural systems consist of cantilever structures.
- Axial systems (B) can be considered as longitudinal systems in which the loads are transferred parallel to the pitch. The loadbearing systems consist mainly out of flexural trusses or bridge like cable pylon systems.
- Simulated spatial systems (C) have identical characteristics to longitudinal (axial) systems which are connected in the corners. The main load carrying structure still spans in one direction. The foundations which are located in the corners can be shared with the longitudinal system perpendicular to it.
- True spatial systems (D) are structural systems in which the span in two directions also assists in the loadbearing function. This can be the case with shell and ring constructions as well as with space, textile and cable frames.

The stadium roofs depicted in Figure 8-6 provide a first insight in possible roof structures. In order to further elaborate and assess potential roof structures, inspiration is gathered from practice. An explanation is presented concerning the absence in reality of certain possible roof structures depicted in Figure 8-6 and whether or not this research should take these into consideration.

8.3 Roof systems encountered in practice

The overview presented in Figure 8-6 depicts possible roof structures and can be regarded as a typology study based on the direction of load transfer. Although this typology study is already insightful, it could be altered to improve the design process of a transportable and demountable stadium roof structure. Since a transportable stadium will be erected multiple times, the recurring costs are of major influence on the financial feasibility of the stadium. Therefore, aspects influencing the recurring costs will function as a starting point for the typology study. A study is performed to identify which roof structures are applied in (soccer) stadiums build around the world.

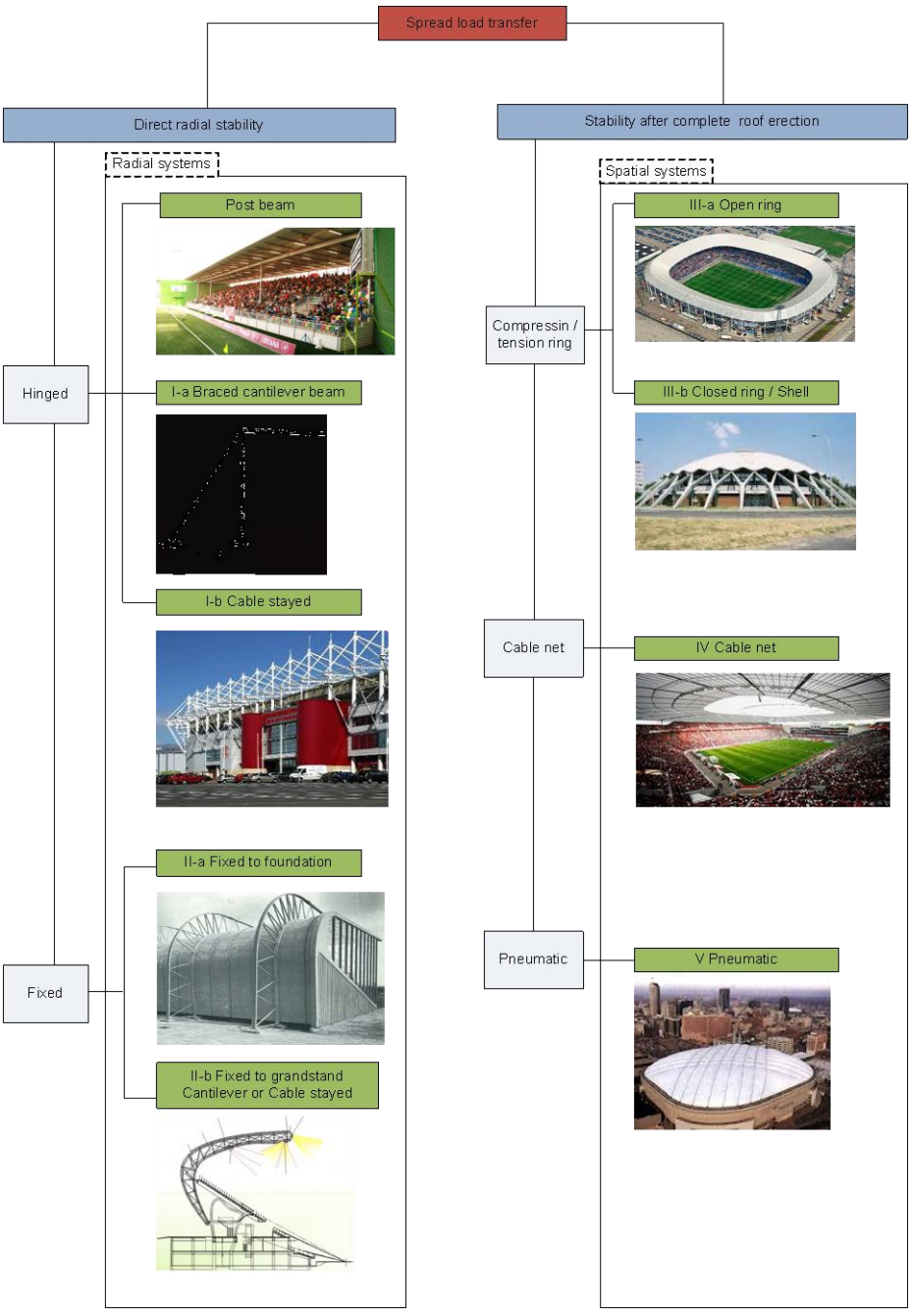
Reader guide

Chapter 8.3 is build up as follows: Firstly, the two aspects influencing the arrangement of the typology study are discussed and the resulting typology study is presented. Secondly, the similarities between the typology study based upon the roof structures applied in practice and the typology study derived from literature are discussed. Thirdly, arguments are presented for the absence of roof structures derived from theory which are not encountered in practice. Finally, a conclusion is presented in which the roof structures that are further examined in this research are discussed.

8.3.1 Key aspects for typology study

Two key aspects derived from the transportable and demountable demand concern the structure's load spread and stability during erection and deconstruction. These two aspects have a high impact on the recurring costs. Therefore, they will start as a starting point for the typology study.

The typology study presented below, based on stadium roof structures applied in practice, is constructed as follows: Firstly, a division is made between the load spread of the roof structure. Subsequently, a division is made concerning stability during erection and deconstruction.



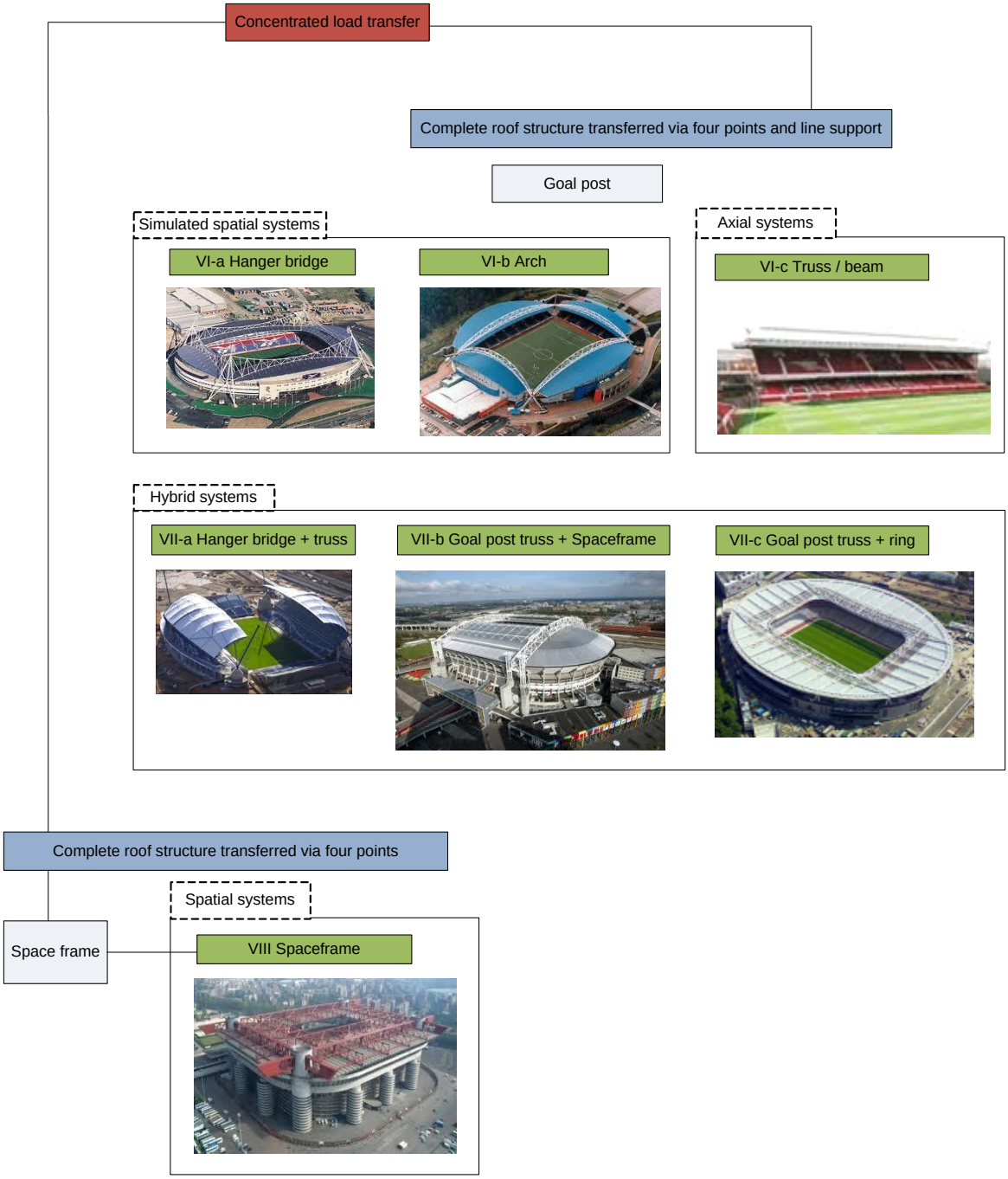


Figure 8-7 Typology study Source pictures: www.stadiumdb.com

8.3.2 Similarities between roof structures found in literature and practice

The following similarities can be identified between above typology study and the theoretical overview presented in Figure 8-6:

- The radial systems have spread load transfer and are direct stable in plane and obtain out of plane stability either directly or after placement of at least two segments.
- The axial systems have a concentrated load transfer in the corners and are only stable when a section (quarter) of the roof is erected.
- The simulated spatial systems have identical characteristics as the axial system.
- Most of the true spatial systems have a spread load transfer and are only stable when the entire structure is erected. The depicted spaceframe transfers the load to four points. Other spaceframe configurations leading to either a spread or concentrated load transfer are also possible.

N.B. Hyrbid systems are systems in which the roof is carried by a combination of multiple load carrying systems (e.g. combination of goal post truss system with a ring system). Although already several hybrid stadium roof structures are depicted it is noted that there are also other hybrid versions not depicted. Because this typology study has the goal to provide insight in the characteristics of different structural systems only several hybrid versions are presented. When different systems have complementary beneficial characteristics, hybrid versions should be considered.

8.3.3 Absence of roof structures from theory in practice

Not all roof structures depicted in Figure 8-6 have been identified in practice. Therefore, some types of roof structures do not show up in Figure 8-7. Their absence can be twofold. On one hand, they might have disadvantages which causes them to not be applied in practice. On the other hand, it could also be that systems are applied in practice but are not encountered during this research.
Most of the systems which are not identified in practice are in the category true spatial systems (D). The textile frame and cable tent structure are not encountered in practice. Both structures require great efforts to erect because of their post tensioning necessity. Due to the transportable demand an effort intensive construction process is undesired. Moreover, in these two systems the roof completely covers the field. For a soccer stadium it is undesired to have a permanent roof cover over the pitch. The grass requires natural daylight which is retained by the roof. Thus, these roof structures will not be further considered in this research. Moreover, some systems in Figure 8-6 are grouped together in Figure 8-7. Because they have large similarities not each subsystem is displayed. (e.g. radial cantilever systems) Furthermore, also the post-beam structure will not be further investigated due to its view obstructive columns.

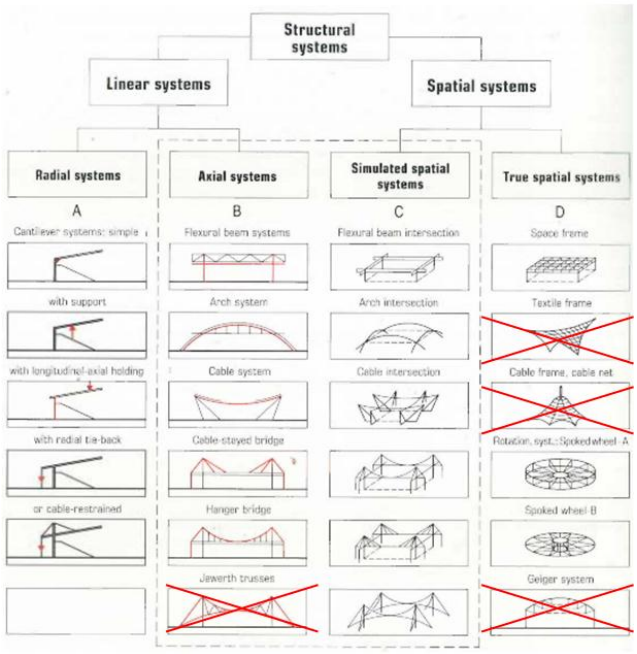


Figure 8-8 Absence of roof structures from theory in practice

8.3.4 Conclusion

Based on typology study depicted in Figure 8-7, the following conclusion could be drawn. Cantilever roof structures transfer loads perpendicular to the pitch and obtain direct in plane stability during erection and deconstruction. Therefore, they minimize recurring costs and are advantageous. Although this study is insightful, other criteria influencing the recurring costs have not been taken into account. Thus, the conclusions are still too thin to be decisive. Therefore, the other three design criteria are taken into account and all typologies are considered.
Furthermore, several roof structures derived from theory are not encountered in practice. This is either due to their disadvantageous erection process, their complete covering of the pitch, or it could be that they are applied in practice but not encountered during this research.

8.4 Performance of stadium roofs on design criteria

The roof structures encountered in practice are assessed on criteria imposed by the transportable and demountable demand. These criteria are: Load spread, stability during erection and deconstruction, modular design, adaptable design and amount of material. Weight factors are determined to take the different impact of each criteria on the recurring costs into consideration. Both the score as well as the weight factor allocation is validated with a survey held among structural engineers employed at IMd.

Reading guide

The build up of this chapter is as follows: Firstly, the importance of each design criterion (cost driver) is explained. Subsequently, the encountered performances of each roof system is presented with an indicative score of plusses and minuses. Secondly, each design criterion has a different impact on the recurring costs. Therefore, weight factors are allocated to each assessment criterion. Thirdly, the roof systems encountered in practice are scored on a scale of 1 to 10 and a total score is determined, taking the weight factors into account. The top 6 performers are used to validate both the scores as well as the weight factors with a survey among IMd engineers. After this validation, the top 2 performers are further examined.

8.4.1 Scoring of each systems

In this sub chapter an indicative score is assigned to roof systems on their encountered performances on each criterion. Furthermore, the load spread criterion is elaborated to validate the importance of this criterion.

8.4.1.1 Load spread

In the design criteria paragraph of Chapter 8.1 the following is stated concerning an even load spread:

- It provides the opportunity to apply cheap Stelcon plates compared to an expensive pile foundation.
- An even load spread will lower the resulting forces at the supports. Therefore, if piles are necessary, slender and short piles instead of thick and deep piles may be. Moreover, with small reaction forces, timber piles could become an option which is more sustainable compared to a concrete pile foundation.

Although these statements seam valid, there are several nuances. Firstly, in order to apply Stelcon plates, ground improvement is often required. This activity can be a costly endeavor decreasing the attractiveness of a pile foundation. Secondly, the load spread is determined by the load transferring mechanism of the roof structure. Due to the ascending asymmetric shape of a stadium grandstand and the demand for a roof without view obstructing columns, the internal load transferring mechanism will require many modifications to enable a spread load transfer. Thirdly, the soil should have sufficient loadbearing characteristics to take up the load. Fourthly, if Stelcon plates are applied, each support will have a similar spring stiffness which may disturb the desired internal load transferring mechanism.

In this sub paragraph the following steps are undertaken to validate this assumption and find out if the desired stadium is suitable for a Stelcon plate foundation.

1. Estimate the occurring loads.
2. Determine the type of load transfer.
3. Determine the resulting forces.
4. Discuss soil type loadbearing characteristics.
5. Conclude if the stadium can be supported by Stelcon plates.

Estimation on occurring loads and type of load transfer

In order to gain a first insight in the resulting forces it is assumed that the roof loads, working over a ctc distance of 5,4 m, are transferred through the grandstand and evenly distributed over 6 Stelcon plates with each a ground surface of 4m^2. This type of load transfer is chosen because other roof load transferring mechanisms will lead to higher concentrated loads. [24]

Therefore, not only loads acting on the roof but also loads acting on the grandstand are considered. The horizontal wind forces are not yet considered. However, the horizontal wind forces will provoke a moment which has to be taken up by a fore couple which could interfere with the desired load spread. Attention is paid to this phenomenon in a later stage of this research.

Loads		q_k
Dead load (PG)		
Roof	Structure	2,0 kN/m^2
Grandstand[25]	Structure	3,0 kN/m^2
Foundation slab	Stelcon plates	2,4 kN/m^2/plate
Live load (PQ)		
Roof	snow	0,6 kN/m^2
Grandstand[26]	People	4,0 kN/m^2

Table 37 Stadium loads

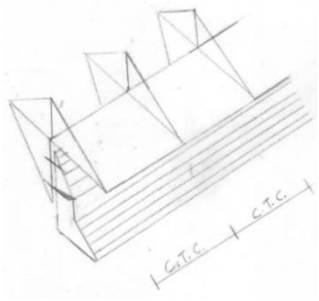


Figure 8-9 Center to center distance

Resulting forces

The loads on the ground are the loads acting on the stadium over a surface of 40 * 5,4 m (depth * ctc) and are transferred via 6 Stelcon plates with a surface of 4m^2. Thus, the resulting loads on the soil are:

PG: [(2,0+3,0) * 40,5 * 5,4 + 6*2.4]/ (6*4) = 46,1 kN/m^2 (8.1)

PQ roof: (0,6 * 40,5 * 5,4) / (6*4) = 5,5 kN/m^2 (8.2)

PQ Grandstand: (4,0 * 40,5 * 5,4) / (6*4) = 36,5 kN/m^2 (8.3)

Considering load combinations described in Table 7 the loads acting on the soil are:

6.10a: 1.50 * 46,1 + 0,99 * 36,5 + 0,90 * 5,5 = 110,2 kN/m^2 (8.4)

6.10b: 1,30 * 46,1 + 1,65 * 5,5 + 0,99 * 36,5 = 125,6 kN/m^2 (8.5)

The least favorable value of 6.10a and 6.10b is governing. Therefore, the governing downwards directed load results from 6.10b and is estimated to be 125,6 kN/m^2.

Assumptions and uncertainties of the estimation

In above calculation the assumption is made that the distributed loads acting on the roof (and grandstand) also act as distributed loads on the foundation. However, this will not be the case in practice. Furthermore, horizontal forces which could cause undesired tension in the foundation is neglected. Nonetheless, this method can be applied to get a first insight in the size of the occurring forces on the foundation. When a roof and grandstand configuration is chosen, the above calculation will be performed with the proper mechanical scheme.

Although above calculation contains several substantial estimations the outcome still provides a first insight in the occurring forces. This implies that soil characteristics of at least 125 kN/m^2 are sufficient to carry the loads resulting from the roof structure with a ctc of 5,4 m.

[24] All roof systems depicted in Figure 8-7 which do not transfer roof forces through the grandstand will lead to higher concentrated roof forces compared to roof forces transferred via grandstand.

[25] Pre tensioned concrete elements with a height of 8 cm as applied in FC Groningen Euroborg

[26] Due to fixed seating, the live load in gathering places is 4 kN/m^2 [NEN-EN 2002:b)

Soil type loadbearing characteristics

While the loadbearing capacity highly differentiates within soil types between locations, there do exist some (conservative) estimations on loadbearing capacities of different soil types.

Cohesiveness	Type of Soil	Loadbearing capacity [kN/m^2]
Rocks	Hard rocks (e.g. granite)	3240
	Laminated rocks	1620
	Soft rocks	440
Cohesionless soils	Gravel	440
	Medium sand, compact and dry	245
	Fine sand, loose and dry	100
Cohesive soils	Hard clay, dry	440
	Moist clay and sand clay mixture	150
	Soft clay (penetrateable several cm with thumb)	50

Table 38 Soil type loadbearing characteristics Source: (Prasad, 2012)

Besides solely loadbearing characteristics, settlements also play an important role in the load transfer into the soil. Although settlement behavior is discussed in more detail later on in this research the following is stated: Settlements can occur between different segments and within a segment. Due to the small ctc distance settlements between segments are estimated to be within limits. The settlements within a segment can have a negative impact. These aspects are considered in the technical elaboration of the recommended design.

Conclusion

Rough calculations indicate that the occurring stadium soil loads are ≈ 125 kN/m^2. This means that areas with similar or higher soil loadbearing characteristics are suitable. The only soil type where the stadium can not be employed is soft clay. Almost every country has numerous locations where soil types with higher loadbearing characteristics than soft clay are present. Therefore, the transportable stadium can be widely employed and a spread load transfer may lead to a Stelcon foundation.

Scoring of roof performances encountered in practice

The load spread characteristics of the stadiums are listed below and indicative scores are assigned.

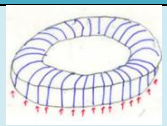
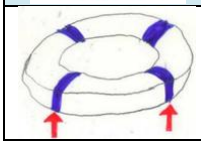
Performance			Score
	load transfer per segment/frame (radial & spatial systems)	Multiple transferring points per segment	++
		Two load transferring points per segment	+
		One load transfer point per segment	+/-
	Entire roof system load transfer to four point + line support		-
	Entire roof system load transfer to four points		--

Table 39 Load spread performances encountered in practice

8.4.1.2 Stability during erection

The stability during erection characteristics of the stadiums are listed below and indicative scores are assigned.

Performance	Score
Direct in plane and out of plane stability per segment	++
Direct in plane stability and out of plane stability after connecting at least two segments	+
In and out of plane stability after completion of section of the roof (roof divided in four parts)	-
In and out of plane stability after complete roof erection	--

Table 40 Stability during erection performances encountered in practice

8.4.1.3 Modular design

The modular design characteristics of stadiums are listed below and indicative scores are assigned.

Performance	Score
Modular, similar low tech construction technologies (e.g. all identical segments with bolted connections)	++
Modular, multiple medium tech construction technologies (e.g. bolted connections and cable connections)	+
Modular, High tech connections (e.g. post tensioning)	--
Not Modular, high tech connections (e.g. post tensioning)	--

Table 41 Modular design performances encountered in practice

8.4.1.4 Adaptable design

The adaptable design characteristics of the stadiums are listed below and indicative scores are assigned.

Performance	Score
Can adapt number of segments and depth of roof	++
Can number of segment but can not adapt depth of roof	+
Can not adapt number of segment but can adapt depth of roof	-
Can not adapt number of segments and can not adapt depth of roof	--

Table 42 Adaptable design performances encountered in practice

8.4.1.5 Amount of material(Load transfer as efficient as possible)

The type of load transfer is considered as indicator for efficient usage of material. When load is transferred via normal forces efficient use is made of the material. When load is transferred via bending inefficient use is made of the material. In order to visualize the type of load transfer an overview of the loadbearing direction is presented, a dummy vertical load is applied and the mechanical schemes are displayed. Multiple sections are presented to explain the loadbearing structure in the case of load transfer in two directions or a combination of structural systems. The schemes are presented in Appendix 10.

Furthermore, horizontal forces play an important role in the design of a stadium and its roof structure. The impact of the horizontal forces is considered further on in this chapter.

Scoring of roof performances encountered in practice

The amount of material characteristics of the stadiums are listed below and indicative scores are assigned.

Performance	Score
Transverse normal force + longitudinal normal force	++
Transverse bending + longitudinal normal force	+
Transverse bending + longitudinal bending	-
Transverse cantilever bending + longitudinal bending	- -

Table 43 Amount of material performances encountered in practice

8.4.2 Weight factor criteria

The roof structures are scored on five criteria influencing the recurring costs of a stadium. Each criterion will have a different impact on the recurring costs. Therefore, weight factors should be applied to the criteria. The graduate student has developed a weight factor allocation himself. Furthermore, a survey is performed with experienced structural engineers employed at IMd to validate the assigned weight factors.

Methods to assign weight factors

The best method to determine the weight factor of each criteria would be to assess a demountable stadium and determine the impact of each aspect on the recurring costs. Not only is this a cumbersome task, the lack of transportable stadiums build make it impossible to apply this method. Therefore, the weight factors are assigned on basis of common sense and a concise argumentation.

The following weight factor is decided upon:

- The load spread is considered to have the highest impact on the recurring costs. An even load spread will minimize the required depth and thickness of a pile foundation or even create the opportunity to apply Stelcon plates. [35%]
- The stability during erection will also have a substantial impact on the recurring costs due to temporary scaffolding structure which is required to create stability during the construction and deconstruction process. These will have large dimensions (height of 37 m) and be therefore an effort intensive structure to (de)construct. Furthermore, this structure should either be rented at each location or transported with the stadium. [25%]
- A modular design influences the required efforts for the (de)construction organization process and the (de)construction technologies. [15%]
- An adaptable design improves the employability of the structure. [10%]
- The amount of material influences the (de)construction and transportation efforts. [15%]

Summary

Criteria	Argumentation	Weight factor
Load spread	Cheap Stelcon plates instead of an expensive pile foundation	35%
Stability during erection	Roof can be erected without large scaffolding structure	25%
Modular design	Quick (de)construction organization process and technologies	15%
Adaptable design	Improve the employability of the stadium	10%
Amount of material (load transfer mechanism)	Less containers to transport over the world and less (de)construction efforts	15%

Table 44 Cost driver weight factor allocation

8.4.3 Performance overview of roof system

In this paragraph an absolute score, ranging from 1 to 10, is assigned to each roof system. Furthermore, the final score, taken the weight factors into account, is presented. All results are presented in Appendix A11.

Outcome of multi criteria analysis

As displayed in Figure 8-10, three systems end up in the top 6. Cable stayed-, cantilever- and pneumatic structures seem appropriate for a demountable stadium roof. This is due to the following reasons: The cable stayed and cantilever structures are modular, adaptable and do not require a temporary scaffolding structure. The pneumatic structure requires little material because the load transfer of the entire roof occurs via normal forces.

The weight factors and the scores assigned to these top 6 performers are validated with an IMd survey.

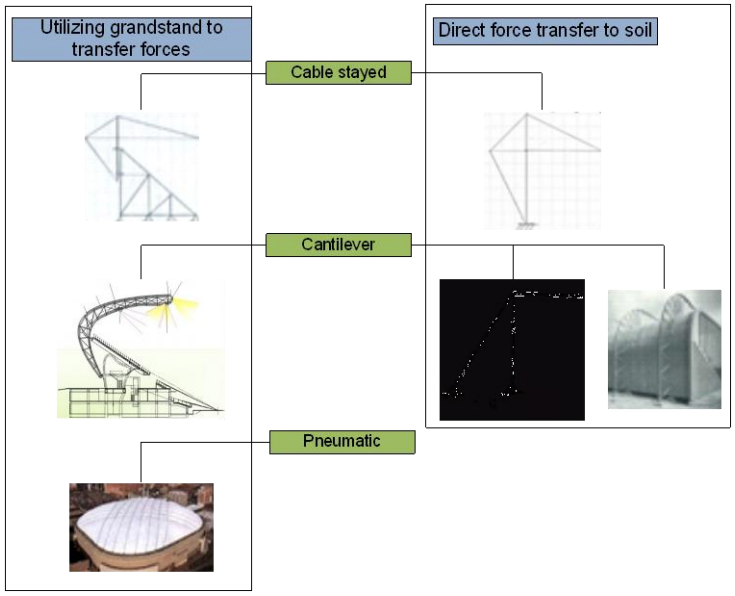
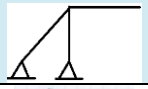
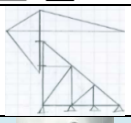
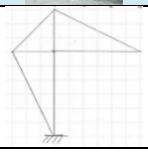


Figure 8-10 Typolgy study Top 6 performers

Rank	Picture	Score
1.		7,9
2.		7,8
3.		7,6
4.		7,5
5.		6,9
6.		6,4

8.4.4 Validation performance and weight factor with IMd survey

In order to validate the assigned scores and weight factors a survey is held among experienced IMd engineers.[27] In total ten engineers participated in the survey. The results of the survey is presented below. When the IMd weight factor distribution is applied to Klomp's scores, the same systems end up in the top 6.

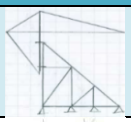
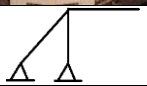
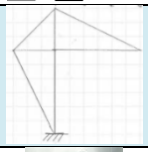
Rank	Picture	Score
1.		7.5
2.		7.4
3.		7.0
4.		6.2
5.		6.0
6.		5.7

Table 45 IMd survey results

8.4.5 Discussion, differences between results Klomp and IMd

The following differences are identified in the weight distribution between Klomp and IMd.

Criteria	Weight factor assigned by Klomp	Weight factor by IMd engineers
Load spread	35%	22%
Stability during erection	25%	22%
Modular design	15%	19%
Adaptable design	10%	11%
Amount of material	15%	27%

Table 46 Difference in weight factor distribution

The main observations are:

- IMd engineers value the importance of load spread less.
- IMd engineers value the importance on the amount of material more.

During the course of this research the graduate student came to the insight that, as indicated by the IMd engineers, indeed the amount of material plays a dominant role in determining the feasibility of a transportable stadium. Among others, it influences the number of containers which are required for transportation, the complexity of the building organization process and the amount of material, thus costs required to manufacture the structure. Luckily, increasing this weight factor resulted in a similar group of top performing roof structures.

To conclude, the survey pointed out the importance of the amount of material criterion and confirmed the scores assigned by Klomp.

[27] The survey can be found in Appendix A12.

8.4.6 Conclusion, top performing roof structures

The attractiveness of each of the top 6 roof structures is discussed. Subsequently, two roof structures are recommended to be investigated more closely.

The fixed to the ground roof structures, ranked 5 and 6 in both surveys, will not be further considered. The required foundation to transfer the moment into the ground is effort intensive to construct and hard to remove after the event. Therefore, these roof structure will not be further investigated.

The cantilever bracingd beam roof structure transfers the forces via a force couple, being two support reactions. The distances between these two supports defines the amount of force. In order to minimize the required compression and tension force the distance between these two supports has to be substantial. This large distance requires much material to transfer the force to the outer support and these structural components interfere with the functional area surrounding the stadium. Furthermore, the force couple results in tension forces which require expensive undesired tension piles. Therefore, the cantilever bracingd beam is considered to be unattractive.

Although the pneumatic structure performs good it will not be considered because of the following arguments. The erection and deconstruction process is effort intensive and high tech with its post tensioning. Furthermore, undesired (external) tension forces are introduced due to the pre tensioning, which has to be transferred to and taken up by the foundation. Moreover, a closed roof is considered to be undesired due to the demand for fresh air for the grass. Additionally, with a permanent roof a lot of ventilation is necessary to supply the athletes as well as the crowd with sufficient fresh air. Therefore, the pneumatic structure will not be further investigated.

The fixed to grandstand cable stayed system and the fixed to grandstand cantilever system are highly attractive because the grandstand assists in transferring the roof forces. Hence, creating an improved load spread. Furthermore, both systems perform well on the other four design criteria.

In chapter 8.1.1 it was stated that the number of different elements play a part in the attractiveness of a roof structure as well. Of the top performing roof structures, the pneumatic structure has a minimum amount of building components. The other top 5 performers are estimated to have a similar number of different components. Nonetheless, the pneumatic structure has too many disadvantages, listed above, to be further considered in this research.

Hence, the fixed to grandstand cable stayed system and the fixed to grandstand cantilever system are further elaborated to determine the optimal roof structure.

8.5 Conceptual design of top two performing roof systems

As concluded in the previous paragraph, the fixed to grandstand cantilever roof system and the fixed to grandstand cable stayed roof system appear to be the most attractive roof structures for a transportable and demountable stadium. In this paragraph both systems are further investigated.

This chapter is structured as follows. Firstly, similarities between the two systems are discussed including a brief intermezzo. Secondly, differences such as internal load transferring mechanisms as well as erection and deconstruction methods are discussed. Finally, a comparison between these two top performers and a recommendation on the optimal roof structure for a demountable stadium is presented.

8.5.1 Differences between the roof systems

The systems have two similarities:

- The global load transferring mechanism of the entire system (roof, grandstand and foundation) is similar.
- The roof height is identical. Therefore, the occurring wind forces on the roof are identical.

Global load transferring mechanism

The system of both the cable stayed- and cantilever fixed to grandstand structure can be modeled as a cantilever beam fixed on a triangular grandstand. The loads working on the roof can be schematized as a vertical force and a moment working on the location where the roof is connected to the grandstand. The grandstand has to transfer both the vertical force as well as the moment to the foundation. In Figure 8-11, mechanical schemes and reaction forces are presented. These correspond to both the cable stayed as well as the cantilever system. In order to get a first insight in the structure, it is considered that all elements have an identical stiffness. In the design elaboration phase the system is modeled more accurately. The situation in which downward directed loads are governing and the situation in which the upward directed loads are governing are discussed.

Downward directed loads

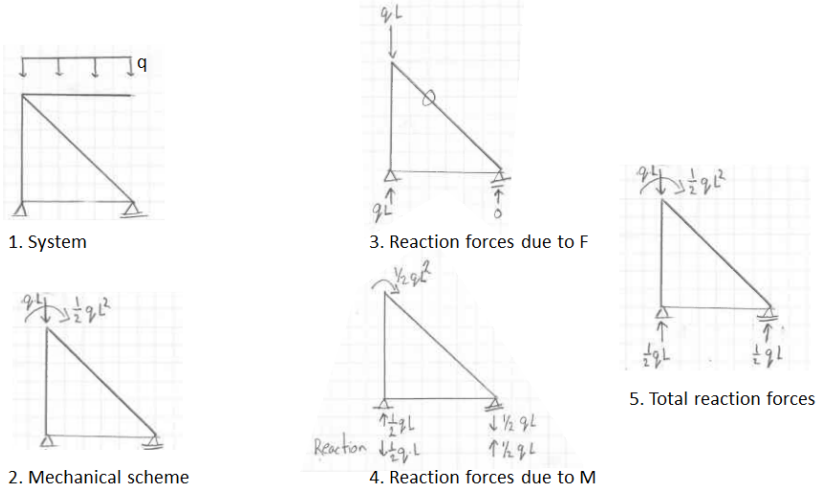


Figure 8-11 Mechanical scheme global structural system downward

The resulting upwards reaction forces from the foundation are $\frac{1}{2}$ql. The moment has an advantageous affect because it reduces the compression forces at the back column of the grandstand. With a very stiff bottom beam multiple supports can be placed to distributed the loads evenly.

Upward directed loads

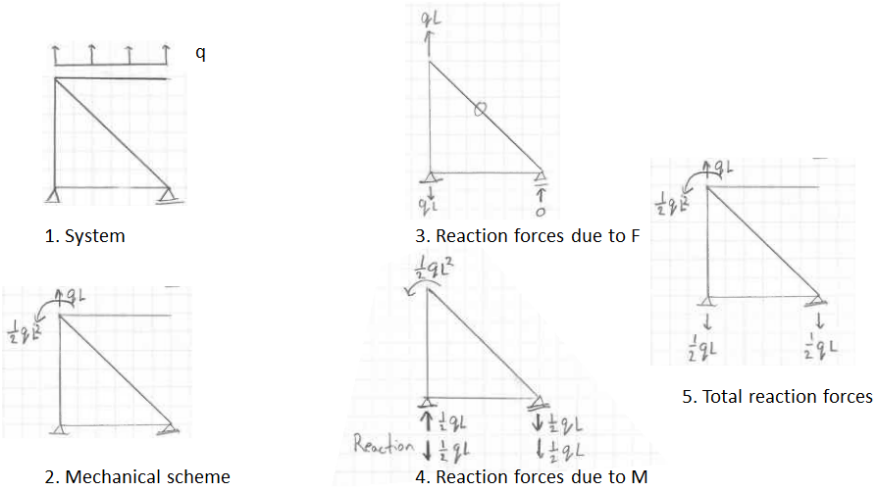


Figure 8-12 Mechanical scheme global structural system upward

The resulting downward reaction forces from the foundation are $\frac{1}{2}$ql. This implies that if the upward forces are governing, the structure requires undesired tension piles to stay in place.

Conclusion

- The resulting forces from a downward directed governing loading combination on the roof will lead to $\frac{1}{2}$ql compression forces on both ends of the grandstand. With a cleaver grandstand design these forces can be distributed evenly over the ground.
- The resulting forces from an upward directed governing load combination on the roof will lead to undesired $\frac{1}{2}$ql tension forces on both ends of the grandstand.
- When both roof and grandstand are designed, a check should be made if the permanent available downward directed loads are sufficient to ensure that the governing loading combination always results in compression forces in the foundation.

8.5.2 Intermezzo: Application of a counterweight

Appendix 13 discusses the suggestion to counterbalance the weight of the roof. If the weight is counterbalanced the moment resulting from own weight can be neutralized.

Although the application of a counterweight reduces the moments in the columns it is undesired due to the following reasons:

- When there is an upward directed wind force, the counter weight increases the occurring moment which will lead to even higher undesired tension forces in the grandstand.
- The addition of the contra weight will increase the column load.

8.5.3 Differences between the roof systems

The main differences between these two roof structures is expressed in the mechanical schemes and the erection and deconstruction methods.

Mechanical schemes

Although the mechanical scheme in which the roof, grandstand and foundation is considered, is similar, the mechanical scheme of the roof itself is not.
In both situations the moments active in the roof are substantial. Therefore, the roof itself is constructed as a truss which takes up moment forces via tension and compression forces.

Cable stayed

The cable stayed system can be schematized to have a roll support at the location where the cable connects to the roof. Figure 8-13 demonstrates the mechanical scheme of the roof under a vertical load.

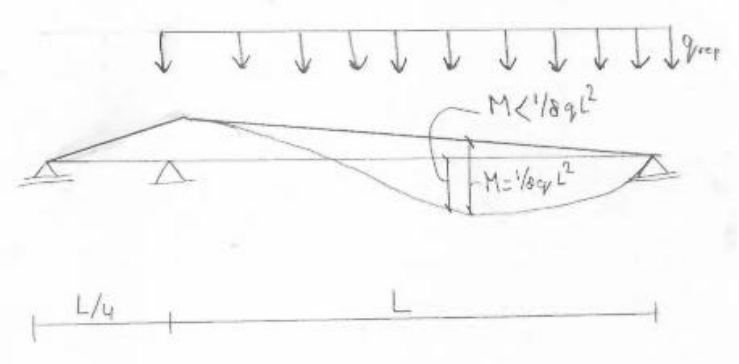


Figure 8-13 mechanical scheme cable stayed roof truss under downwards vertical load

When the roof is loaded in a downward direction, the cable will transfer tension forces. However, if the upward directed loads are governing a problem arises. A cable is not capable of transferring compression forces which will lead to an undesired floatation of the roof. Two measures can be taken to prevent this phenomenon. Either an additional cable will be added which is located between the grandstand and the bottom of the roof, or the cable on top of the roof has to be designed as a compression element. The first solution is undesired because this will block the sightlines of the crowd. When the second option is considered, the following occurs. By creating a compression element on the top of the roof, the roof will function as a cantilevering truss and thus have similar characteristics as the cantilever roof structure. The maximum moment derived from the mechanical scheme is smaller than 1/8 q $l^{2,}$

Cantilever

The cantilever beam has a mechanical scheme similar to the global mechanical scheme, truly cantilevering. The cantilever beam is designed as a truss. Therefore, the bending moments are taken up with normal forces. But the occurring bending moments are higher compared to the cable stayed systems. The maximum moment derived from the mechanical scheme is ½ q l^2 and thus higher than the cable stayed roof variant.

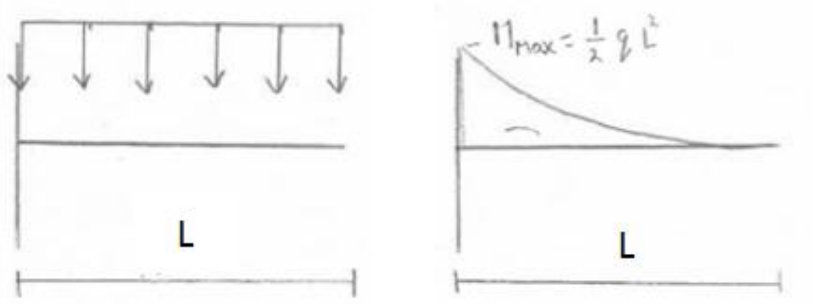


Figure 8-14 Mechanical scheme cantilever under downwards vertical load

Erection and deconstruction methods

Cable stayed

The cable stayed systems requires several procedures to be erected and deconstructed. Firstly, the truss will have to be assembled on the ground. Secondly, the diagonal 'compression cable' element and the supporting column have to be fitted. When this is performed the structure can be hoisted and mounted to the grandstand. When the structure is disassembled a crane should carry the weight of the roof so that the connection with the grandstand can be dismounted. Then, the roof can be laid on the ground where all the separate elements can be dismantled.

Cantilever

The cantilever truss systems requires two procedures to be erected and deconstructed. Firstly, the truss will have to be assembled on the ground. Secondly, the truss is hoisted and mounted to the grandstand. When the structure is disassembled a crane should carry the weight of the roof so that the connection with the grandstand can be dismounted. Then, the truss can be laid on the ground where all elements can be dismantled.

8.5.4 Conclusion comparison top two performs

Comparing the cable stayed and the cantilever fixed to foundation roof structures the following is concluded:

- The roof's own weight is insufficient to neutralize the governing upward directed load combination.[28] Therefore, the cable stayed roof structure has to be fitted with a compression element instead of a cable. Hence, with this compression element, the 'cable stayed' roof structure will behave similar to the cantilever.
- The erection and disassembly procedure of the cantilever system requires less activities.

Thus, the cantilevering fixed to grandstand roof structure is recommended as the optimal roof structure.

[28] This research states that the cable stayed roof structure will have wind uplift and is therefore undesired. Examples have been found of stadiums with a cable stayed roof structure similar to the considered design. Three arguments are presented why this is possible.

1. Roof stadiums are sunk into the ground minimizing the roof height. Therefore, smaller wind thrust meaning less wind uplift.
2. The stadiums have a fixed location and the local wind conditions are less severe.
3. The roof was designed with an old building code which has a safety factor of 1,5 instead of 1,65.
4. Wind tunnel tests are performed which could provide evidence that the wind amplification factors prescribed in the Euro Code are too conservative.

8.6 Conclusion roof structure

In this chapter the following conclusions are drawn:

- A roof structure has many possible shapes depending on structure's function, designer's preference and loadbearing direction possibilities.
- The roof structures are judged on their transportable and demountable behavior. Assessment criteria, cost drivers, are derived from literature and common sense. Scores are assigned on each roof structure which is validated with a survey among IMd engineers:
    - The load spread is considered to have the highest impact on the recurring costs. Stelcon plates are easier to install compared to a pile foundation. Furthermore, it requires lots of effort to remove the piles when the stadium is deconstructed. [35% By Klomp and 22% with IMd survey]
    - The stability during erection will also have a substantial impact on the recurring costs due to temporary scaffolding structure which is required to create stability during the construction and deconstruction process. [25% By Klomp and 22% with IMd survey]
    - A modular design influences the required efforts for the (de)construction organization process and the (de)construction technologies. [15% By Klomp and 19% with IMd survey]
    - An adaptable design improves the employability of the structure. [10% By Klomp and 11% with IMd survey]
    - The amount of material influences the building organization, (de)construction and transportation efforts. [15% By Klomp and 27% with IMd survey]
- The IMd engineers value the amount of material more compared to the amount of load spread. In hindsight, the amount of material plays a very import factor in the recurring costs. Among others, it influences the number of containers which are required for transportation, the complexity of the building organization process and the amount of material, thus costs, required to manufacture the structure.
- The same roof systems are most advantageous adhering to either Klomp's- or IMd structural engineer's weight factors allocation.
- The roof structures with its loadbearing direction perpendicular to the pitch (radial) are advantageous on basis of amount of load spread and stability during erection. It transfers the load through multiple segments with a relative short center to center distance. The systems require little or none temporary structures to establish in- and out of plane stability. When the other three demountable and transportable performance criteria are also considered the radial structures are still the most advantageous.
- Within the radial structures, the systems in which the roof is fixed to the grandstand are most advantageous because this creates the possibility to spread the load.
- Spatial and longitudinal systems are not beneficial because they have concentrated load transferring points at the corners of the stadium and require temporary structures.
- A scale model wind test should be performed to determine the wind suction coefficient.

When comparing the top two performing systems, cable stayed- and cantilever roof fixed to grandstand structures, the following conclusions are drawn.

- The roof's own weight is insufficient to neutralize the governing upward directed load combination. Therefore, the cable stayed roof structure has to be fitted with a compression element instead of a cable. Hence, with this compression element, the 'cable stayed' roof structure will behave similar to the cantilever.
- The erection and disassembly procedure of the cantilever system requires less actions.
- The global mechanical scheme of both variant is similar. Hence , the resulting forces on the ground resulting from the live loads are similar.

The cantilever roof fixed to grandstand is considered to be the optimal roof design. An even load spread is realized through its connection to the grandstand. Furthermore, no temporary scaffolding structures are required during assembly. Moreover, it is a modular and adaptable structure.

9 Grandstand loadbearing frame design

After identifying the pitch dimensions, deciding on the appropriate lay-out type and determining roof skin, roof structure and horizontal grandstand system, it is possible to design the grandstand loadbearing frame.

Reader guide

This chapter is structured as follows. Firstly, the loads acting on the loadbearing frame and the governing load combinations are discussed. With the loads defined, the design considerations are elaborated; Discussing the materialization, the force transferring mechanisms, dynamic behavior of total system and the function of the bracings. Furthermore, the foundation of the loadbearing frame is presented. Subsequently, the out of plane stability of the loadbearing frame is discussed. Finally, five interesting connection details are presented.

9.1 Loads on loadbearing frame

The loads acting on the stadium are presented with two figures. In Figure 9-1, the permanent loads acting out of the plane on the loadbearing frame are presented. In Figure 9-2 the live loads acting in plane on the loadbearing frame are presented. Table 47 summarizes the occurring loads which are defined in Appendix A1.

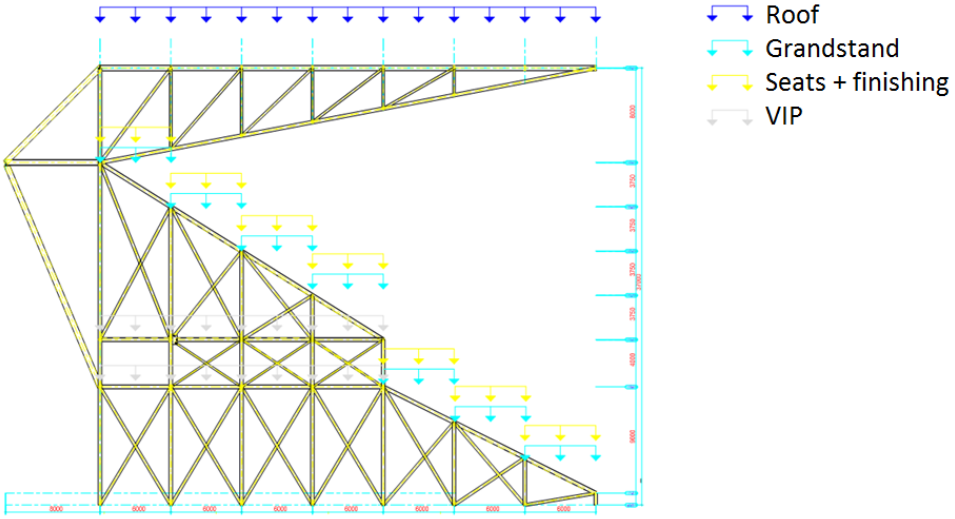


Figure 9-1 Load scheme permanent loads out of plane.

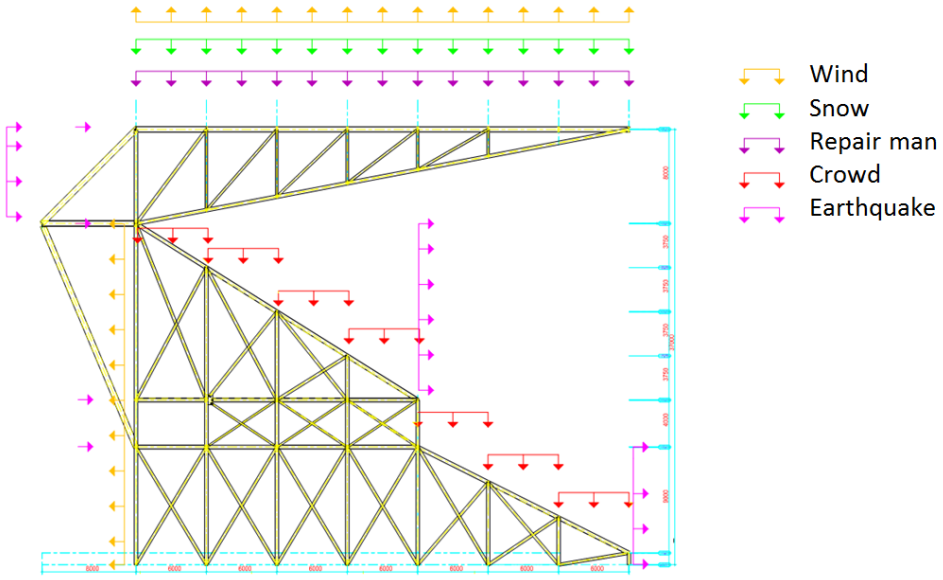


Figure 9-2 Load scheme live loads in plane

The value of each load is determined in Appendix A1.

	Value	Load on roof truss Span: 9,8 m	Load on roof truss Span: 10,2 m	Load on roof truss Span: 10,8 m
Roof: Alu plate	0,05 kN/m^2	0,49 kN/m^1	0,51 kN/m^1	0,54 kN/m^1
Roof: Girder	0,65 kN/m^1 gider	1,26 kN/m^1	1,26 kN/m^1	1,26 kN/m^1
VIP floor + ceiling	3,0 kN/m^2	-	30,6 kN/m^1	32,4 kN/m^1
Grandstand	0,36 –0,55 kN/m^1	7,1 kN/m^1	5,5 kN/m^1	5,3 kN/m^1
Seating +finishing	0,51 kN/m^2	4,90 kN/m^1	5,10 kN/m^1	5,40 kN/m^1
Wind suction	1,96 kN/m^2	19,20 kN/m^1	20,00 kN/m^1	21,20 kN/m^1
Snow	0,56 kN/m^2	5,49 kN/m^1	5,71 kN/m^1	6,05 kN/m^1
Repair man	1 kN per 10 m^2	0,98 kN/m^1	1,02 kN/m^1	1,08 kN/m^1
Repair man	4 kN/m^2	39,2 kN/m^1	40,8 kN/m^1	43,2 kN/m^1
Crowd	4 kN/m^2	39,2 kN/m^1	40,8 kN/m^1	43,2 kN/m^1
Earthquake	The phenomenon earthquake and its resulting loads on the structure are discussed in Appendix A4.			

Table 47 Summary loads on loadbearing frame

9.1.1 Loading combinations

Different load combinations are considered to determine the governing load combinations.

	Dead load				Live load				
	Roof	Grand-stand	VIP	Finish-ing	Crowd	Wind façade	Wind roof	Snow	Earth-quake
Governing upward	0,9*G	0,9*G	0,9*G	0,9*G	-	1,65*Q	1,65*Q	-	-
Governing downward V1	1,3*G	1,3*G	1,3*G	1,3*G	1,65*Q	-	-	1,65*Q	-
Governing downward V2	1,3*G	1,3*G	1,3*G	1,3*G	1,65*Q	0,99*Q	0,99*Q	-	-
Earthquake	1,0*G	1,0*G	1,0*G	1,0*G	-	-	-	-	1,0*G

Table 48 Governing load combinations and corresponding safety factors – loadbearing structure Source: NEN-EN 1990: N.B. 5

9.2 Design considerations

With the loads defined the loadbearing structure is designed. The load transfer and reaction forces are studied. The amount and location of columns and bracings are explored as well as the grandstand dimensions. Multiple configurations are designed and the force transfer and reaction forces for the different load combinations are considered. This led to the following insights.

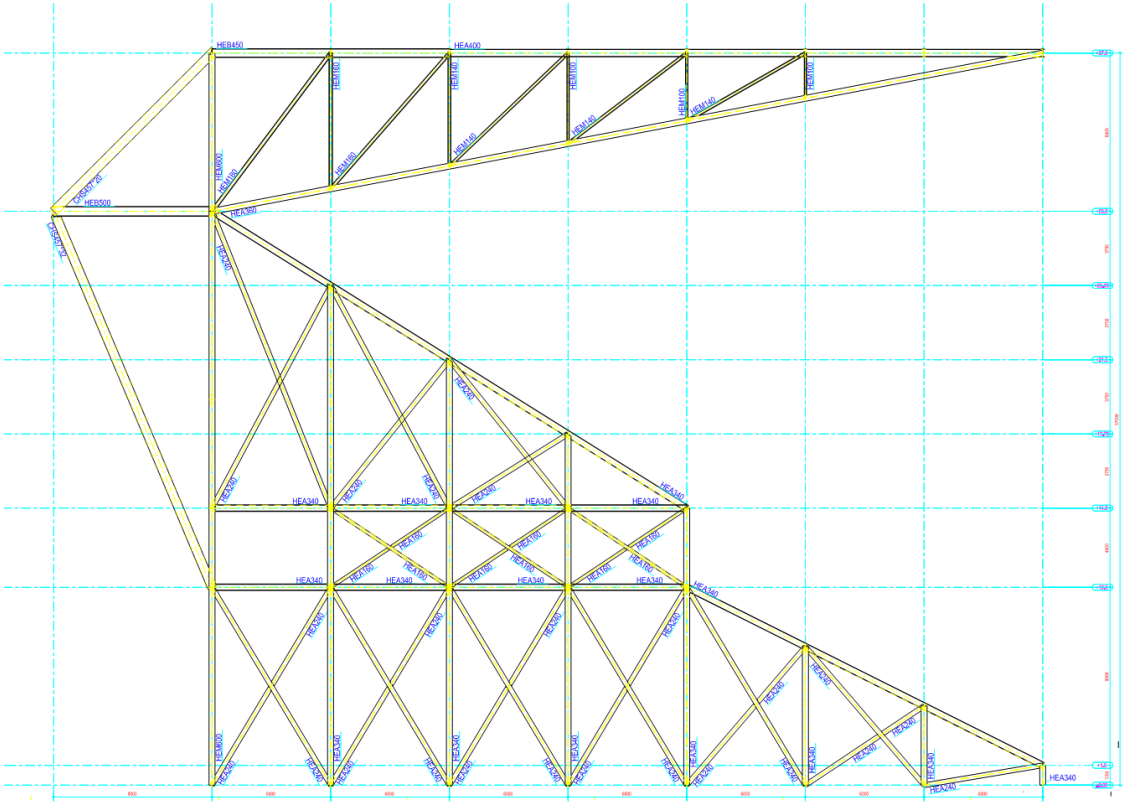


Figure 9-3 Overview grandstand loadbearing frame (an enlarged, scaled, drawing is attached in Appendix A3)

Materialization

Table 47 demonstrates that high forces act on the loadbearing frame. Hence, either concrete or steel are desirable materials. Concrete is undesired because it is not demountable. Thus, steel is chosen.

Force transferring schematization

The governing load combination is considered in Figure 9-4, being the external wind uplift. The wind has a horizontal force which also results, due to the suction on the roof, in a vertical component. The horizontal wind load provokes a moment leading to, in the depicted case, tension reaction forces on the right side and compression reaction forces on the left side. Furthermore, the entire width of the stadium experiences uplift due to the wind suction acting on the roof. The dead load of the stadium causes compression reaction forces. In Figure 9-4, the vertical forces are depicted to be even over the entire width. This will not be the case since the mass distribution of the own weight is not evenly spread. However, the global idea remains valid.

Calculations are performed to determine whether the dead load is sufficient to neutralize the wind uplift and wind moment. Hence, preventing the demand for an undesired expensive tension pile foundation. Because the stadium belongs in consequence class 3, the wind uplift is increased with 65% while the advantageous dead load is decreased with 10%. This increases the odds of requiring a pile foundation. The occurring reaction forces and required pile foundation are determined in Chapter 9.4

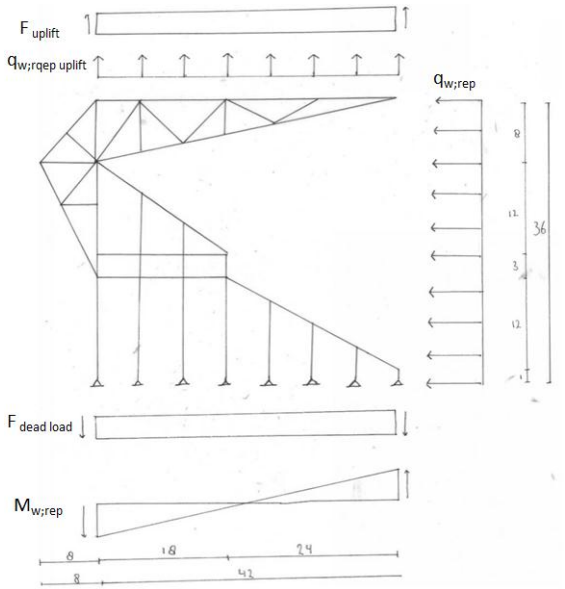


Figure 9-4 Force transferring schematization grandstand frame with roof

Internal force transferring mechanism

The transfer of the roof loads to the foundation are a critical aspect in the design of the loadbearing frame. As Figure 9-5 depicts, the roof uplift load provokes a moment represented as a force couple. The moment will firstly be transferred through the top left triangle with a tension and compression force over a relative short distances leading to high forces. This is depicted as the red couple. Subsequently, the moment is introduced in the second tier grandstand triangle with a tension force in the grandstand diagonal and a compression force introduced at the floor between the first and second tier. This is depicted as the blue couple. Finally, the moment is transferred over the grandstand loadbearing columns. This is depicted as the green couple. The tension forces can be spread over multiple columns by the usage of bracings.

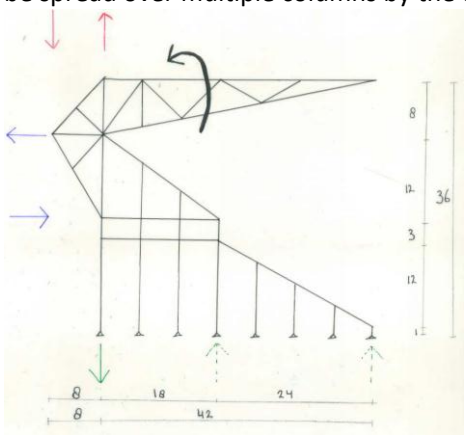


Figure 9-5 Load transfer of wind loads acting on roof provoking an internal moment force

In the load transferring mechanism depicted in Figure 9-5 the following statements hold:

- A larger distance between a force couple will lower the forces (Moment = arm * force).
- There are two advantages to connect the roof diagonal to the lower floor VIP area. Firstly, the distance between the couple is larger resulting in lower forces. Secondly, the bracing of the triangle of the lower tier is in line with the location where the compression force is introduced resulting in a smoother load transfer.
- Due to the high wind load, tension forces are inevitable. Compensating dead load is insufficient to completely diminish the occurrence of tension forces.
- By decreasing the center to center distance of the frame the resulting reaction forces drop. This is because the live loads play a dominant part in the resulting reaction forces and decrease linear proportional to the frames center to center distance.

- By introducing more columns in the frame, the load spread is more equal. The downside is that more columns will increase the assembly process and transportation volume.
- Besides tension forces, high compression reaction forces occur due to the high downward directed spectators crowd load.

Concerning the location and effect of bracings the following is stated:

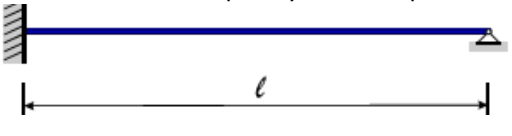
- The moment is transferred through stiff triangles being the first and second tier. The ends of these triangles are supported by only one column resulting in high local forces. Therefore, bracings are introduced to spread the forces evenly.
- The bracings should have sufficient stiffness to take up the loads. The amount of forces which the bracings take up depends on the stiffness ratio between the bracings and the stiff grandstand triangle. When the triangle is far more stiff compared to the bracing, the bracing will not take up much load. This leads to an undesired concentrated load to the columns at the triangle ends. Hence, rather large stiff profiles are applied as bracings.
- By introducing bracings only over 1 bay ('beuk'), all the forces are transferred through this bracing. The resulting forces are higher because the distance between one bay is smaller than the width of the triangle.
- Bracings can be designed to either take up solely tension forces, or take up both compression and tension forces. When the latter is applied and a bracing system of crosses is applied each column is supported on both sides by bracings of which one is loaded in tension and the other in compression. This leads to an improved load spread which outweighs the downside that the bracings should be designed to prevent buckling.
- Bracings will take up the load via normal forces. Otherwise, the columns will transfer the forces via bending leading to undesired large profile dimensions.

Thus, multiple bracings should be applied to spread the forces as much as possible and transfer the load via normal forces instead of bending.

In the grandstand configuration, the architectural form of the VIP area influences the structural loadbearing design. If the VIP is removed, one continuous diagonal grandstand is created. Hence, the grandstand acts as one stiff triangle. With the VIP interruption, two triangles are created. By having only 1 triangle the outer column, which experiences most of the tension force, has little compensating dead load above the support. This results in a larger tension reaction force. Hence, the VIP interruption is desirable. The results of this study are presented in Appendix A14.

Dynamic behavior total system

In the design of the horizontal grandstand system the aluminum grandstand is designed to have a natural frequency above 5 Hz. The total system should also fulfill this demand. The bracings ensure that the entire system; grandstand, diagonal beam which supports the grandstand and support columns have sufficient stiffness. However, the diagonal beam, supporting the aluminum grandstand, between two columns does not enjoy the stiffness of the braces. Hence, this is the most critical point of the entire system regarding dynamic loading. The continuous diagonal beam, supporting the grandstand, is schematized as a clamped and hinged supported beam. Equation 9.1 determines the natural frequency of a clamped and hinged supported beam (Hivos, 2008).



$$f = \frac{2}{\pi}\sqrt{\frac{3\,EI}{0{,}2\,\Psi_2\,\mu\,l^4}}\;Hz \qquad (9.1)$$

Beam	E [N/m^2]	I [m^4]	μ [kg/m] [29]	L [m]	f [Hz]
HE-A 340	210*10^9	27690*10^{-8}	2805	7 m	7,25

Table 49 Natural frequency loadbearing frame

[29] $\mu = \Psi_2$ * (mass beam + mass crowd + mass grandstand) = 0,6 * (104,8 + (4000 * 10,8 / 9,81) +578) 2805 [kg/m]

The dynamic behavior of the total system is approximated by equation 9.2 (Hivos, 2008).

$$\frac{1}{f_{total}^2} = \frac{1}{f_{frame}^2} + \frac{1}{f_{grandstand}^2} \quad (9.2)$$

The natural frequency of the grandstand system is defined in Chapter 6.6.2 and is 7,10 Hz. The natural frequency of the HE-A 340 beam is 7,25 Hz.
Thus, according to equation 9.2 the natural frequency of the total system at its most critical point is 5,07 Hz. This is > 5 Hz and thus fulfills the demand.

To conclude, this is a rather conservative approximation since it is assumed that the entire crowd (4 kN/m^2) is jumping simultaneously and no damping effect has been taken into account. Hence, the total system fulfills the dynamic behavior demands with flying colors.

9.3 Design optimization

- The upward directed forces are governing for the roof truss design. Therefore, the roof diagonals are placed from bottom left to top right. Hence, the diagonals are loaded in tension during the governing load combination. The vertical field beams, having a shorter (buckling) length, are loaded in compression.
- The lower tier has less rows than the top tier. Therefore, the width of the top left stiff triangle is increased. With an increased width (arm) the forces are decreased.
- Most left bracings are removed from VIP floor to ensure the internal routing. For the first and second tier the distance between the bracings is sufficient to ensure adequate routing.
- CHS profiles are applied at the top left roof truss. The advantage is that CHS profiles have an equal buckling resistance in both directions.
- In the roof truss CHS profiles are undesired. The connections with CHS profiles occurs via protruding end plates which create an unattractive view. The bottom edge beam of the roof truss is supported in plane every field by a field beam and out of plane every two fields. Therefore, the weak axis is in plane and the strong axis is out of plane.

9.4 Foundation design

This chapter discusses the impact, and desired value, of the spring stiffness of the foundation as well as the foundation material and (dis)assembly process. Furthermore, the situation in which the estimated soil loadbearing characteristics is inaccurate is discussed. Next, it is determined if over-dimensioning is necessary to have a safe structure when the load transfer is disrupted due to inaccurate soil loadbearing characteristics compared to the anticipated soil loadbearing characteristics.

Spring stiffness

Up to this point, the structure is modeled with infinite stiff supports. In reality, this will not be the case. Each support has different maximum and minimum forces which it attracts during the different load combinations. Each support should have sufficient capacity to transfer the maximum occurring loads. Since these differ per support, not all supports are identical. Hence, the stiffness differs per support. A column which experiences the highest loads will require a stronger and thus stiffer foundation. The different stiffness of each support could influence the internal load transferring mechanism. Different configurations and their impact are discussed.

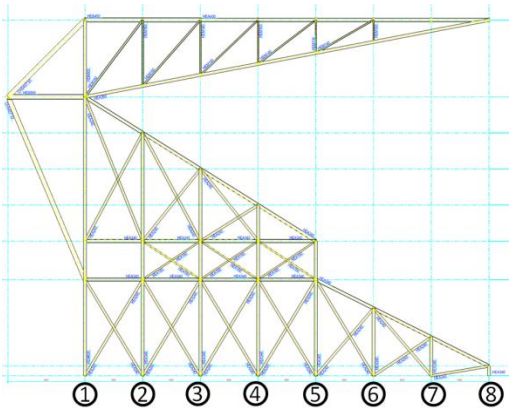


Figure 9-6 Overview with loadbearing frame with numbered supports

In Table 50, the reaction forces of the infinite stiff structure are presented in both the governing upward and downward load combination. The governing upward directed load combination results in a maximum support reaction tension force of 95 kN at support 5. This force can be taken up by a prefab concrete pile due to adhesion with the surrounding soil. It is assumed that the maximum adhesion capacity of a concrete compression pile is 150 kN. This value is a rough estimation since it depends at the specific soil characteristics. Nonetheless, 150 kN is a commonly applied indicator.

In Table 50, in the realistic column, the stiffness' magnitude stands in relation to the amount of force which the foundation is expected to experiences based on the infinite stiff reaction forces. The following stiffness values are assigned to the springs. Support 1 has a spring stiffness of 150.000 kN/m^1, 2 till 5 have a spring stiffness of 100.000 kN/m^1 and 6 till 8 have a spring stiffness of 50.000 kN/m^1. These values are representative for a concrete pile foundation.
It is concluded that a realistic spring stiffness of the support improves the load spread of the structure.

In Table 50, in the slack column, the amount of stiffness stands in relation to the amount of force which the foundation is expected to experiences based on the infinite stiff reaction forces but are less stiff compared to the realistic column. The following stiffness values are assigned to the springs. Support 1 has a spring stiffness of 100.000 kN/m^1, 2 till 5 have a spring stiffness of 50.000 kN/m^1 and 6 till 8 have a spring stiffness of 10.000 kN/m^1. These values are representative for a slack concrete pile foundation.
It is concluded that a slack foundation disrupts the desired load transfer, especially in the downward directed load combination, load on pile 5 is increased with 359 kN (+33% compared to realistic estimation). Nonetheless, no local failure occurs with a slack foundation but settlements within the frame could become critical which should be prevented.

	Infinite stiff				Realistic				Slack			
	Upward		Downward		Upward		Downward		Upward		Downward	
	x	z	x	z	x	z	x	z	x	z	x	z
1	169	916	195	1119	149	855	232	1262	172	949	203	1185
2	-44	473	166	966	-81	412	216	951	-58	351	153	840
3	92	151	63	1160	56	221	94	1046	66	189	16	1056
4	141	-14	-2	1209	119	68	4	1093	123	43	-58	1249
5	170	-90	-92	971	162	-52	-68	1075	149	-91	-13	1434
6	174	-74	-75	644	181	-72	-52	561	154	-45	69	355
7	180	-95	-42	560	287	-102	-199	535	268	-68	-141	402
8	-21	-18	-213	316	-12	-84	-228	422	-13	-81	-228	424
SUM	*861*	*1247*	*0*	*6945*	*861*	*1247*	*0*	*6945*	*861*	*1247*	*0*	*6945*

Table 50 Reaction forces in kN. Foundation designed with infinite stiff-, realistic and slack stiffnesses.

Inaccurate soil characteristics

The situation could occur, that the soil loadbearing characteristics estimated by a geophysicist are inaccurate. Hence, two situations are considered in which two vital supports, respectively support 1 and 5, have a stiffness which is either 20% more or less compared to the assumed value.

	Realistic				Support 1 20% more				Support 1 20% less			
	Upward		Upward		Downward		Upward		Downward		Upward	
	x	x	z	x	z	x	z	x	x	z	x	z
1	149	855	232	1262	149	856	233	1260	149	855	231	1264
2	-81	412	216	951	-82	412	221	960	-81	413	212	943
3	56	221	94	1046	59	220	106	1069	57	222	83	1026
4	119	68	4	1093	118	66	25	1134	120	69	-13	1057
5	162	-52	-68	1075	162	-45	-62	939	162	-57	-73	1190
6	181	-72	-52	561	182	-73	-68	592	180	-70	-38	534
7	287	-102	-199	535	289	-103	-227	557	286	-101	-176	516
8	-12	-84	-228	422	-12	-84	-229	433	-13	-84	-227	413
SUM	*861*	*1247*	*0*	*6945*	861	1247	0	6945	861	1247	0	6945

Table 51 Reaction forces in Kn. Foundation designed with support 1 20% more and less stiff

From Table 51 is it concluded that inaccurate soil loadbearing characteristics and thus different stiffness of support 1 has a negligible influence on the load transfer. The reaction forces are almost identical and no local failure occurs in the structure.

	Realistic				Support 5 20% more				Support 5 20% less			
	Upward		Upward		Downward		Upward		Downward		Upward	
	x	x	z	x	z	x	z	x	x	z	x	z
1	149	855	232	1262	136	798	213	1178	159	898	247	1326
2	-81	412	216	951	-94	457	198	1017	-72	379	230	902
3	56	221	94	1046	54	244	90	1081	57	203	96	1020
4	119	68	4	1093	121	76	7	1107	118	61	2	1083
5	162	-52	-68	1075	167	-53	-61	1073	159	-51	-73	1076
6	181	-72	-52	561	188	-76	-42	554	176	-68	-59	566
7	287	-102	-199	535	301	-109	-179	524	277	-96	-215	543
8	-12	-84	-228	422	-11	-90	-226	412	-13	-79	-229	430
SUM	*861*	*1247*	*0*	*6945*	861	1247	0	6945	861	1247	0	6945

Table 52 Reaction forces in Kn. Foundation designed with support 5 20% more and less stiff

From Table 52 is it concluded that inaccurate soil loadbearing characteristics and thus different stiffness of support 5 has a negligible influence on the load transfer. When the stiffness is 20% increased the downward directed load spread is evenly slightly improved while the downward directed load spread is slightly worse. This situation is vice versa when the stiffness of support 5 is decreased with 20%.

Thus, no additional measures are required when the deviation of inaccurate soil loadbearing characteristics is roughly 20%. The impact of the different stiffnesses for the critical supports hardly affects the load transferring mechanism. Hence, the structure does not require alterations (e.g. overdimensioning) to cope with inaccurate soil loadbearing characteristics.

Foundation material

In the building industry either steel or concrete foundations are applied. Furthermore, in the past timber was also an attractive foundation material. When considering these materials the following is stated. Timber piles can take up compression forces upto 150 kN. Hence, they can not bear the resulting loads of the stadium (Infomap-Constructieleer, 2006). Steel foundation piles are expensive and therefore undesired. Concrete foundations are the most commonly applied and

economical option. A disadvantage of the concrete piles is the limited ability to take up tension forces making it less straightforward to remove the piles when the stadium is dismantled.

Type of pile

A concrete pile foundation can be constructed in different configurations. In-situ or prefab concrete can be used. Furthermore, the pile can be placed in the ground with soil suppression or by soil extraction. Soil suppression is advantageous because it improves the loadbearing characteristics. However, during the insertion process vibrations are introduced in the soil. If neighboring structures limit vibrations this option becomes undesired.

Removability of the foundation

When the stadium is dismantled, the foundation can either be removed or remain in the soil. Although the foundation could be re-used by another structure, this is highly unlikely because the new structure will have to adapt its load transferring mechanism. Yet, the concrete pile foundation can be removed from the ground without substantial efforts. Water is injected next to the pile under high pressure removing soil around the pile which abrogates the adhesion. Therefore, the pile can be easily removed from the soil while keeping the foundation pile intact.

Conclusion

A concrete pile foundation is desired. It has the stiffness required to create an advantageous load transfer. Furthermore, it is commonly applied, cheap and widely available. The concrete foundation can also be removed after the event. The desired stiffnesses are: Support 1 has a spring stiffness of 150.000 kN/m^1, 2 till 5 have a spring stiffness of 100.000 kN/m^1 and 6 till 8 have a spring stiffness of 50.000 kN/m^1. Furthermore, if the most critical supports 1 and 5 have a stiffness which differs 20% compared to the desired values the impact on the load transferring mechanism is limited and no additional measures are necessary.

9.5 Out of plane stability

Up to this point, only in plane stability is considered. However, two aspects are of importance when assessing the out of plane stability. The wind forces and the elongation or diminution effects imposed by temperature changes throughout the day. To deal with temperature induced loads two solutions are possible; Either the structure should be capable of handling the stresses imposed when the elongation, due to temperature fluctuations, is obstructed or sufficient freedom should be provided via a displacement joint ('dilatatie') to enable unobstructed elongation or diminution.
In this chapter both the displacement joint as well as the stability of the stadium is considered.

9.5.1 Roof

Displacement joints

When a displacement joint is applied the stadium is cut into pieces. Each separate piece should still be stable in both in and out of plane direction. First the stresses are calculated if a displacement joint is omitted.

$$\text{Strain due to temperature fluctuations: } \varepsilon = \alpha_T * \Delta T \quad (9.3)$$

$$\text{Resulting stresses due to temperature fluctuations } \sigma_t = E * \varepsilon \quad (9.4)$$

The elongation, ε, is a product of the linear heat elongation coefficient, α_T, and the temperature difference, ΔT, between the temperature during construction and the actual temperature. α_T is defined in the Euro Code NEN 1991-1-5 Appendix C to be $10*10^{-6}$ /°C for steel components active in a structure with different materials, aluminum in this case. Because the stadium can be built anywhere in the world a large ΔT is considered. If we assume that different components are assembled in the morning with temperatures around 15°C and a maximum temperature during the day of 50°C a ΔT of 35 °C is applicable. Hence, the stresses imposed by the temperature fluctuation is $\sigma_t = E * \varepsilon = E * \alpha_T * \Delta T = 210000 * 10*10^{-6} * 35 = 73{,}5$ N/mm^2. These stresses are too high to be taken up by the structure. This situation occurs in the Serviceability Limit State in which the other loads are also imposed on the structure. Hence, since these stresses are too high, displacement joints are applied.

Displacement joints are created via slotted holes ('slobgaten') at the connection between the roof girders and the roof truss. An angle plate is mounted on the roof truss which has a horizontal gap larger than the bolt to provide space for elongation. Figure 9-7 depicts this connection.
Firstly, the locations of the displacement joints are defined. Since the displacement joints will cut the structure into separate pieces each piece should remain stable. Hence, with too many displacement joints much measures are required to ensure a stable structure between each displacement joint. With too little displacement joints the large length of the pieces results in too large elongations which can't be obtained via slotted holes. When the location of the displacement joints are defined the stability of each segment is discussed.

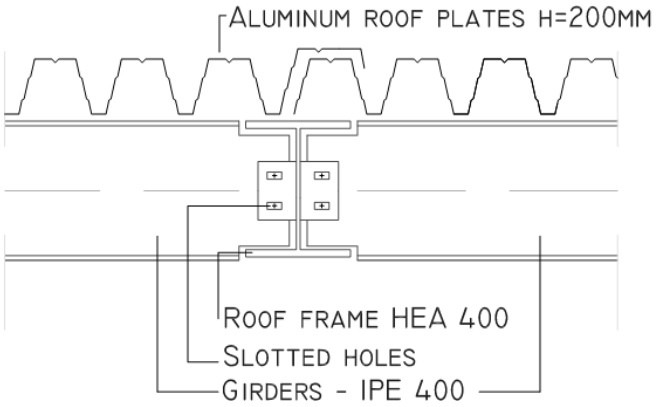


Figure 9-7 Girder roof frame connection at location of displacement joint

Figure 9-8 depicts the location of the displacement joints as well as the stabilizing elements.

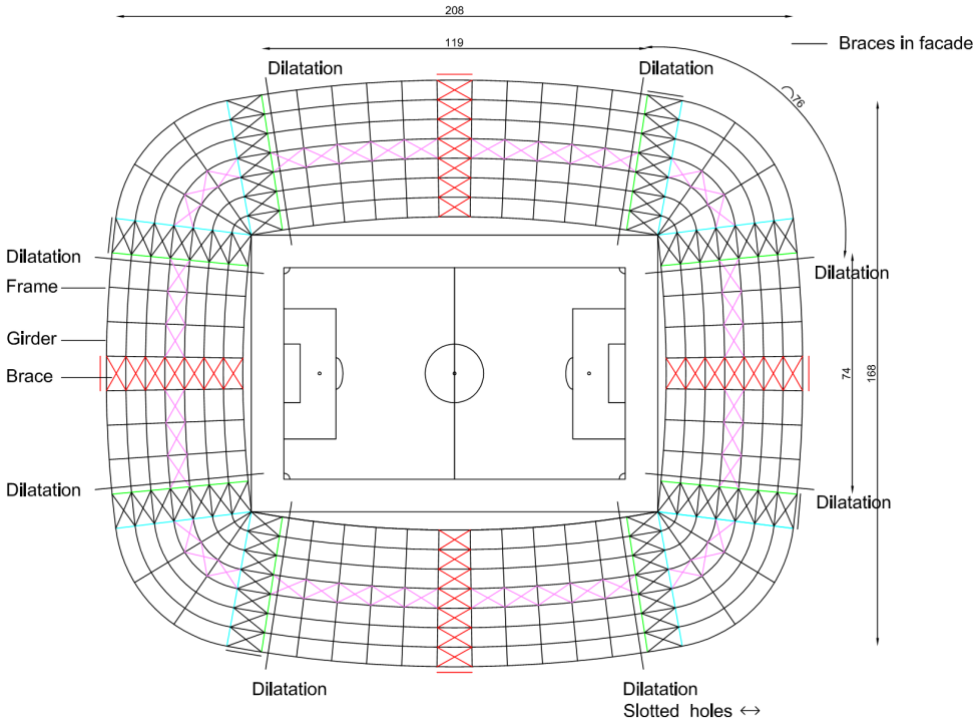


Figure 9-8 Displacement joint locations and stabilizing elements

The required lengths of the slotted holes is determined in Table 53. The assumption is made that the shrink effect is similar to the elongation effect. Thus, the length of the slotted hole is double the distances provoked by elongation. The lengths of the slotted holes are considered to be acceptable. Hence, the chosen displacement joints are valid from an elongation point of view.

$$\text{Strain: } \varepsilon = \alpha_T * \Delta T \quad (9.5)$$

$$\text{Elongation: } u = L * \varepsilon \quad (9.6)$$

Sector	Length	Elongation	Elongation per slotted hole	Length of slotted hole
Long side	119 m	42 mm	21 mm	42 mm
Short side	74 m	26 mm	13 mm	26 mm
Corners	76 m	27 mm	13,5 mm	27 mm

Table 53 Slotted holes determination

In the direction of the frame, perpendicular to the pitch, no displacement joints are necessary because movement in this direction is unrestricted and will not impose stresses.

Stability

Each separate section should remain stable. The slotted holes prevent force transfer parallel to the pitch.

Long and short side sections.

When wind perpendicular to the pitch hits the façade the stiff frame itself is capable of transferring the wind force to the foundation. However, bracings parallel to the pitch between the frames, depicted in pink in Figure 9-8, are necessary to make sure that each segment is activated when wind load perpendicular to the plane is active. In the case when obstacles provoke an uneven load spread, the pink bracings ensure that the loads are spread evenly and settlements between the frames are prevented.

The section should obtain its own stability within the displacement joint boundaries with the slotted holes parallel to the pitch. Bracings perpendicular to the pitch between the frames, depicted in red in Figure 9-8, are necessary to transfer the wind friction forces which act parallel to the pitch. The wind friction forces are transferred as a cantilever moment through the red bracings. The longitudinal pink bracings will also assist in activating multiple frames to transfer the perpendicular forces wind friction forces. The red bracings are continuous through the façade and transfer the forces to the foundation. In this situation it is assumed that the red bracings only span between one bay. When the red bracings span between multiple frames the moment arm is increased which decreases the resulting forces in the frame. Further research is required to determine the exact amount of forces and the necessity to use multiple spans to transfer the forces.

To conclude, the pink bracings assist in activating all the frames and preventing uneven settlements between the frames when the wind is perpendicular to the pitch. Furthermore, the pink bracings will also assist in spreading the longitudinal wind friction forces over multiple frames. The red bracings assist in transferring wind friction forces parallel to the pitch and continue through the façade to transfer the forces to the foundation.

Corner sections
The blue frames in the corner, combined with the girders and pink bracings, act as a stiff triangle enabling stability in both directions. However, the working line ('werk lijn') intersect in one point. Hence, the corner section will rotate along this point. When the corner wants to rotate the bracings activate the green frames which have a different intersection points. The bracings activate the green frames and therefore the frames transfer the forces to the foundation. Furthermore, one of the two roof wind bracings will be continued in the façade. In this way, three stabilizing lines exist to provide sufficient stiffness. Moreover, with the bracings at only one side between the displacement joints the structure can still elongate freely. The pink bracings will perform a similar function as in the long and short side sections.
Furthermore, the girders curved, depicted in Figure 9-8, should be straight to make them less sensitive to buckling.

Bracing type
For the bracing type strips, corner beams, profiles and cables are options. Strips or corner beams are insufficient due to the large (horizontal) span. Since the structure will be (dis)assembled multiple times the assembly efforts should be minimized. During transport the profiles could bend, expend and so on. Hence, adjustment freedom during assembly is advantageous. This adjustment freedom is more available with cables than profiles. Hence, the bracings are designed as cables.

Redundancy
Progressive collapse should be prevented at all times and the stadium should have redundancy. If a stabilizing element fails, the section between two displacement joints become unstable. When frames start to move out of plane, they will use the length of the slotted hole before being supported by the adjacent segment. The stabilizing elements of the adjacent segment should be designed to provide sufficient support for the adjacent sector to enable evacuation in the case of a failing stabilizing system. Hence, progressive collapse is prevented and a reliable and safe stadium is realized.

9.5.2 Grandstand
The grandstand will have similar displacement joints as the roof. However, bracings are omitted since the floors in the grandstand are stiff enough to spread the loads over multiple spans. The bracings in the façade should be designed to be stiff enough to transfer the horizontal forces imposed by the crowd to the foundation as well. Further research is required to determine the actual dimensions. However, the stability design mechanism holds its validity.

9.6 Connection details

Figure 9-5Figure 9-9 depicts the connection details which are investigated. The connections are calculated, visualized and presented in Appendix A3.

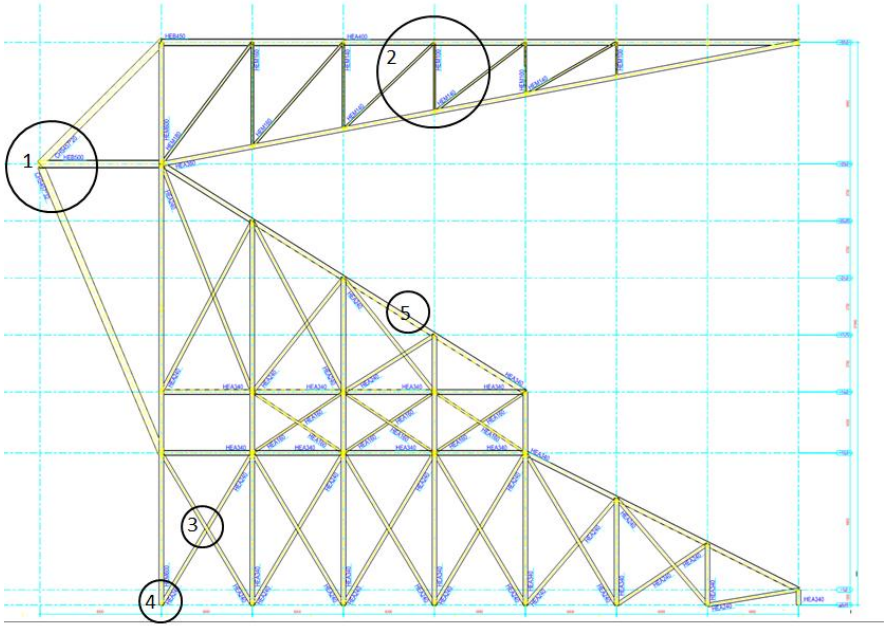


Figure 9-9 Overview connections

9.7 Conclusion

In this chapter the following conclusions are drawn:

- Steel is an advantageous material for the loadbearing frame. It has good loadbearing characteristics and can be designed with easily demountable connections.
- The top left two diagonal beams experience high compression forces during the governing load combination. Therefore, a CHS is desired which has identical loadbearing characteristics in- and out of plane. Thus, preventing multiple girder supports in the weak axis of the profile. The other elements are designed using HE profiles. These can be connected in an aesthetic appealing manner. Furthermore, the HE profiles are placed with their strong axis in- or out of plane depending on the governing buckling length.
- The roof field beams are configured to be loaded in tension under the governing load combination. In this case, the compression forces is taken up by the vertical field beams. Because these have a shorter buckling length, smaller profile dimensions suffice.
- The governing load combination is an upward directed wind load with solely compensating dead load. This provokes a moment which has to be spread as much as possible to create an even load spread.
    - The ratio between the stiffness of the bracings and the grandstand beam determines the amount of force which is transferred via the bracings. Hence, rather stiff bracings are chosen.
    - The upper tier has more rows than the lower tier in order to create a larger width over which the moment is spread.
- The foundation stiffnesses are in line with the support reactions when the supports are modeled as infinite stiff. In this manner, an optimal load spread is realized.
- The foundation is erected in concrete. A concrete foundation is cheap, has the required stiffness and can be removed after the event.
- The temperature changes during the day causes elongation. This is taken up via displacement joints. Stability is realized via bracings between each displacement joint section.
- The connection details, and their design arguments, are discussed in Appendix A3.

10 Impressions final design

A 3d-model is created to present the findings of the previous chapters into clarifying images. Large scale images are located in Appendix A16.

Figure 10-1 depicts the entire structure. The bracings which ensure out of plane stability are marked. They are also present on the opposite side of the marked long and short side. The foundation is not designed on a tangible level and is therefore omitted in Figure 10-1.

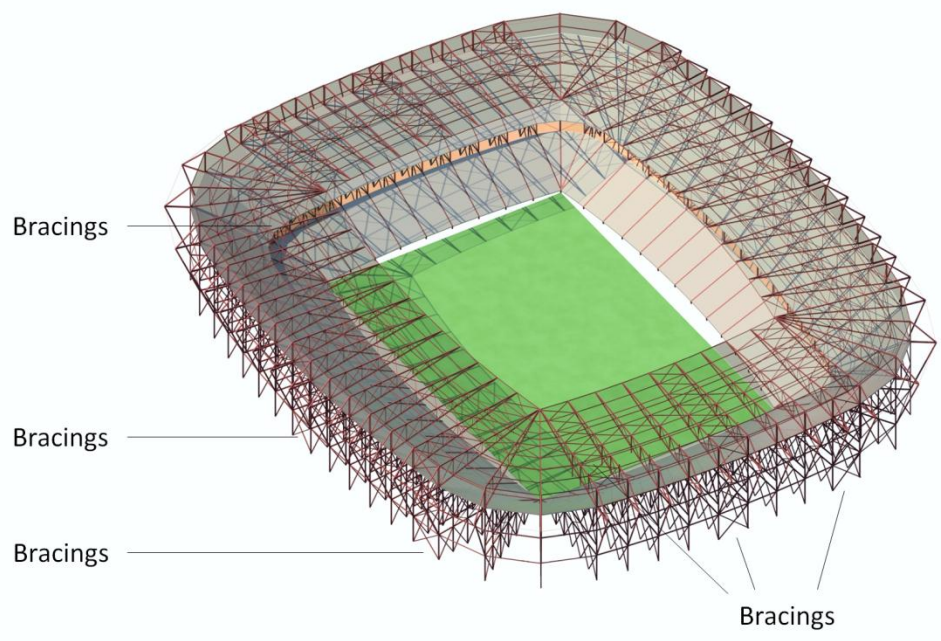


Figure 10-1 Impression overview stadium

Figure 10-2 depicts the corner section of the grandstand. The different structural components considered in this thesis are marked. The floor and ceiling of the VIP arena and the loadbearing frame out of plane stabilizing elements are omitted to prevent a blur picture. The stabilizing out of plane elements between the frames are visible in Figure 10-1, located between the frames at the height of the VIP area floor and ceiling. The foundation is not yet thoroughly designed. The foundation is solely depicted to present a holistic overview.

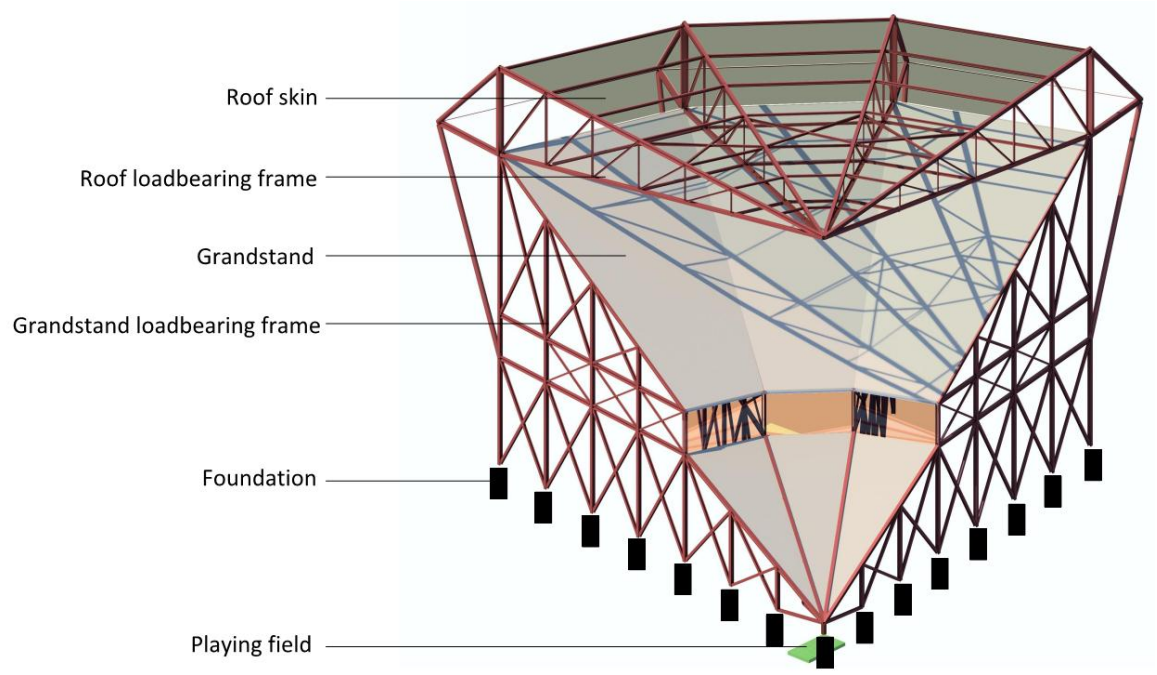


Figure 10-2 Impression section corner stadium

Figure 10-3 depicts the inside of the stadium. The bracings in the longitudinal direction and the bracing in the transverse direction are clearly visible. Furthermore, the girders on top and bottom edge beam of the roof truss are visible. The glass plate between the tiers represents the VIP area in which business seats are located.

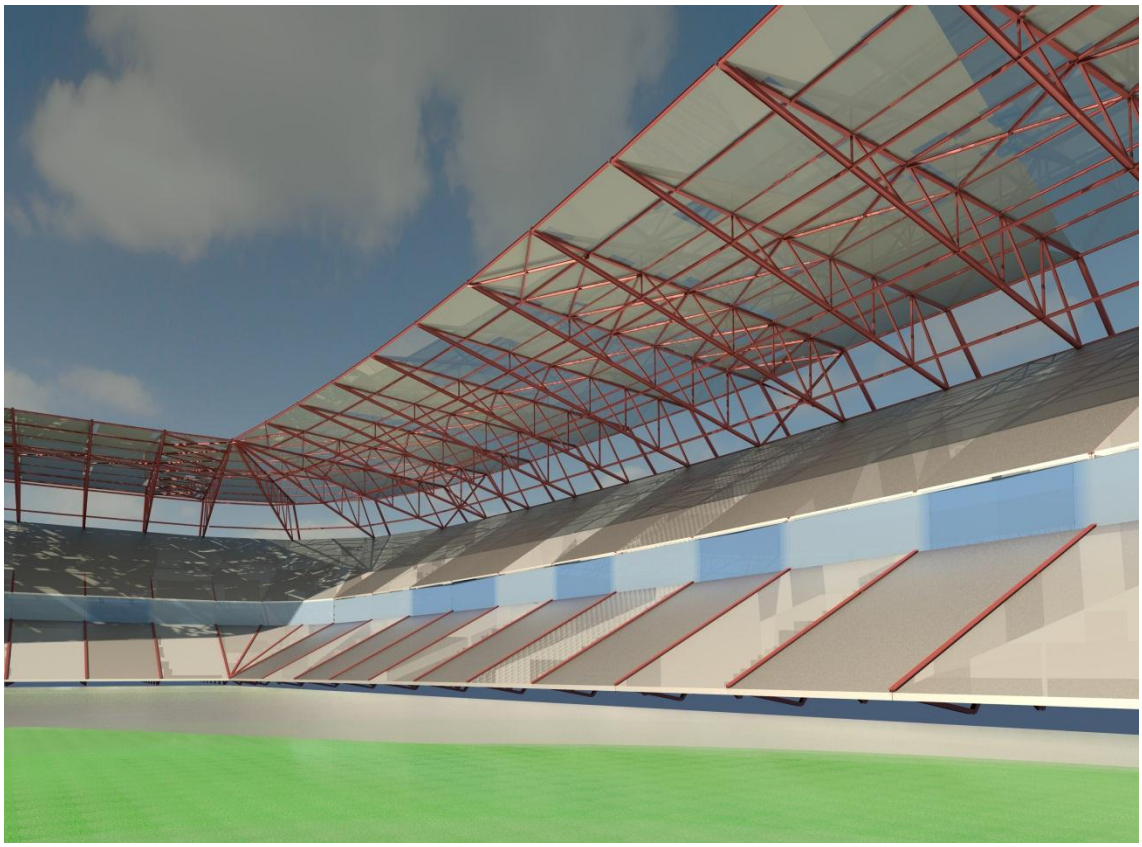


Figure 10-3 Impression inside stadium along grandstand

Figure 10-4 gives an impression of the view of the spectators located in the corner on the grandstand. The roof shadows on the field clearly depict the roof bracings.

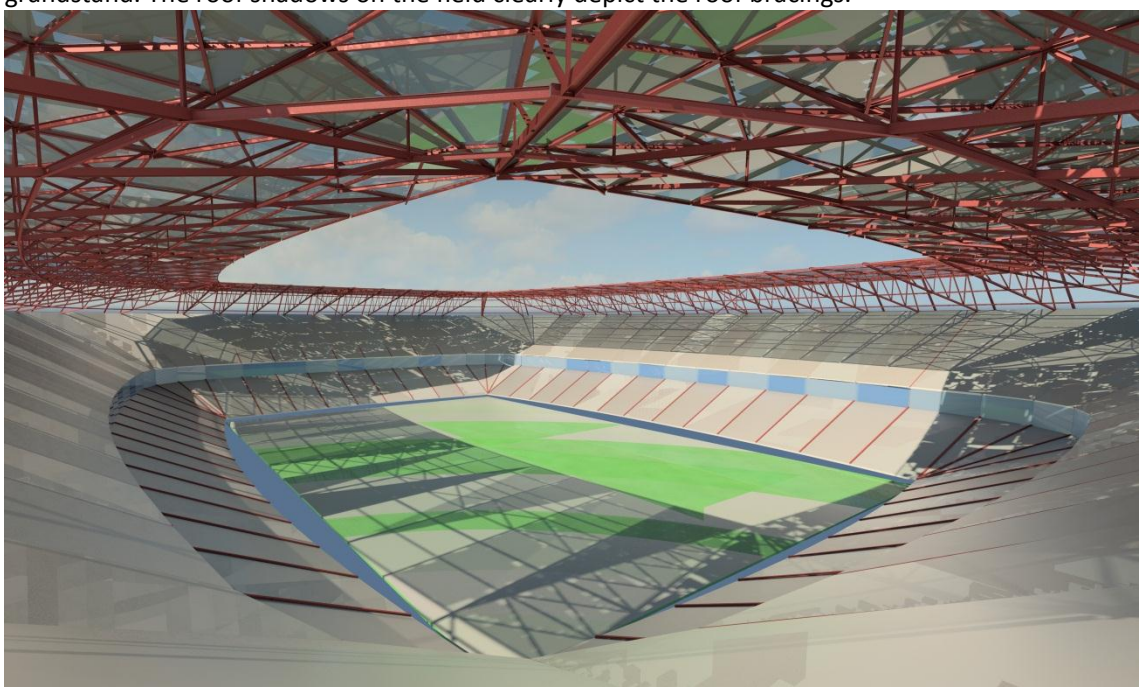


Figure 10-4 Impression inside stadium from corner

11 Business case

A business case is performed to determine the financial feasibility of the transportable stadium. The goal of the business case is to compare the lease fee of a transportable stadium to the total costs of a stadium build for a onetime event in which the demand for the stadium diminishes after the event. In a business case the costs and revenues which occur over the entire life time are considered. Empirical data and expert judgment is used to estimate which costs and revenues occur throughout the lifetime of the stadium. The business case aims to answer the following question. *If an event organization is aware that the demand for the stadium will vanish after the event, will leasing a transportable stadium become more attractive compared to building a permanent stadium?*

Reader guide

This chapter is structured as follows. Firstly, the life cycle of a stadium structure is presented. Secondly, a qualitative breakdown of potential costs and revenue sources are discussed. Next, the assumptions used to quantify the potential costs and revenue sources are discussed. When these are defined, three cash flow diagrams are presented. Respectively, a financial profitable permanent stadium, a stadium built for a onetime event with no revenues after the event and the cash flow diagram of a transportable stadium. Subsequently, the required minimal lease fee to create an economically feasible transportable stadium is compared to the costs of a permanent stadium. Furthermore, a sensitivity study which assesses the impact when conditions are altered is performed to determine the sanity of the business case. Finally, suggestions to optimize the revenue sources are presented.

11.1 Life cycle

The lifecycle is discussed to demonstrate the differences between a permanent and transportable stadium which also expresses itself in the different cash flow diagrams.

The life cycle of any (civil) structure, in this case a permanent stadium, is depicted in the grey boxes in Figure 11-1. The difference between a transportable and permanent stadium expresses itself in the blue boxes. The structure will be dismantled, transported and potentially stored before constructed once again. Storage costs can be prevented with a lease time exceeding the event duration. In this way, the hosting organization can make longer use of the stadium and storage costs are not applicable.

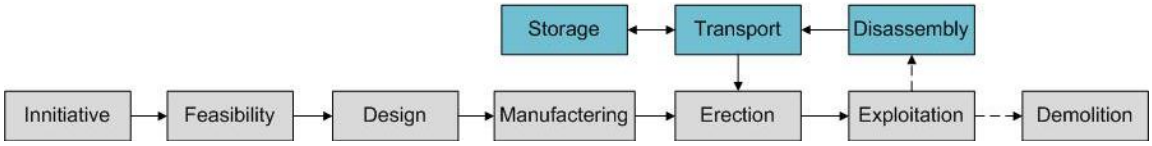


Figure 11-1 Life cycle (civil) structure

11.2 Revenue and cost breakdown

A permanent stadium should be built if a business case has indicated that there are stable revenue sources throughout the lifetime of a stadium. Possible revenue sources are:

- Ticket fees
- Broadcast fees
- Non sport events (congress, tours etc.)
- Lease fee for sport club
- Sponsors (stadium naming rights etc.)
- Catering
- Parking

Furthermore, the stadium will have to bear costs. Possible costs are:

- Design
- Manufacturing
- Construction
- Exploitation
    - Operating costs
    - Staffing costs (stadium management)
    - Insurance
- Maintenance
    - Small maintenance activities, yearly applicable
    - Large maintenance activities, occur every 10 years
- Demolition

Often, the owner of a stadium has inadequate financial means to finance the stadium. Hence, the owner turns to a bank to pay for the design, manufacturing and construction costs. This loan is repaid in a defined amount of time and interest is applicable over the outstanding debt. Therefore, in the cash flow diagrams, the design, manufacturing and construction costs are not depicted. They are covered by the loan which is depicted.

In the business case the costs of a transportable stadium are compared to the costs of a permanent stadium in which the demand for the stadium quickly ceases after the event. The amount of revenues produced during a sport event is independent on the stadium type (transportable versus permanent) as long as the stadium's capacity is identical. Therefore, the revenues do not play a role in this business case. Thus, the business case will compare the lease fee of a transportable stadium with the total cost of a stadium which is unused after the event. Nonetheless, in order to provide a comprehensive financial picture, revenues are depicted in the cash flow diagrams.

11.3 Business case conditions

A business case requires assumptions on conditions defining which cash flows, and their amount, will occur during the stadium life cycle. Firstly, the considered conditions are summarized. This is followed with a validation of the assumptions. In the sensitivity study the governing conditions are changed and their impact on the business case is discussed.

11.3.1 Conditions

1. The lease fee of a transportable stadium is compared to the costs of a permanent stadium which has no local demand after the onetime event. So, the stadium will be abandoned by the owner three years after the event and maintenance and exploitation activities are withdrawn from that point on.
2. The revenues produced during a sport event are independent on the type of stadium.
3. The total initial costs of the stadium, covering design, manufacturing and construction costs, are determined with the indicator of €4.000,- /seat. This indicator is applicable to high quality new stadiums in 2012 (ArenaAdvisory, 2013).
4. The total initial material costs of the permanent and transportable stadium are identical.
5. A transportable stadium will be rented at least 8 times and should break even after 8 venues.
6. The bank demands a constant loan repayment of 3,33%. This implies that in 30 years, the stadium is owned by the operator.
7. Interest on the loan is 6% and is charged over the remaining debt of the stadium owner.
8. The exploitation costs for the operator are yearly 0,3% of the initial total costs.
9. The small maintenance costs are yearly 0,8% of the initial total costs of the stadium.

10. The large maintenance costs are 5% of the initial total costs and occur every 10 years.
11. The transportation, assembly, disassembly cost are considered to be 18% of the total initial costs of the stadium.
12. Unforeseen damage occurs at the transportable stadium after each dis- and reassembly. These unforeseen damages are considered to be 5% of the total initial costs.
13. Storage costs of the stadium are omitted. The stadium remains at an event location till it is transported to its next location.
14. The demolition costs of a permanent stadium are 4% of the total initial costs. The demolition costs of a transportable stadium are 2%.
15. Yearly international inflation is expected to be 3%.
16. The lifetime of the stadium is considered to be 30 years.
17. In the first two years only design, manufacturing and construction costs are made. No revenues are produced.

11.3.2 Validation conditions

1. Lease fee comparison with a permanent stadium which has no revenues after the event
Already numerous articles are written which state that the present yearly revenues of South Africa World Cup stadiums can hardly cover the yearly exploitation costs. [30] Similar articles are found for the Olympic Stadiums of Beijing and Athens. Therefore, the lease fee may be compared to the permanent stadium with little or none revenues after the onetime event. Furthermore, to limit the total costs of the unused stadium. The owner will abandon it and withdraw exploitation and maintenance costs three years after the event.

2. Revenues independent on type of structure (permanent versus transportable)
The revenues of a stadium, listed earlier in this chapter, are independent of the type of structure as long as the capacity is identical. Therefore, this assumption is valid (ArenaAdvisory, 2013).[31]

3. Total initial costs
In this research the costs of the loadbearing structure is determined. However, the costs of the loadbearing structure makes up a small portion of the entire stadium costs. Davis Landon[32] states that 32% of the total initial costs can be awarded to the loadbearing structure whereas a KPMG stadium feasibility study[33] applies 18%. Therefore, it is hazardous to estimate the costs of the entire stadium on the basis of the costs of the loadbearing structure. Therefore, usage is made of a cost model developed by Davis Langdon. Davis Langdon applies a cost indicator per seat for a high quality football stadium of €4.000,- / seat (Davis Langdon, 2004) Thus, the total initial costs, for a stadium for 50.000 spectators, are €200 million. Other sources confirm the range of cost per seat.

4. No initial costs difference between transportable and permanent stadium
Due to the transportable demand, the initial costs of the stadium are increased. Both the horizontal aluminum grandstand elements and the steel vertical grandstand frame are more expensive compared to the commonly applied (permanent) concrete structures.[34] However, because the stadium can be transported, the manufacturing location of the stadium can be chosen freely.

[30] www.telegraph.co.uk/news/worldnews/southafrica/South-Africas-white-elephant-stadium
[31] Amsterdam Arena Advisory assists organizers of large sporting events as well as stadium owners in performing business cases and optimizing cash flows. Both through cost reduction as well as revenue increasing measures.
[32] Davis Langdon is a leading global construction consultancy, providing managed solutions for clients investing in infrastructure, property and construction. Cost estimation dates 2004.
[33] KPMG – Behoefte- en haalbaarheidsanalyse multifunctionele voetbalstadions Vlaanderen, 2007
[34] The other elements of a transportable stadium are considered to be pricewise identical to a permanent stadium

Therefore, a country with low labor costs and low raw material costs is chosen. Hence, it is assumed that the initial costs for the building elements do not differ between a permanent and transportable stadium.

5. Transportable stadium will be rented at least 8 times

The amount of times the stadium will be used depends on the amount of tournaments for which it is suitable and the duration required to assemble and disassemble the structure.
Concerning the amount of venues: The transportable stadium can adapt to different playing fields making it suitable as an Olympic stadium, an (American) football stadium, a hockey stadium and a tennis stadium. Nowadays, more and more large scale sport events are organized in locations where there exists little local demand for a permanent large scale stadium. Thus, the assumption that the transportable stadium will be leased at least 8 times is valid. From reference studies the erection and disassembly time may be assumed to take up 6 to 8 months.[35] Therefore, a stadium can be rented every 2 years. So, with an estimated life time of 30 years and a potential event every 2 years the assumption of 8 venues is a realistic estimation.

6, 7, 8, 9 and 10. Bank interest rate, loan repayment duration, design costs, exploitation and maintenance costs

The conditions concerning the loan rate, duration as well as structure related costs are determined with assistance of Amsterdam Arena Advisory, 2013. These conditions were than validated by Rob Stark, (financial) board member of IMd.

11. Assembly, disassembly and transportation costs

The costs involved with the disassembly, transport and assembly of the stadium have been based on the following three empirical values.

- Hollandia performed a project (2011) concerning a large, pitch covering, stadium roof. The material costs contained 71%, assembly costs where 24%, and the transportation costs where 5% of the initial costs.
- Anne den Hollander (2010) performed her thesis on a transportable stadium as well. She was assisted by 4Building b.v. to determine the stadium costs. In her research the material costs contained 70%, assembly costs 25%, and the transportation costs where 5% of the initial costs.
- The thesis of Myrte Loosjes (2011) states that the material costs contained 93%, assembly costs 5%, and the transportation costs where 2% of the initial costs.

Because the entire stadium is optimized regarding transportation and assembly demands, the costs indicators of Hollandia and Den Hollander are considered to be too high concerning the assembly and transportation costs. However, Loosjes states a slightly too ideal picture. Therefore, the assumption is made that the total transportation, assembly and disassembly costs of the stadium are 18% of the total initial costs.

12. Dis- and re-assembly damage

Each time the structure is disassembled, transported and re-assembled it is vulnerable to unforeseen damage. Because there are little to no references for transportable stadiums, the cost indicator is slightly arbitrary chosen at 5%. However, special attention is paid to this phenomenon in the sensitivity study.

[35] Nussli constructed semi high quality soccer stadium, Empire Field Vancouver, with a capacity of 27.500 in 3 months' time. www.nussli.com

13. Storage costs are omitted
It is assumed that in the lease fee the stadium will remain at a location until the new location is suitable for the erection of the stadium.

14.Demolition costs
Demolition costs are highly depended on the structure. When a structure is demolished all building elements ought to be separated. This is not a troublesome procedure for stadiums because they are constructed with few different material types which are almost never entwined. However, if components of the demolished structure can be reused they still have value. Therefore, the steel structural components can be sold while a concrete structure will solely cost money. Thus, the demolition costs highly differ per structure. Reference studies indicate that demolition costs of a permanent concrete stadium structure with a capacity of roughly 50.000 seats are approximately 4% of the initial stadium costs.[36] Because the transportable structure can resell much of it structural components the demolition costs for a transportable stadium are approximated to be half, thus 2% of the total initial costs.

15. Inflation
The international inflation is determined with assistance of the Dutch Central Bureau of Statistics and the World Economic Outlook of the International Monetary Fund and is assumed to be 3%.[37]

16. Stadium lifetime
The stadium lifetime is assumed to be 30 years. Empirical data indicate a general trend that after 30 years the demands for a stadium have changed too much to continue using the stadium. Either severe stadium face lifts take place or the entire structure is demolished. Nonetheless, the building is designed adhering to Euro Codes demands of a lifetime of 50 years. So in practice, the stadium will have a longer lifetime than assumed in the business case. Hence, the outcome of the business case is a conservative approach. This increases the value of the results.

17. First two years only costs
The first two years is used to design, manufacture and erect the stadium. Hence, no revenues are produced during this period. However, the bank's loan and its interest is already present.

[36] http://www.scribd.com/doc/89821440/Stadiums-39p-c
[37] http://www.imf.org/external/pubs/ft/weo/2012/02/pdf/text.pdf #13

11.3.3 Permanent stadium built for onetime event with stable demand afterwards

The conditions above are applied to a permanent stadium with 50.000 seats, with total initial costs of €200 million, and the cash flow is derived.[38] A high income from the onetime event and stable income afterwards is assumed. Hence, in this depicted case no demand for a transportable structure arises due to the assumed stable revenue sources. This cash flow diagram will not be used in the business case. Its sole purpose is to provide the reader insight concerning the quality and quantity of cost and revenue sources.

Reader guide graph

The inflation causes the constant growth of stable costs and revenue sources. All the costs and revenues are depicted on the left axis. The cumsum, which is a summation of all cost and revenues is depicted along the right axis and is connected with a line. The design, manufacturing and construction costs are omitted and incorporated in the bank's loan.

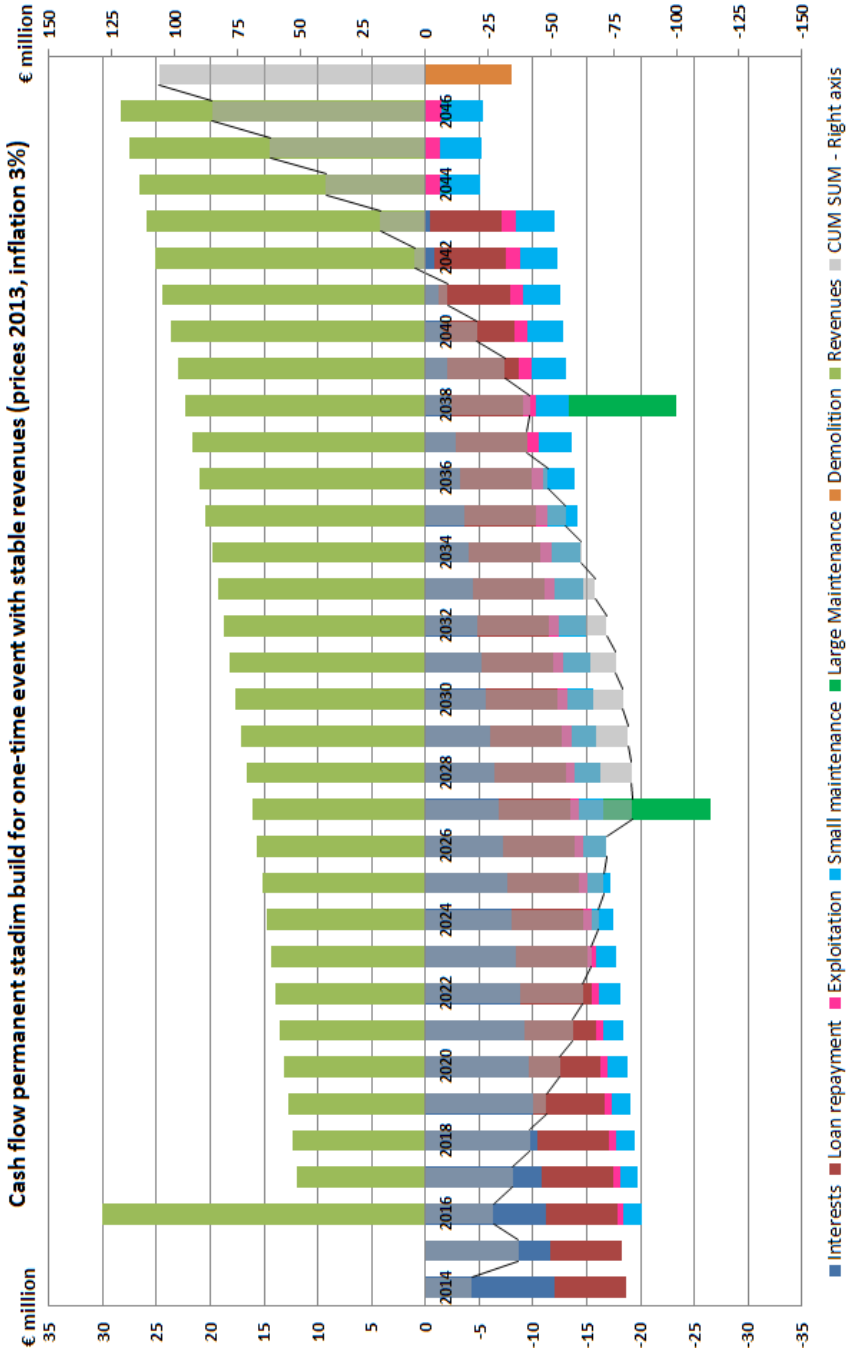


Figure 11-2 Cash flow permanent stadium with healthy demand after onetime event

[38] The excel input which is used for the cash flow diagrams can be found in Appendix A15.

11.3.4 Permanent stadium build for a onetime event with no demand afterwards

A transportable stadium becomes attractive if the organization of a high profile event has determined that the local demand for the stadium will diminish after the onetime event. Hence, the revenue sources will either decrease severely or be none-existent after the event. Figure 11-3 depicts the influence of this phenomenon on the revenue and cost breakdown of a permanent stadium built for a onetime event with a capacity of 50.000 and €200 million initial costs.

The assumption is made that the maintenance and fixed costs are repelled 3 years after the event. This is assumed because after that time the organization realizes that there is no demand for the stadium and that keeping these costs will only increase the total costs. In this case, the total costs of the stadium are €401 million. The total costs of the interest and loan repayment contribute to €386 of the total €401 million.

Reader guide graph

All the costs and revenues are depicted on the left axis. The cumsum, which is a summation of all cost and revenues is depicted along the right axis and is connected with a line. The design, manufacturing and construction costs are omitted and incorporated in the bank's loan.

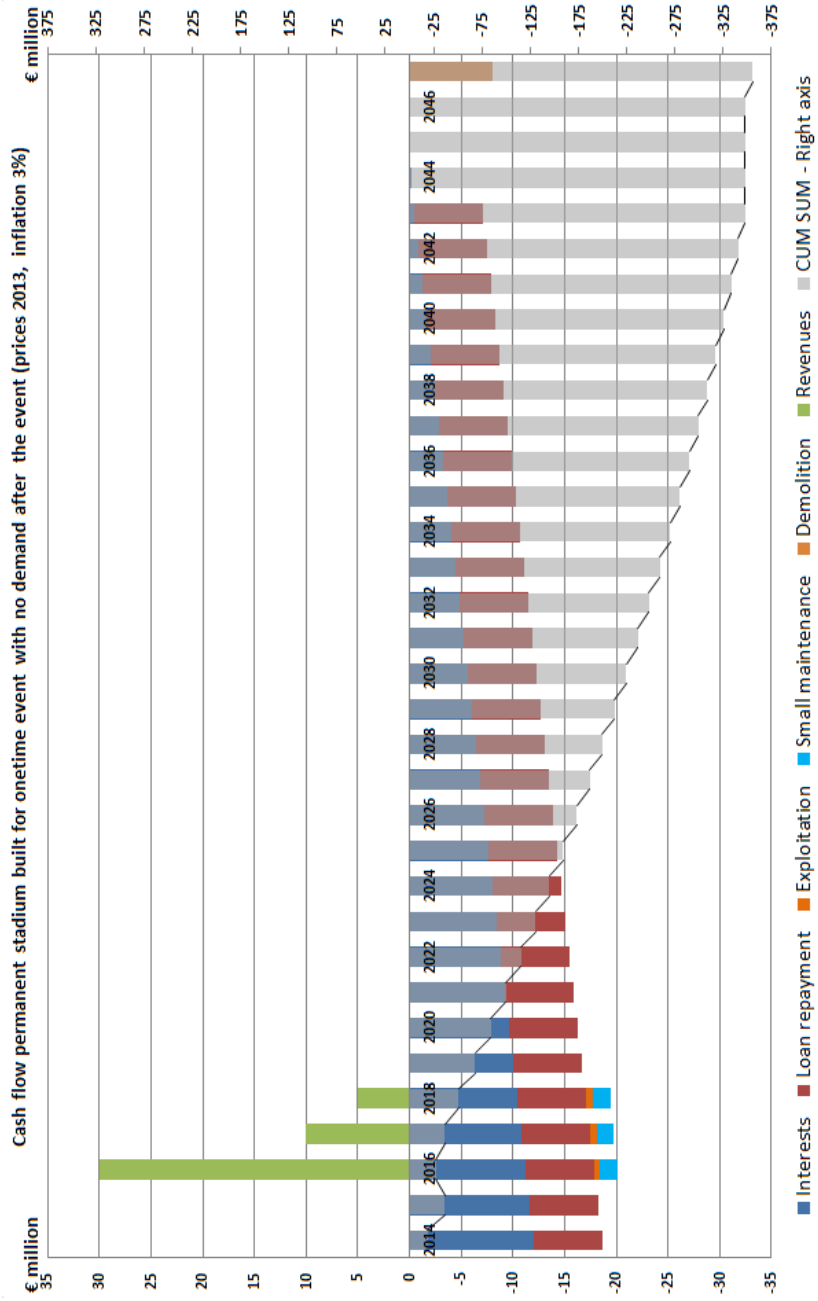


Figure 11-3 Cash flow permanent stadium built for onetime event with no subsequent demand

11.3.5 Transportable stadium build for onetime event

The owner of a transportable stadium has different costs and revenue sources. The revenue source is the lease fee. Furthermore, transportation + (dis)assembly costs are introduced to the costs applicable to a permanent stadium. In order to make a financially feasible transportable stadium the lease fee multiplied by the number of expected events should be higher than the total costs. Figure 11-4 is a cash flow diagram for the owner of a transportbla stadium. The depicted revenues are the costs of the organizing committee leasing the transportable stadium.

Reader guide graph

The inflation causes the constant growth of stable costs and revenue sources. All the costs and revenues are depicted on the left axis. The cumsum, which is a summation of all cost and revenues is depicted along the right axis and is connected with a line. The design, manufacturing and construction costs are omitted and incorporated in the bank's loan.

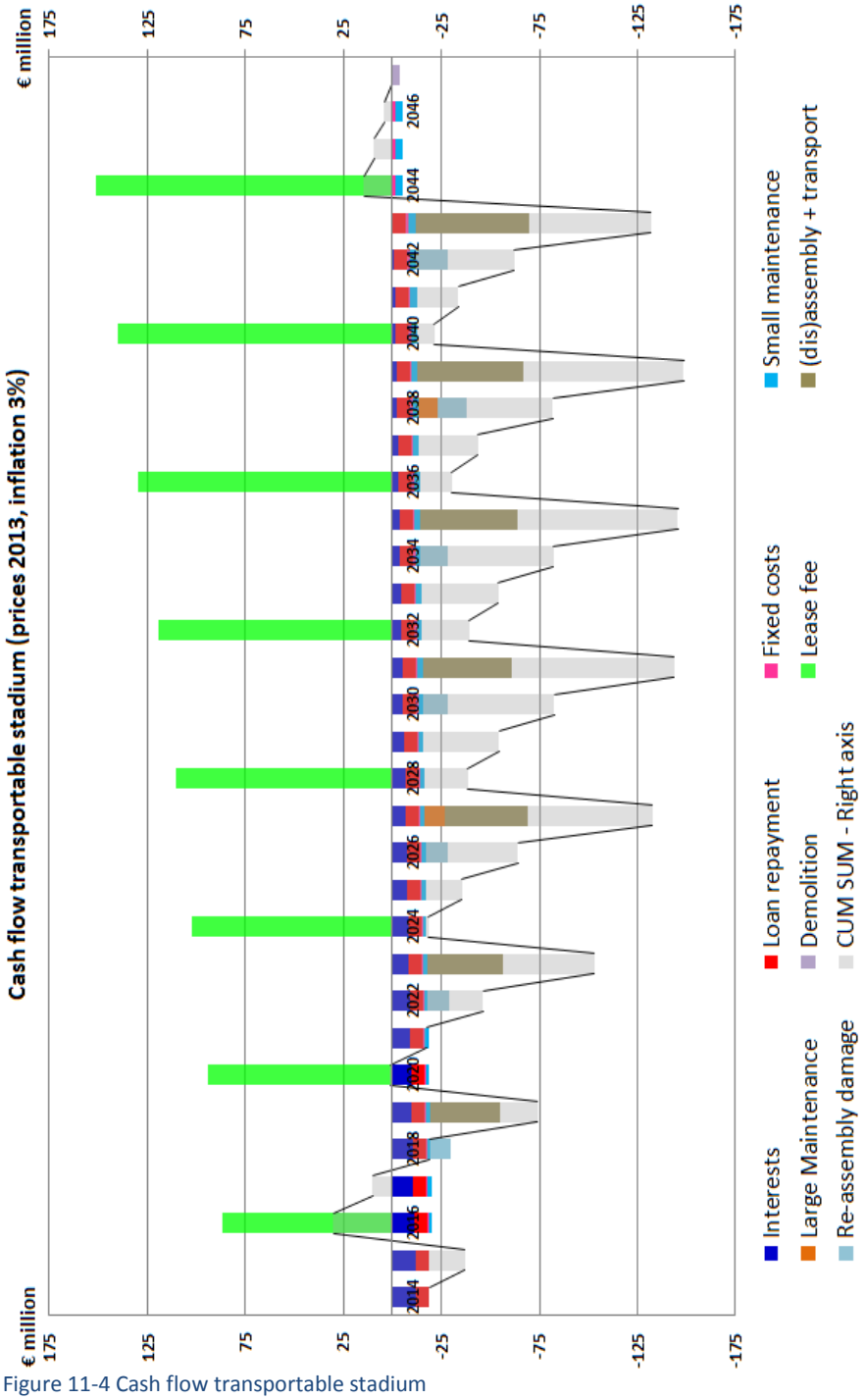


Figure 11-4 Cash flow transportable stadium

11.4 Results

The assumption is made that the operator of the transportable stadium wants to break even after 8 events. Hence, this cumsum costs in the lifetime of the stadium should be paid for over 8 events. With inflation incorporated, the first required lease fee is €87 million. If the organization of a onetime event abandons the stadium 3 years after the event he still has to pay a total amount of €401 million. Thus, with the lease fee of €87 million he only requires to pay 22% of the costs of a permanent stadium while having identical revenues compared to a permanent stadium assuming that the demand for the stadium is little or none after the event.
In this study the lease fee is expressed as a percentage of the total costs of permanent stadium. For the total costs of a permanent stadium it is assumed that the organization requires a bank loan to cover the initial costs. A large portion of the total costs consists of the interest on the bank's loan. However, this bank loan is not incorporated in the lease fee. Although the lease fee is a substantial smaller amount, it is likely that the organization should also close a loan to cover the lease fee. This phenomenon is included in the sensitivity study.

Market research should be conducted to validate whether an organization of a sporting event which is aware that it will end up with a unused stadium is willing to pay 22% of the costs of a permanent stadium to rent a temporary transportable stadium. Furthermore, when the transportable stadium is removed, offices or other functions can be located at the location. With the infrastructure already present this will highly increase the value of the area. This is far more attractive compared to the devaluation of an area containing an abandoned stadium.

11.5 Sensitivity study

A sensitivity study is performed to identify how governing conditions influence the required lease fee and the costs of a permanent stadium. The governing conditions are altered for both the permanent and transportable stadium and the required lease fee is expressed as a percentage of the total costs of a permanent stadium. The alteration of the governing conditions leads to the following insights.

- The total initial costs of the stadium are of no influence on the percentage of the required lease fee on the total costs of a permanent stadium (costs/seat of €3.000,- and €5.000,- have been applied). The total initial costs do influence the attractiveness of the investment but this is applicable to both stadium types.
- The current transportation costs are 18% of the total initial costs. If these are 10%, the required minimal lease fee is €74 million. This lease fee is 18% of the total costs for a permanent stadium. If the transportation costs are 25%, the minimal lease fee is €99 million. This lease fee is 25% of the total costs for a permanent stadium.
- When the number of events for the transportable stadium is reduced to 6 events, the required minimal lease fee is €103 million. This lease fee is 26% of the total costs for a permanent stadium. When the number of events is increased to 10 events, the required minimal lease fee is €79 million. This is 20% of the total costs for a permanent stadium.
- If the interest rate is 8%, the total costs for a permanent stadium become €463 million. The required minimal lease fee is €93 million. This is 21% of the total costs for a permanent stadium. If the interest rate is 4%, the total costs for a permanent stadium is €339 million . The required minimal lease fee is €81 million. This is 24% of the total costs for a permanent stadium. Hence, higher interest rates improves the attractiveness of a transportable stadium.
-

- If the transportable stadium is 10% more expensive compared to a permanent stadium, the required minimal lease fee is €89 million. This is 22% of the total costs of a permanent stadium. If the transportable stadium is 20% more expensive compared to a permanent stadium, the required minimal lease fee is €98 million. This is 24% of the total costs of a permanent stadium.
- If the unforeseen damage after each transportation is 15% instead of 5%, the required minimal lease fee is €98 million. This is 24% of the total costs of a permanent stadium. If the unforeseen damage is 25%, the required minimal lease fee is €115 million. This is 29% of the total costs of a permanent stadium.
- If a loan is closed to pay the lease fee of €87 million and a similar amount is used to pay back the loan, the lease fee will be repaid in 13 years with total costs of €211 million being 50% of the total costs of a permanent stadium.
- If a loan is closed to pay the lease fee of €87 million and the bank loan will be repaid in 8 years, the total costs are €110 million being 25% of the total costs of a permanent stadium.

If a 'horror' scenario occurs in which after each event the unforeseen damage is 25%, the transportation costs are 25% and the total initial costs are 20% higher compared to a permanent stadium. In this case, the required lease fee is €151 million. This is still a mere 38% of the costs of a permanent stadium.

A lot of indicators influence both the costs of the permanent- and the transportable stadium. Hence, the minimal required lease fee range is fairly close, ranging between 18% and 29% of the costs of the permanent stadium. Even if the 'horror' scenario occurs the lease fee is 38% of the costs of a permanent stadium. Thus, the outcome of the sensitivity study demonstrates that the business case is not volatile regarding the percentage of the lease fee compared to the costs of a permanent stadium. This increases the reliability of the business case outcome.

11.6 Revenue optimization

Several opportunities exist to optimize the revenues of the transportable stadium. A few examples are discussed below.

- Letter of recommendations by FIFA, ATP, CGF and IOC stating that the stadium suits the standards desired by them.
- In the last decades, the sustainability performance of an organizing entity is emphasized to win the bid for a large sport event (ArenaAdvisory, 2013). A transportable stadium improves the sustainability performance. This should be emphasized when marketing the stadium.
- Market the value of a prosperous area development when the transportable stadium is removed and the infrastructural facilities remain. These conditions are ideal to developed the area as a business or mixed use area. This will enhance the value of the area compared to a sad sight of an abandoned stadium.
- Make brochures of each different stadium configuration; Olympic ring, soccer, tennis and hockey stadium in order to approach potential customers with a matching offer.
- The containers used to transport the stadium can house several functions when they are empty. Examples are small cinemas, offices and even apartments. Furthermore, the possibility of renting containers during the transportation period should be investigated.


Figure 11-5 Different container uses. Source Left: www.cgarchitect.com Right: www.kriterionrotterdam.nl/

11.7 Conclusion financial feasibility study

Literature demonstrates that not all stadiums necessary to host a large sport event have sufficient (local) demand to make use of each of the stadiums throughout their lifetime. Therefore, building a permanent stadium for a onetime event appears inefficient. Since the revenues of a sport event do not differ per stadium type, a comparison is made between the costs of a permanent stadium and the required lease fee for a financially feasible transportable stadium.
The required lease fee is €87 million when assumed that the transportable stadium will break even after 8 venues, has (dis)assembly costs of 18% of the total initial costs and there is 5% collateral damage after each venue. If an organization of a onetime event abandons the stadium 3 years after the event, it still has to pay a total amount of €401 million. Thus, with the lease fee of €87 million, the organizer only has to pay 22% of the costs of a permanent stadium. Even if a 'horror' scenario occurs in which unforeseen damage is 25% of the total initial costs, the transportation costs are 25% of the total initial costs and the total initial costs itself is 20% higher compared to a permanent stadium, the required lease fee is still a mere 38% of the costs of a permanent stadium. In above situations, it is assumed that the organization has sufficient liquidity to directly finance the lease fee. If a loan should be closed to pay the lease fee of €87 million and the loan will be repaid in 8 years, the total costs are €110 million. This is 25% of the total costs of a permanent stadium and does not disrupt the positive outcome of the business case.

To conclude, the initial costs of a permanent stadium, €200 million, are higher than the initial costs (onetime lease fee) of a transportable stadium, €87 million. The interest applicable to a loan implies that small loans are less expensive from a rent point of view than large loans. The business case demonstrates that the interests plays a dominant role in the total financial feasibility of a transportable stadium. Finance structures should be further investigated to determine if the initial costs solely comes from a bank or from other entities. Market research should be performed to validate if organizers of large sport events are willing to lease a transportable stadium for 22 % of the price of building a permanent stadium which has no use after the onetime event. When the results of the market research are positive, the transportable stadium is financial feasible.

12 Conclusion

This chapter answers the main- and sub research questions posited in Chapter 1.

Main research question

What is the optimal structural configuration of roof, grandstand and foundation of an A-venue demountable and transportable stadium with a focus on minimizing recurring costs?

Multiple aspects play an important role in the quest to design the optimal structural configuration of roof, grandstand and foundation of an A-venue demountable and transportable stadium with a focus on minimizing recurring costs. These aspects are discussed below:

- Transportable and demountable demands
- Design order
- Architectural shape
- Structural design of [39]
    - Grandstand
    - Roof skin
    - Roof
    - Grandstand loadbearing structure
    - Foundation

Transportable and demountable demands

In the design of a transportable stadium it is vital that the efforts required for assembly, disassembly, transport and re-assembly are minimized. Seven design criteria are formulated which the design should adhere to. On the next page, the performance on the design philosophy of the structural components is discussed.

- Load spread. An even load spread will spread the occurring loads over multiple supports. This results in relative low and balanced support reactions. Therefore, slender piles can be used and even the possibility of Stelcon plates arises.
- Stability during erection. When direct in- and out of plane stability is created, temporary structures are not necessary during (de-)construction. Hence, recurring costs are reduced.
- Modular design. A modular structure has multiple advantages. Firstly, because the structure consists of identical modules, the (de-)construction process is efficient due to repetition. Secondly, the segments do not require a specific location which improves the building organization process.
- Adaptable design. When a stadium can respond to different functional demands, the stadium can be used for multiple purposes. Hence, potential revenue sources increase.
- Amount of material. The amount of material is influenced by the load transferring mechanism (e.g. normal forces versus bending). In order to reduce the amount of material load transfer via normal forces is recommended.
- Optimize transportation means: The recurring costs are influenced by the transportation costs. Hence, the structure should be transported as efficiently as possible.
- Minimize assembly and disassembly procedures. In order to minimize the recurring costs the assembly and disassembly procedures should be minimized.

[39] In this research the roof and grandstand have both been divided in two separate components. The grandstand consist of the horizontal component, labeled grandstand, and a vertical component, labeled loadbearing structure. The roof consists of the roof loadbearing frame and the horizontal roof skin.

Design order
In order to produce an intelligent design the horizontal elements are designed first. When these are defined, and thus the occurring loads, the vertical loadbearing structural components can be designed. To improve the load spread the roof is connected to the grandstand. Therefore, the horizontal span of roof skin and grandstand are identical. The grandstand plays a dominant role in the total amount of material required for the stadium. Therefore, the optimal span is designed for the grandstand first. Subsequently, the roof skin should adhere to this span. Finally, the roof and grandstand loadbearing frame is designed together with the foundation.

Architectural shape
In order to create an intimate atmosphere, a bowl-shaped stadium configuration is desired. However, if this bowl shape is designed as an ellipse, the grandstand components will not be modular. Therefore, the short and long sides of the grandstand are designed out of segments of a circle. Hence, the entire stadium, except for the corners, is modular and all roof, grandstand and loadbearing frame components are identical. The radius of the circle is determined in accordance with the desired span to make sure that a whole number of spans fit without the need for an non-modular 'half span' solution towards the corners. Furthermore, in order to provide perfect sightlines the riser height should ascent parabolic. However, this results in a non-modular shape. Therefore, three riser heights are used throughout the entire stadium to approximate the parabola. In this way, excellent sightlines are created while keeping a modular structure. Finally, in order to create the desired capacity of 50.000, the stadium requires 53 rows which ought to be divided over two tiers with a maximum of 30 rows per tier[40]. The first tier has 23 rows and the second tier has 30 rows. In this way, the second tier, which acts as a stiff triangle transferring roof forces, has a larger width which lowers the support reaction forces.

With above aspects defined. The structural components can be designed in accordance with the design philosophy, design order and architectural shape of the transportable stadium.

Structural grandstand design
A three stepped simply supported aluminum profile spanning 10,8 meters is the optimal structural grandstand design. The profile makes use of the riser height to create the necessary stiffness to achieve this span. Moreover, to ensure good viewing conditions, while creating a modular design, only three unique riser heights are applied in the stadium of 360, 450 and 550 mm. Furthermore, with the floor and step integrated in one profile the amount of assembly procedures is minimized. The number of steps is optimized regarding transportation means and minimizes assembly efforts. Due to the light weight of the structure only 38 containers are necessary to transport the grandstand. Hence, the grandstand design is in line with the design philosophy.

Structural roof skin design
An aluminum roof plate spanning 5,4 meters in the transverse direction between IPE 400 girders is considered to be the optimal structural roof skin variant. With its light weight and modular design, it is mendable for construction workers and its click-system minimizes assembly efforts. Furthermore, if damage occurs to the roof skin during (dis)assembly, the damaged roof plates can be substituted cheaply and easily.

Structural roof design
The cantilever roof fixed to grandstand is considered to be the optimal roof design. An even load spread is realized through its connection to the grandstand. Furthermore, no temporary scaffolding structures are required during assembly due to direct in and out of plane stability after the erection of the two frames with bracings in between. Moreover, it is a modular and adaptable structure.

[40] The maximum number of rows is prescribed by means of escape in case of calamities.

Structural loadbearing frame design

The structural loadbearing frame is created out of steel. Steel has good loadbearing characteristics and can easily be constructed with demountable connections. The field beams in the roof truss are configured to be loaded in tension under the governing (upward) load combination. Furthermore, a stiff structure is realized through bracings which assist in load spread and are designed to transfer both tension and compression forces. Therefore, the loads are transferred via normal forces in the grandstand loadbearing frame instead of bending thus minimizing the amount of material and improving the load spread. Furthermore, throughout the entire stadium an identical loadbearing frame is applied. Hence, a modular and adaptable stadium is realized.

Foundation

A concrete pile foundation is recommended as the optimal foundation variant. A steel foundation is too expensive and a timber foundation is not capable of transferring the occurring forces into the soil. The stiffness of each foundation support is in line with the anticipated maximum load the support experiences. This improves the load spread. Furthermore, techniques are available to remove the concrete foundation afterwards with minimal efforts.

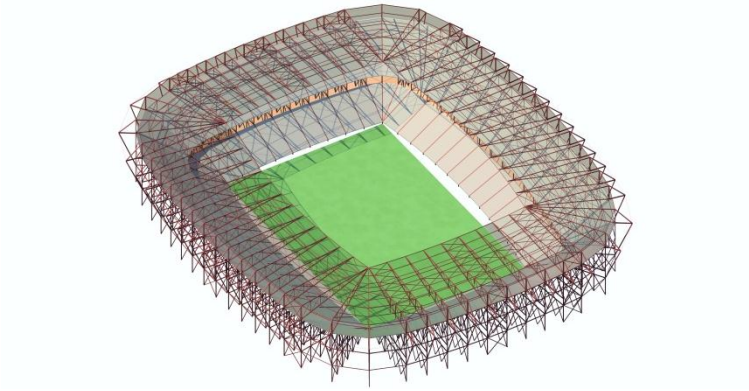


Figure 12-1 Final design

Sub questions

1. *What are the conditions for a financially feasible transportable stadium?*

Literature demonstrates the following trend. Not all stadiums necessary to host a large sport event have sufficient (local) demand to make use of each of the stadiums throughout their lifetime (Reuters, 2012).[41] Furthermore, the amount of revenues which a stadium generates during a large event does not depend of the stadium type. Respectively, a transportable or permanent stadium.

A business case is performed which estimates the costs throughout the lifetime of both a permanent and transportable stadium. After defining the costs of both stadium types and a realistic estimation of the number of times a transportable stadium will be leased, the required lease fee for a financially attractive transportable stadium is determined. When assumed that the transportable stadium will break even after 8 venues, has (dis)assembly costs of 18% of the total initial costs and 5% collateral damage after each venue the required lease fee is €87 million. If an organization of a onetime event abandons the stadium 3 years after the event, it still has to pay a total amount of €401 million. Thus, with the lease fee of €87 million, the organizer only has to pay 22% of the costs of a permanent stadium while having identical revenues compared to a permanent stadium. The considered conditions are discussed combined with a sensitivity analysis in Chapter 11. It is concluded that a transportable stadium is financially feasible.

2. *Which typologies can be listed in current stadium roof, grandstand and foundation design?*
3. *Which typologies are beneficial from a demountable and transportable point of view?*

As discussed previously, both the grandstand and roof are divided in two separate components.

[41] Multiple stadiums build for the soccer World Cup of 2010 in South Africa have little or none revenue sources in 2012. (www.telegraph.co.uk/news/South-Africas-white-elephant-stadium)

Grandstand
Three different loadbearing systems are encountered in practice and discussed in Chapter 6. In loadbearing system 1 the grandstand floor and riser are integrated in one element. Therefore, the stiffness available in the riser height is used to create the span. In loadbearing system 2 and 3 beams are used to span between the loadbearing frames and separate floors elements span between the beams. Loadbearing system 2 and 3 are undesired for the following two reasons. Firstly, by having a separate riser and floor element, the assembly procedure is less ideal compared to the integrated system of loadbearing system 1. Furthermore, because the floor spans between the beams no usage can be made of the riser height. This results in undesired large floor dimensions.

Roof skin
Three different roof skins are encountered in practice and discussed in Chapter 7. Respectively, roof plates, single layer membrane cover and multi-layer membrane cushion roof skins. A multi-layer membrane cushion is expensive and requires much secondary material increasing the transportable volume making is less attractive. The single layer membrane can be configured in different configurations and the single curved configuration is considered to be the most attractive. The single curved configuration has an effort intensive post tensioning assembly procedure. Furthermore, if damage occurs at the membrane the entire cloth has to be replaced which is rather expensive. Therefore, the aluminum roof plate is most advantageous. With its light weight it is mendable for construction workers and its click-system minimizes assembly efforts. Furthermore, if damage occurs to the roof skin during (dis)assembly, the damaged roof plates can be substituted cheaply and easily.

Roof loadbearing structure
Roof structures are encountered in numerous shapes and discussed in Chapter 8. The variety in stadium shapes exists (partly) because each stadium has a different capacity, function and different demands concerning the load transfer. Hence, different optimal roof structure can be preferred. Subsequently, because the roof plays a dominant role in the appearance of a stadium, the owner's and architect's preference also influences the design. The cantilever roof fixed to grandstand is considered to be the optimal roof design. An even load spread is realized through its connection to the grandstand. Furthermore, no temporary scaffolding structures are required during assembly. Moreover, it is a modular and adaptable structure. Successively, the cable stayed roof fixed to grandstand variant is a very attractive variant. This roof structure scores also very well on the design criteria and has an improved load transferring mechanism due to the cable which can be schemed as a role support. However, due to the governing upward directed load combination the cable should be a compression element making this variant undesirable.

Loadbearing frame
Both concrete and steel loadbearing frames have been applied in practice. Connections made in concrete are very effort intensive to disassemble and re-assemble. Furthermore, the large weight of concrete components combined with weight restrictions of the transportation means results in an undesired high number of containers required to transport the loadbearing frame. Thus, a steel loadbearing frame, with low efforts demountable connections, is advantageous.

Foundation
The most commonly applied foundation type is a concrete foundation. However, also steel and timber foundations could be applied. A concrete pile foundation is recommended as the optimal foundation variant. A steel foundation is too expensive and a timber foundation is not capable of transferring the occurring forces into the soil. Techniques are available to remove the concrete foundation afterwards with minimal efforts making it similar desirable and cheaper compared to a steel variant. The stiffness of each foundation support is in line with the anticipated maximum load the support experiences. The horizontal force transfer of the foundation is not yet considered.

13 Recommendations

This graduation research aims to design a financially feasible loadbearing structure of a transportable stadium.
Unfortunately, in a research with a defined scope and duration, aspects arise which require further investigation. By clearly defining these recommendations, the research retains its value and can motivate further research. The recommendations are divided in aspects which concern either the structural configurations and financial feasibility and aspects which are outside the scope of this research.

The recommendations 1, 2, 3, 8 and 9 have the highest priority and are most urgent to provide a holistic view on both the financial feasibility and structural design of this transportable stadium.

Recommendations regarding structural and financial feasibility

1. The foundation is investigated on a conceptual level. The required spring stiffnesses and foundation material are determined and sketches are presented. However, the horizontal reaction force is not yet considered and further research is required to bring the foundation to a more tangible design.
2. The assembly procedure and building organization process on the building site have not been thoroughly investigated. Nonetheless, these two aspects highly influence the recurring costs and thus the financial feasibility of the transportable stadium. Therefore, further research is strongly recommended to provide a holistic view on the assembly and building organization process.
3. The wind loads acting on the stadium are difficult to estimate for a complex shape such as a stadium. In practice, wind tunnel tests are performed to approximate the occurring wind loads. With the wind load defined, the loadbearing structure can be designed. Due to the predefined time for this research wind tunnel test or computational fluid dynamic software programs have not been used to approximate the occurring wind loads. Hence, a conservative wind load is considered. Wind tunnel test are recommended to estimate the wind loads with more certainty and hence creating a less conservative design condition.
4. In this research, fire safety engineering is briefly discussed. The effects of the required measures on the loadbearing structure should be further investigated in additional research. Furthermore, the fire resistance duration should be aligned with the evacuation time. This will substantially reduce the requirements currently imposed by the Euro Code.
5. The loadbearing frame is identical throughout the entire stadium. However, the aluminum horizontal grandstand, girders and roof plates in the corner will have slightly different dimensions. Designing these components will result in a comprehensive structural design.
6. Several conditions are assumed in the business case. Although arguments are presented to validate these conditions, an expert committee is recommended to empower the presented validation. Furthermore, the business case is performed on a high level. A more detailed business case will provide more accurate insights. Nonetheless, the main outcome of this business case remains valid.
7. The method in which the stabilizing bracings provide out of plane stability between the displacement joints is discussed in Chapter 9.5. However, the bracings are not yet dimensioned. Nonetheless, the considered stabilizing scheme remains valid.

Recommendations regarding topics which are not considered in the scope

8. This research aims to design a completely transportable structure. However, a permanent small scale stadium which can easily temporary increase its capacity could be an attractive alternative for an organization of a sport event compared to a transportable stadium. Little knowledge is currently available concerning the design of a permanent small scale stadium with possibility to temporary increase the capacity. Often ad hoc design solutions are considered if a stadium's capacity is increased. Hence, further research is recommended regarding a stadium which is designed to have its capacity easily temporarily increased.

9. The cladding, façade and interior are non-structural components and are not considered in this research. Further research is recommended to design optimal transportable configurations of non-structural stadium components.
10. Currently, the multi-functional behavior expresses itself in the ability to host different sport events in the transportable stadium. However, with proper acoustics the stadium can also host music events which increases the potential revenue sources. Hence, the acoustic performance of the stadium should be Investigated.
11. The building industry is continuously innovating and improving the loadbearing characteristics of materials (e.g. carbon composite, ultra high strength concrete etc.) It takes time to update the building codes to incorporate these innovations. Therefore, this study is based on the characteristic of the materials without incorporating front running innovations. However, to provide a comprehensive design comparison, these innovations in the material characteristics should be further investigated.
12. Although the stadium will be transported via containers, little attention is paid to the usability of the container itself. Possibilities to allocate functions, both structural and commercial, to the containers during the time the stadium is in use should be further investigated. Furthermore, the possibility of renting, instead of owning, containers when transportation is required could also be an attractive alternative. Hence, additional research is required concerning the usability of the containers.

14 Reflection

With the research questions answered and the recommendations defined it is possible to reflect on the research. In this reflection the following three questions are discussed.

- Does the transportable stadium design adhere to the requirements posited in Chapter 5.6?
- Is the design framework, design philosophy, applicable to other transportable structures?
- What is the impact when the conditions, assumed in this research, change?

14.1 Performance design on list of requirements

In this chapter the performance of the stadium on the requirements posited in Chapter 5.6 are discussed. The numbers correspond to the requirements defined in Chapter 5.6.

Functionality

1. The final design has performed well on the seven design criteria;
    - I. An even load spread is realized via the radial frames and the connection between the roof structure and the grandstand.
    - II. Stability during erection is realized as soon as two frames with the wind bracings in between are erected. From that point on, the other frames can be erected without the need for large temporary scaffolding structures.
    - III. The stadium design is modular due to its identical grandstand and roof segments.
    - IV. Adaptability is realized via the frames. These can be added or removed to adapt to the desired capacity. However, to decrease the capacity of a single frame is not considered in this research.
    - V. The amount of material is reduced with load transfer via normal forces due to the applied bracings.
    - VI. The span of the horizontal grandstand and roof elements, and thus their dimensions, is designed to optimize the transportation means.
    - VII. The (dis)assembly procedures are minimized due to a modular structure which consists of hinged connections. Furthermore, the lightweight aluminum minimizes the required efforts for the (dis)assembly procedures.
2. The design can adapt to different pitch dimensions and is therefore multifunctional.
3. The stadium provides sufficient flexibility to allocate functional areas underneath the grandstand with a center to center distance of the frames of 10,8 m.
4. Fire compartments are not yet defined.
5. The desired starting point capacity of roughly 50.000 spectators is achieved.

Safety and comfort

6. The natural frequency of the individual stadium components as well as the total system is above 5 Hz. Hence, undesired vibrations imposed by the dynamic live load are prevented.
7. The stadium components adhere to the deflection requirements.
8. The evacuation routes are not yet considered. However, the open space within a frame is sufficient to provide appropriate escape possibilities.
9. The spectators have a good and unobstructed view on the playing field.
10. The spectators are sheltered from direct sunlight and rain.
11. The grandstand steepness is smaller than 35°.

Structural aspects

12. The stadium adheres to demands regarding stability, strength and stiffness defined in the Euro Code.
13. The stadium can cope with moderate earthquakes and severe wind conditions.

14. The structural fire safety of the structural components is not thoroughly investigated. Further research is required to fulfill the fire safety requirements.
15. Progressive collapse is prevented due to the simply supported horizontal grandstand and roof span. Furthermore, if a stabilizing wind bracing fails. The enclosed frames will travel through the tolerance of the slotted whole and the stabilizing wind bracings in the other displacement joints parts will provide stability. Hence, progressive collapse is prevented in the case of failure of a stabilizing wind bracing.

Financial

16. The transportable stadium is an attractive alternative for a permanent stadium if the owner is aware that the demand after the event is minimal. The required lease fee is roughly between 18% -29% of the total costs of a permanent stadium while the revenues are independent on the stadium type.

14.2 Applicability design philosophy in other fields

The design philosophy is defined to optimize the structural loadbearing structure of a transportable stadium. When this design philosophy is also applicable to other transportable structures the value of this research is increased. This chapter discusses the possibilities of applying the design philosophy on other transportable structures.

Structures such as dwelling and utility buildings require a lot of finishing. The efforts to assemble and transport all these individual components make these functions less ideal to design into a financially feasible transportable variant.
When finishing is not required the design philosophy retains its value. I believe that the design philosophy can be used to design functions such as transportable parking facilities and bridges. These structures require little or none finishing. Furthermore, both functions could be desired on a temporary basis creating the demand for a temporary, and hence transportable, structure.

Table 54 lists the applicability of the design criteria for different transportable structures. For parking each criterion of the design philosophy is applicable. For bridges the load spread location to location. Hence, a transportable bridge should have a load transfer type which can be implemented in different possible site variants. For dwellings and utility building the stability during erection and amount of material criteria are of less importance. The stabilizing elements required for an utility building or dwelling require less efforts compared to the stadium. Furthermore, in dwellings the dimensions of structural components are often defined by acoustics rather than structural demands. Hence, the impact of these aspects is considered to be smaller compared to the other five criteria.

Design criteria	Parking	Bridges	Dwellings	Utility buildings
Load spread	✓	✗	✓	✗
Stability during erection	✓	✓	✗	+/-
Modular structure	✓	✓	✓	✓
Adaptable structure	✓	✓	✓	✓
Amount of material	✓	✓	✗	+/-
Transportation means	✓	✓	✓	✓
Minimize (dis)assembly efforts	✓	✓	✓	✓

Table 54 Applicability design philosophy in other fields

To conclude, the design philosophy is applicable to other transportable structures than stadiums as long as the amount of finishing is limited. The design philosophy could be used to design transportable temporary parking facilities or bridges.

14.3 Conditions discussion

In order to perform a design study is it necessary to define conditions. These conditions steer the design process. If these conditions change, the outcome of the design study will most likely change as well. This discussion lists the different conditions and defines their impact on the design process. The conditions are divided into design conditions, financial conditions and other conditions. The goal of the discussion is to provide insight on the impact of the different conditions on the design process.

14.3.1 Design conditions

Generic structure

The stadium is designed to be located at a large geographical area. Therefore, the structure is designed to cope with all possible forces present over the entire geographical employable area. Hence, designing a structure to cope with forces imposed by multiple geographical areas will result in a structure which is over dimensioned considering the forces present onsite.

Actual time employed versus life time design

The Euro Code prescribes that a structure which will be disassembled and reassembled on a different location may not be considered as a temporary structure. This leads to a discrepancy between the actual employable life time of the structure and the life time considered by the Euro Code. When we assume that the stadium will be employed every other year for 6 months, this will lead to an actual life time of 150 months, 12 years. However, Euro Code prescribes that the structure has to be designed to cope with forces which occur once every 50 years. Thus, a very conservative approach is imposed.

Wind load conditions

The Euro Code is considered to determine the wind loads. However, a stadium has a rather complex shape. Therefore, it is unreliable to approximate the actual wind values adhering the Euro Code. Hence, literature recommends to perform wind tunnel tests to determine the actual wind loads (Biagini, 2007). These wind tunnel test could lower the occurring wind loads. When the wind load becomes less governing, the design of the roof and loadbearing structure could be altered.

Transport

In this research transportation via sea containers is assumed, as discussed in chapter 3.1. A sea container has both a volume and weight restriction. If the weight restriction is not applicable, the container can be loaded more compact with heavier elements leading to a reduction in the number of containers. This will decrease the importance of transportation costs in the financial comparison of different design variants. Furthermore, if the volume restriction is not applicable, larger elements can be transported leading to a reduction in assembly efforts.

Transportable stadium versus adaptable stadium

In this research a stadium is considered which is entirely disassembled after an event and transported to a different location.[42] Organizers of an event could also desire to keep a permanent stadium with a smaller capacity and desire a temporary capacity increase. This will change the design considerations and the desired outcome.

Climatic installations

In this research the climatic installations (HVAC), applied in the VIP area, are not considered. The demands for these installations differ from region to region and the range of desired demands is very broad. This makes it difficult to design one climatic system which can cope with these different demands. Furthermore, during the literature study little or none examples of climatic installations of a large scale which are designed to be disassembled and reused have been found.

[42] It could be that the foundation remains at the temporary stadium location if this is attractive from a costs point of view.

Material characteristics
Certain building materials have been around for centuries, such as concrete and steel, and other materials have recently been introduced, such as membrane systems. Nonetheless, constant innovation is taken place in the entire building industry leading to improved material loadbearing characteristics. A change of loadbearing characteristics could steer the design process.

Quality of assembly workforce
Some connection methods are more straightforward than others. When a poorly educated workforce is considered, only straightforward connections should be designed. However, if the quality of the workforce can be guaranteed more difficult connection methods could be considered. Of course, these difficult connection methods should only be considered if they add value to the design.

14.3.2 Financial conditions

Net present value ('disconteren')
In Chapter 6 and Chapter 7 design variants are compared. Some variants require a high initial investment but have modest transportation costs which will be made in the future. Other variants will have lower initial costs but require higher recurring costs. The net present value should be considered depending on the value of money over time, steered by inflation. In the variant comparison, the net present value is not yet considered. This could potentially provide incorrect results in the financial comparison decision method.
The business case does incorporate the change of value of money in time.

Costs indications ('kengetallen')
In the financial comparison decision method, indicators are assigned to different items ranging from building materials to transportation costs of a sea container. Cost indicators are based on supply and demand and are therefore dynamic. Nonetheless, approximated cost indicators can be applied to gain a general insight. A change to the cost indicators could change the outcome of the comparison decision method.

14.3.3 Additional conditions

Transportable stadium market
The employability of the stadium is influenced by the demand and supply of transportable stadiums. Up to this point there are no known suppliers of transportable stadiums of such scale. However, if different competitors enter the transportable stadium market, there are no guarantees which transportable stadium will be favored and potential revenues should be revised. Moreover, the demand for transportable stadiums should be extensively investigated before investments are made in the design and manufacture of a transportable stadium.

Investor interests
In this research it is assumed that the organization leasing a transportable stadium steers the decision process solely on costs and functional capabilities of the stadium. Aesthetic appearance or other value improving stadium characteristics have not been taken into account. It could be that the a leasing organization has different interests which are difficult to quantify in the decision method. This could alter the comparison outcome.

Learning curve assembly workforce
When the stadium is assembled and transported the workforce will most likely operate more efficiently over time. However, when assessing the total costs of the stadium over time this is not yet taken into account.

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16 List of figures

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