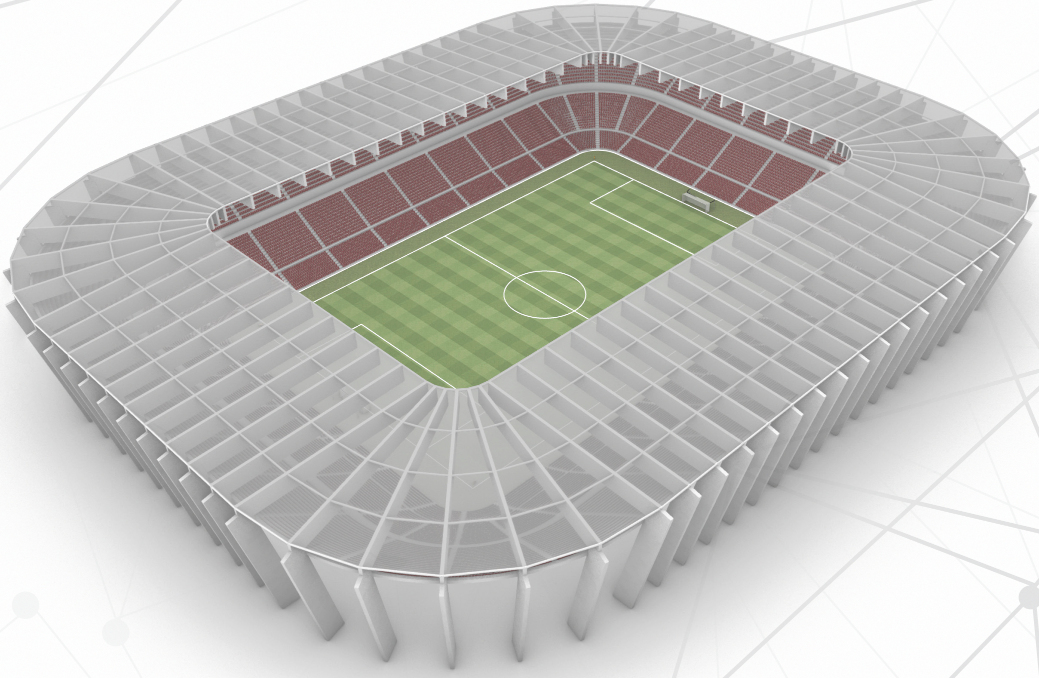
COMPUTATIONAL METHOD FOR FOOTBALL STADIUM RENOVATION

A computational method for the renovation of football stadiums to facilitate designers into making decisions



COMPUTATIONAL METHOD FOR FOOTBALL STADIUM RENOVATION

A computational method for the renovation of football stadiums to facilitate designers into making decisions

ALESSANDRO PASSONI | 4949838

MENTORS

Dr. MICHELA TURRIN | AE+T | Design Informatics
Ir. PETER EIGENRAAM | AE+T | Structural Design & Mechanics

DELEGATE BOARD OF EXAMINERS

Dr. HILDE T. REMOY | MBE | Real Estate Management

Delft University of Technology

Faculty of Architecture and the Built Environment
MSc Building Technology

ABSTRACT

A growing trend is present nowadays towards the renovation of football stadiums with the main objectives of enhancing the capacity of the venues and of improving the user experience of the spectators. The stadium design process requires to blend multiple components together, while evaluating different performances and complying with several requirements. In addition, the complexity of the process is increased in case of a renovation by considering the constraints and the components of the existing stadium. Hence, the decision-making process of the designer results to be difficult and it is likely to produce few inefficient designs. The introduction of computational methods can facilitate the decision-making process, allowing the designer to explore multiple solutions and to produce more efficient designs. This study explores how a computational method can be developed for stadium renovation to support the designer into making decisions in the early design phase, allowing them to explore multiple solutions that improve the initial performances of the stadium. A digital workflow was developed to generate different existing stadiums and to evaluate the performances related to the viewing quality and the roof structure. The study highlights how a designer is able to identify the portions to be kept based on the performances of the stadium and to develop a concept for the renovation, from which multiple design alternatives can be produced in the optimization process. Inefficient designs can be identified quickly and discarded, allowing to concentrate on more efficient concepts for the renovation, which will be further developed in the subsequent phases of the design process.

KEYWORDS

Computational Method | *Stadium Renovation* | *Viewing Quality* | *Structural Design* | *Multi-Objective Optimiation* | *Multi-Disciplinary Optimization* | *Design Exploration*

TABLE OF CONTENTS

ACKNOWLEDGEMENTS

This master thesis represents the end of a wonderful experience I had at TU Delft. I would like my friends and colleagues of Building Technology: you helped me so much in these amazing two years and I grew so much alongside you.

I want to thank my mentors: Dr. Michela Turrin and Ir. Peter Eigenraam which guided me in the realization of this master thesis. Thank you for pushing me in researching different aspects of my project and to explore different topics of the research. I would like to thank also Andrew Edge of ARUP for the advice he provided me during the research to better understand the topic.

I want to thank my parents and all my Italian friends, which supported and sopported me in this amazing adventure. Thank you Mauro, Emanuela and Silvia, my family, for pushing me in the hard moments and for all the support.

Lastly, I want to thank the Italian group in Delft: Luca, Gabriele, Saskia, Elena and Andrea. Thank you for being my second family in Delft. I have such great memories of these two years, and you are always part of one of them.

01 | INTRODUCTION

INTRODUCTION

Football is the most popular sport in the World and its popularity is still rising in various countries (Nielsen, 2018). Multiple football related events are held weekly around the Globe, attracting thousands of fans to the stadiums (Gough, 2019). However, along with the increment of its popularity, security and technical standards for these facilities are turning higher and many teams are forced to build new grounds or to renovate their current arenas in order to meet the requirements set by FIFA (2011), UEFA (2011; 2018) and the National Football Associations.

Stadium design is a process that necessitates the analysis of various aspects related to both the architectural and engineering world, together with several themes and high standards. Computational methods and parametric design are starting to be implemented in the design process of stadiums to generate design alternatives based on multiple measurable criteria, which are related to aspects such as structural design and viewing quality evaluation. Due to these features and the close interrelation among its parts, a computational method can be identified as the most suitable process to develop an efficient design of a building typology such as stadia, or to enhance the variation of an existing one (Patz et al., 2016).

1.1 Football Stadium Overview

As stated by John et al. (1981), a stadium can be considered as a pitch or a track for athletics or team competition in an arena surrounded by rising, stepped tiers for the accommodation of standing or seated spectators, with coverings that do not, however, cover the field to enclose the whole building. There are various typologies of stadiums, but all of them are dictated by the hosted activity and their capacity, intended as the number of spectators that they can accommodate.

In general, stadia are composed of a bowl, which comprises the playing field and the grandstand, and a hull, which includes the outer façade of the stadium and the roof. All these parts have specific purposes and requirements. Regarding the activity of football, UEFA (2011) describes these portions of the building and their specifications in depth.

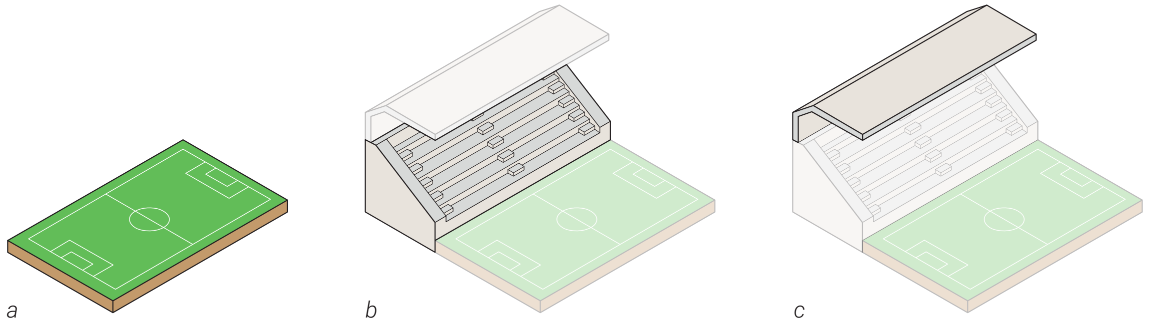


Figure 1. Principal Stadium Components: The playing area (a), the granstands (b) and the roof (c) (Source: Self-Made)

The playing field is the area of the building in which the hosted activity is performed, and it is surrounded by the first row of seating/standing (John et al., 1981). The main requirement is that the spectators have to be as near as possible, but sufficiently distant to secure the safety of the players and the officials.

The grandstand determines the quality of the experience of the supporters that visit the stadium, which is evaluated in terms of comfort, visibility, atmosphere and commitment to the activity. There are three criteria that must be met, which are safety, visibility and comfort. In detail, all seats must fulfill the requirements of the current safety regulations, all spectators should be offered an unobstructed and full sight of the playing field and the circulation through the seating have to be effortless and rapid.

The roof is the portion of the stadium that provides cover for the spectators from the weather conditions. As stated by Nixdorf (2009), the roof is one of the most crucial features of the stadium design since it determines the general impression of the stadia. This portion of the arena is not mandatory, but it affects greatly the comfort of the users and the total cost of the project (John et al., 2013). Therefore, it has to be properly designed based on the country, the purpose of the facility and its structure should respond properly to the layout of the building.

Overall, stadium design is a complex building typology which is composed of various elements strictly related to each other. The development process needs to fulfill multiple functional requirements and therefore it necessitates a detailed analysis of the various parameters that control the various parts of the stadium.

1.2 Why Renovation?

In the past decades, both football as a sport and the stadiums that host the matches changed significantly. As stated by John et al. (2013), on the one hand, the development of new technologies is revolutionizing both the sport and how it can be followed. On the other hand, the succession of unfortunate accidents that caused the death of hundreds of supporters drove the international and national football associations to increase the standards that stadiums need to match. Therefore, multiple stadia have been newly built or refurbished in the past years.

Firstly, the requirements were raised to ensure safety for both the spectators and the players (FIFA, 2011). These modifications were mostly related to the circulation, such as the position and the number of gangways and vomitories to exit the facility, and the transformation of the grandstand to an all-seater layout. Even though most of the regulations published are referred to newly built stadium, they also provide guidelines for refurbishment of existing stadia (Department for Culture Media and Sports, 2018).

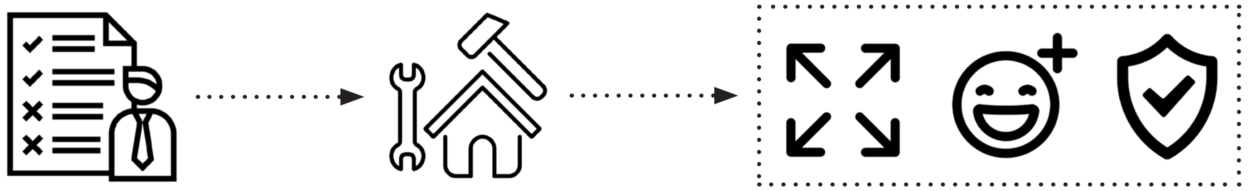


Figure 2. Scheme of the refurbishment process of a football stadium. (Source: Self-Made)

Lastly, the rate of development of new technologies broadened the choices to follow the sport, which resulted in the integration of media facilities inside the stadiums (Palvarini et al., 2013). Indeed, stadia are divided into four categories by UEFA (2018) and this arrangement is strictly related to the presence of a sufficient number of seats and areas devolved to the press. Moreover, technological progress generated an increment in the demands of the spectators for more comfortable spaces and amenities. Tom Jones of Populous (2019) explains how this last aspect enhanced tendency to renovate existing stadiums, instead of building new grounds. The refurbishment of a stadium can provide benefits to the revenues by expanding the capacity, by improving the experience of the supporters and by enhancing the security of both spectators and players (UEFA, 2011).

1.3 Possibilities of Computational Method

As stated by John et al. (2013), many aspects related to stadium design need to be analyzed and developed computationally. Indeed, these typologies of buildings necessitate a 3D representation through computational tools in order to interface successfully with the clients and the users. Overall, computational methods can be utilized to design and analyze various features:

A. **The sightline**, usually identified with the term "C-value", is the most relevant parameter to plan the design of the grandstands (Nixdorf, 2009). It represents the quality of viewing of the spectator. Indeed, this aspect can be analyzed to evaluate the sight comfort of the stands and, more in depth, of every seat in the stadium. John et al. (2013) suggests implementing the analysis of this feature into a computational method in order to avoid inadequate quality.

B. **The grandstand design** is determined by several parameters interrelated among one another. Therefore, the overall layout design is greatly affected by the modification of even a single value that controls the geometry.

C. **The maximum capacity** of the stadium can be evaluated easily through computational tools. Indeed, it is related to the parameters that govern the grandstand design and to the amount and position of the exits. Usually, architectural firms analyze the crowd flows (John et al., 2013) to determine the suitable locations and the quantity of gangways and vomitories to exit the stadium. In fact, the circulation through the stands is a crucial aspect in a stadium design process since the capacity of the arena is influenced by it.

D. **Unobstructed view** from the seats of the stadium can be evaluated through computational tools. The evaluation can affect the choice of the suitable roof structure and its design.

E. **Roof structures** are designed and optimized via computational tools to ensure the safety of the framework and to reduce the material use. Indeed, roof structures can increase greatly the total cost of the designed stadium (John et al., 2013).

Overall, the implementation of stadium design into computational methods can assist designer in resolving various architectural and engineering tasks. Intricate building structures can be analyzed, frameworks can be optimized, spaces can be simulated, and their quality can be evaluated (Patz et al., 2016). Since large-scale buildings such as stadiums present dependencies among their components, these can be parametrically determined in order to quickly adjust all the elements. Furthermore, algorithms-based processes can provide quick feedback for the designers to have an overview of the performances of the design. Therefore, computational methods can enhance stadium design process to quickly evaluate the generated solutions and the performances of the overall building, especially in the case of a renovation project.

1.4 Problem Statement

As previously explained, stadium design is a complex process that necessitates the analysis of different interrelated parameters. Computational methods are usually implemented in the development procedure to evaluate multiple measurable criteria (Joseph et al., 2015):

- Enhance the stadium capacity
- Improve the sightline quality and atmosphere of the stadium
- Optimize the structural framework of roofs

However, these aspects are analyzed individually in the stadium design process (Rodriguez Garcia, 2018). Thus, considering the influence that their performances have on the overall effectiveness of the design and the relationship that exists between them, it should be important to evaluate them jointly in order to achieve an effective design.

Likewise, the renovation or refurbishment of existing stadium introduces further challenges. Indeed, the designer needs to consider the present constraints, limitations and components of the structure, while developing new elements for the arena (John et al., 2013). For these reasons, the stadium design process shifted towards the implementation of performance-based design and computational methods, as for example PCA (Performative Computational Architecture). Indeed, this information can be implemented in computational methods to provide the designer with an overview of the state-of-the-art of the stadium to understand quickly where is necessary and possible to intervene. Moreover, computational methods can be utilized to quickly evaluate more proficient designs, to explore suitable options and to optimize the convenient solutions (Citerne, 2019), avoiding investing time in less efficient concepts

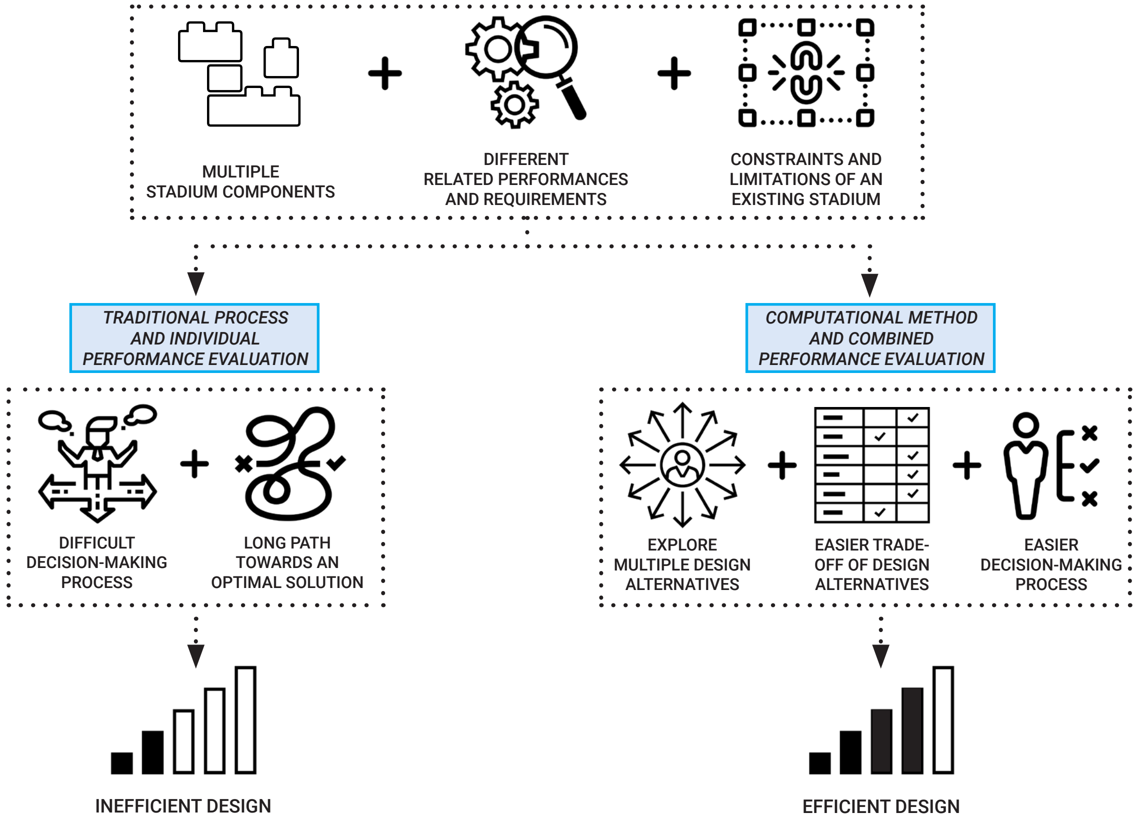


Figure 3. Scheme of traditional approach vs proposed approach (Source: Self-Made)

1.5 Research Questions

In relation to the problem statement, the main research question can be established as follows:

> *"How can a computational method be designed for a stadia renovation process to provide designers and engineers with an overview of the current structural performance of the roof structure and the viewing quality performance of the grandstands, while offering them the possibility to optimize these features jointly?"*

In relation to the computational method and the three phases of PCA, four groups of sub-questions are established as follows:

Computational Method:

- *How is the computational method organized in order to implement stadium renovation?*
- *Which are the steps of the workflow to develop a computational method suitable for stadium renovation?*
- *Which tools are the most suitable to produce the workflow?*

Form Generation:

- *Which components of the stadium should be implemented in the computational method to assess those performances?*
- *Which are the parameters that govern the components of the stadium to be implemented?*
- *What are the constraints of an existing stadium in relation to the viewing quality of the grandstands and the structural performance of the roof?*
- *How can the parameters that govern the components of the stadium be managed in the computational method?*
- *How can the constraints be managed in the computational method?*

Performance Assessment:

- *What is the viewing quality of the grandstand and the roof structure of a stadium?*
- *How can the viewing quality of the grandstand and the roof structure of a stadium be integrated together in a computational method?*
- *How can the structural performance of the roof and the viewing quality performance of the grandstand be evaluated?*

Optimization and Design Exploration:

- *How can the structural performance of the roof and the viewing quality of the grandstand be optimized jointly?*
- *How can the design constraints be implemented in the computational method?*
- *What is the objective of the optimization of the viewing quality performance of the grandstand?*
- *What is the objective of the optimization of the structural performance of the roof?*
- *Which process is most suitable to optimize the performances jointly?*
- *How can the design alternatives be evaluated through the design exploration?*

1.6 Research Objective

Based on the research questions, the research objective of the thesis can be described as follows:

> *"The development of a computational method to provide designers and engineers with an overview of the current viewing quality performance of the grandstand and the structural performance of the roof of the stadium. The computational method will be also implemented with a computational workflow to explore suitable design alternatives to optimize those performances jointly. The computational method will be validated through its application on an appropriate validation case."*

1.7 Research Structure

The envisioned computational method has the objective of evaluating the viewing quality performance of the grandstand and the structural performance of the roof of a stadium, while providing the possibility to explore suitable design alternatives to optimize those performances jointly. It is important to highlight how, in this thesis, the problem statement is tackled from a general perspective. Indeed, this research aims to develop a computational method for the renovation of football stadiums that can be applied on multiple stadia, rather than focusing on a specific case study.

As previously mentioned, the stadium design process consists in blending multiple components together, along with the evaluation of multiple performances and the fulfillment of multiple requirements. Hence, the combination of the different bowl geometries with the multitude of structural systems that can be implemented result to be endless. Therefore, the proposed computational method will consider a limited amount of stadium components and typologies. Likewise, the structural systems and the structural elements implemented in the computational method will be restricted. The proposed computational method will aim to provide useful general guidelines that can be followed to refurbish different typologies of stadiums, rather than focusing on a specific case study. However, this approach can rise problematics regarding how accurately an existing stadium can be implemented in the proposed computational method to optimize the initial performances.

Hence, it must be stressed that the envisioned computational method describes a methodology based on computational tools, which can be followed by the designer in order to produce multiple design alternatives of an existing stadium in the early design phase. Hence, following the phases of the computational method, the designer can generate the geometry of the bowl and the roof structure, perform the evaluation of the performances and produce multiple design alternatives through the optimization process. Subsequently, the produced designs can be explored, and a suitable solution can be chosen to be developed further. Therefore, the computational method described in this thesis is validated by proving that, starting from an original condition, multiple design alternatives which optimize the viewing quality of the bowl and the structural performance of the roof can be achieved.

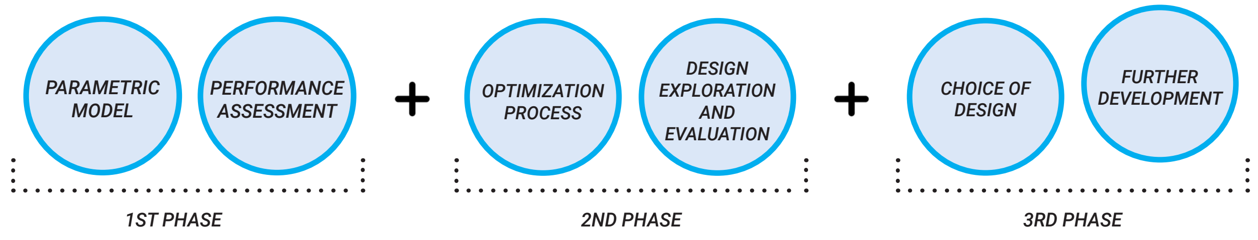


Figure 4. Three Macro-Phases of the Proposed Computational Method (Source: Self-Made)

The proposed computational method can be divided into three main phases:

- The first phase foresees the generation of a parametric model of a stadium which can be controlled by modifying certain parameters. Afterwards, an analysis of the structural performance of the roof and the viewing quality performance of the grandstand can be carried out. Hence, the outcome of this phase is an overview of the current performances of these two aspects of the stadium. Thus, the objective of this phase is to help the designer in detecting the problematics and the critical areas that need to be renovated to improve the mentioned performances. Subsequently, an approach can be determined to improve the initial performances and refurbish the stadium.

- The second phase comprises the production and the exploration of suitable design proposals to achieve the integrated optimization of the mentioned performances. The objective of the optimization will be determined based on different measurable criteria and constraints. Hence, the parameters that govern the parametric model will be altered to achieve the objective of the optimization, while remaining in the determined boundaries. Afterwards, the performances of the produced design proposals will be evaluated as in the first phase and compared to the initial situation. Thus, it will be determined if the optimization has fulfilled the objective.

- The third phase consists in the selection of one design proposal to be developed further. The choice of the design will be based on measurable criteria and aesthetic quality of the proposal. Hence, 3D drawings and sectional drawings of the stadium will be produced to represent the alteration of the refurbished stadium compared to the initial condition.

The research will be conducted in five steps, which can be described as follows:

A. Literature Review:

Step A consists of a literature study to gain knowledge on:

- Stadium design process (stadium components, relations among components, layout typologies, basic requirements)
- Viewing quality (parameters that influences the stadium design, minimum and maximum requirements, evaluation of performances)
- Stadium roof structures (available typologies, support typologies needed, flow of forces, minimum and maximum requirements, advantages or disadvantages)
- Relationship between viewing quality performance of the grandstand and structural performance of the roof (typologies of roofs based on layout typologies, parameters that influence both performances)
- Optimization typologies (process workflow, suitability for the development of the computational method, tools, user interface)
- Design exploration (process workflow, evaluation of solutions, suitability for the development of the computational method, tools, user interface)

B. Definition of Boundaries:

Step B consists of the definition of the boundaries of the computational method based on the output of the literature review. The limitations will be determined according to:

- Stadium components to be implemented in the parametric model
- Complexity of the parametric model
- Number of roof structures implemented to evaluate the current performances
- Number of roof structures to be explored
- Measurable criteria to assess the viewing quality performance of the grandstand
- Measurable criteria to assess the structural performance of the roof
- Objective of optimization for the viewing quality performance of the grandstand
- Objective of optimization for the structural performance of the roof
- Method of visualization of the design proposals
- Workflow and parametric tools

C. Form Generation and Performance Assessment

Step C will be focused on the realization of the parametric model of the stadium and the evaluation of the structural performance of the roof and the viewing quality of the grandstand. The components of the stadium to be inserted in the parametric model will be determined based on the outcome of the literature review. However, the complexity and the hierarchy of the components will be dependent on the interpolation of the design parameters. Thus, it will have an influence on the evaluation of the performances and the optimization process.

Hence, the geometries will be designed in the same parametric environment to maintain control over the performances and the design variables. Thus, Rhinoceros and its plug-in grasshopper will be utilized to design the components of the stadium. Indeed, Grasshopper enhance flexibility in the interpolation of the parameters. Further plug-in such as for example TORO will be evaluated to be implemented. Further plug-in such as for example TORO will be evaluated to be implemented. Indeed, TORO is a plug-in that can be utilized to facilitate the design of stadium components and to analyze the viewing quality of the grandstand. Concerning the performance assessment, the evaluation will be carried out through digital tools. Grasshopper will be utilized to assess the viewing quality of the grandstand. In this case, the analysis can be performed on a medium-scale (grandstand tier) or micro-scale (single seats). The complexity of the geometry, the speed of the analysis and the limitations of the tools will have to be evaluated to determine the scale at which the analysis will be performed and therefore the accuracy of the output.

Concerning the structural performance of the roof, plug-ins such as Karamba or external tools such as DIANA FEA will be utilized. The choice of the tool will be in this case dependent on the flexibility and speed of the evaluation. Indeed, their limitations towards the complexity of the geometries, the connection typologies that can be implemented and the constraints can influence the choice of the digital tool. Hence, a simulation has to be performed in order to determine the most suitable tool.

Lastly, the visualization of the results of the assessments will be provided within Rhinoceros. Since the objective of the graphic output of the analysis is to quickly evaluate the results and determine the critical areas of the stadium that need to be improved, the choice will be taken towards a more user-friendly interface.

D. Optimization Process and Design Exploration

Step D will be focused on the exploration of the suitable design proposals to achieve the integrated optimization of the structural performance of the roof and the viewing quality performance of the grandstand.

Based on the output of the initial performance analysis, three different approaches will be followed:

- Optimization of a grandstand tier and the roof structure
- Addition of a grandstand tier and optimization of the roof structure

Independently from the followed approach, the viewing quality performance and the structural performance will be evaluated and visualized as in step C. This choice is necessary to maintain the same measurable criteria to compare the explored geometries with the initial ones.

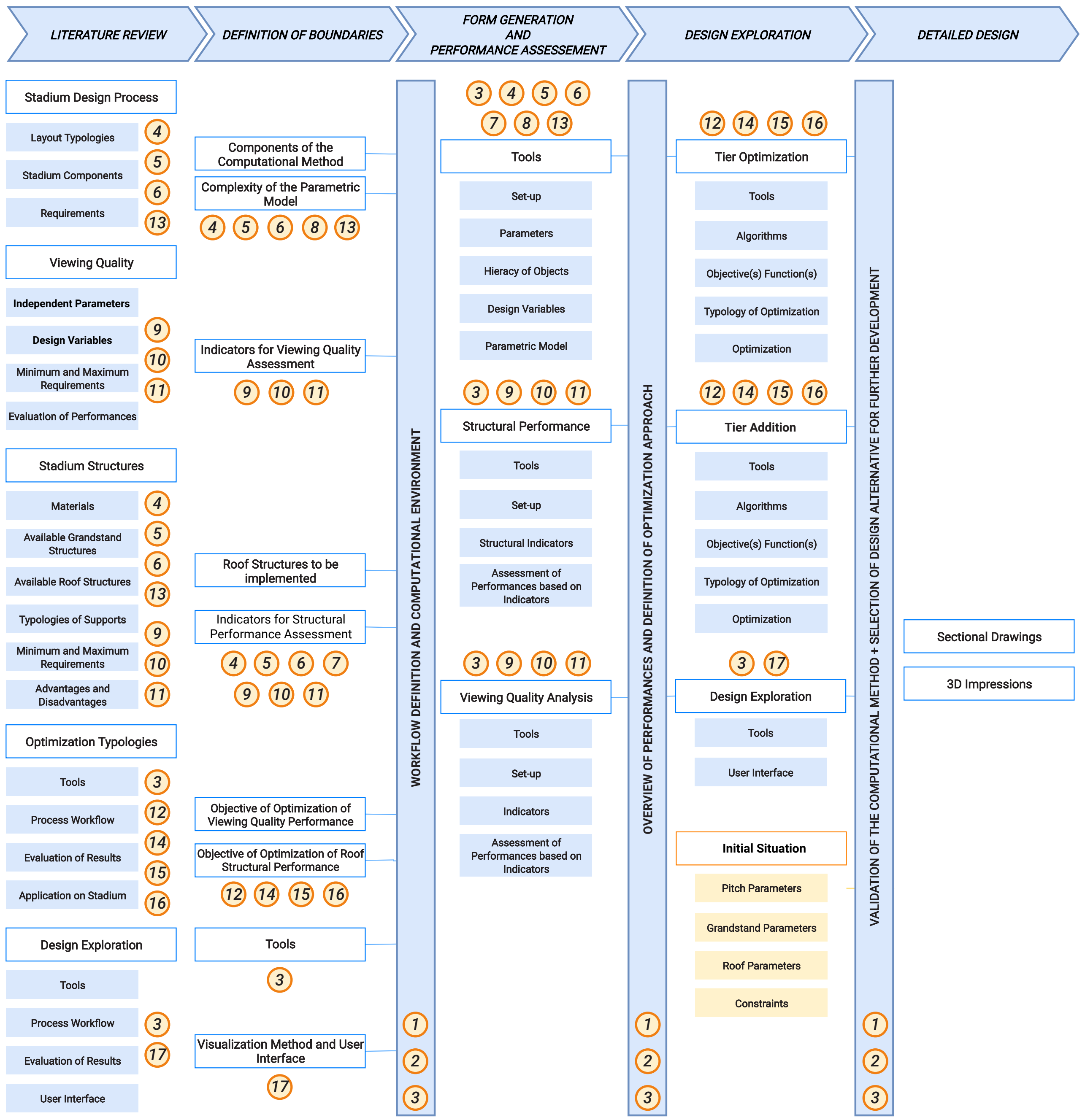
The first approach will be followed in case the viewing quality performance of a grandstand tier is poor. Hence, digital tools and plug-ins such as for example Opossum or ModeFRONTIER will be utilized to optimize the geometry of the selected grandstand and the roof structure accordingly. Thus, the main objective is to improve the viewing quality performance of the selected grandstand, while optimizing the roof structure to adapt it to the new grandstand geometry. The choice of the suitable digital tool is determined by the complexity of the geometry and the typology of constraints to be considered.

The second approach will be followed in case the stadium necessitates to be expanded. In this instance, a new grandstand tier will be designed. Hence, the workflow and the methodology utilized in Step C will be followed to produce the additional tier. Afterwards, digital tools and plug-ins such as for example Opossum or Octopus will be utilized to optimize the geometry of the additional grandstand and the roof structure accordingly. Concerning the structure, the existing constraints should be included, as well as an option to add further supports or load-bearing elements. Thus, the main objective is to enhance the capacity of the stadium by designing a new grandstand tier that fulfils the set requirements for the viewing quality, while not affecting the performance of the existing grandstand. Moreover, the roof structure will be optimized to adapt it to the new grandstand geometry, while still including the initial constraints.

To conclude, the computational method will be validated by proving that, starting from an original condition, multiple design alternatives which optimize the viewing quality of the bowl and the structural performance of the roof can be achieved. Based on the suitability for the computational method, the original condition will be an existing stadium, a simplified version or an arbitrary condition referred to an existing case study.

E. Detailed Design

Step E consists of the selection of one design proposal to be developed further. The choice of the design will be based on measurable criteria and aesthetic quality of the proposal. Hence, 3D drawings and sectional drawings will be produced to represent the alteration of the refurbished stadium compared to the initial condition. Rhinoceros and Grasshopper will be utilized to produce such drawings. This choice is taken to remain in the same design environment.



1. *How is the computational method organized in order to implement stadium renovation?*
2. *Which are the steps of the workflow to develop a computational method suitable for stadium renovation?*
3. *Which tools are the most suitable to produce the workflow?*

4. *Which components of the stadium should be implemented in the computational method to assess those performances?*
5. *Which are the parameters that govern the components of the stadium to be implemented?*
6. *What are the constraints of an existing stadium in relation to the viewing quality of the grandstands and the structural performance of the roof?*
7. *How can the parameters that govern the components of the stadium be managed in the computational method?*
8. *How can the constraints of the existing stadium be managed in the computational method?*

9. *What is the viewing quality of the grandstand and the roof structure of a stadium?*
10. *How can the viewing quality of the grandstand and the roof structure of a stadium be integrated together in a computational method?*
11. *How can the structural performance of the roof and the viewing quality performance of the grandstand be evaluated?*

12. *How can the structural performance of the roof and the viewing quality of the grandstand be optimized jointly?*
13. *How can the design constraints be implemented in the computational method?*
14. *What is the objective of the optimization of the viewing quality performance of the grandstand?*
15. *What is the objective of the optimization of the structural performance of the roof?*
16. *Which process is most suitable to optimize the performances jointly?*
17. *How can the design alternatives be evaluated through the design exploration?*

Figure 5. Research Structure Overview (Source: Self-Made)

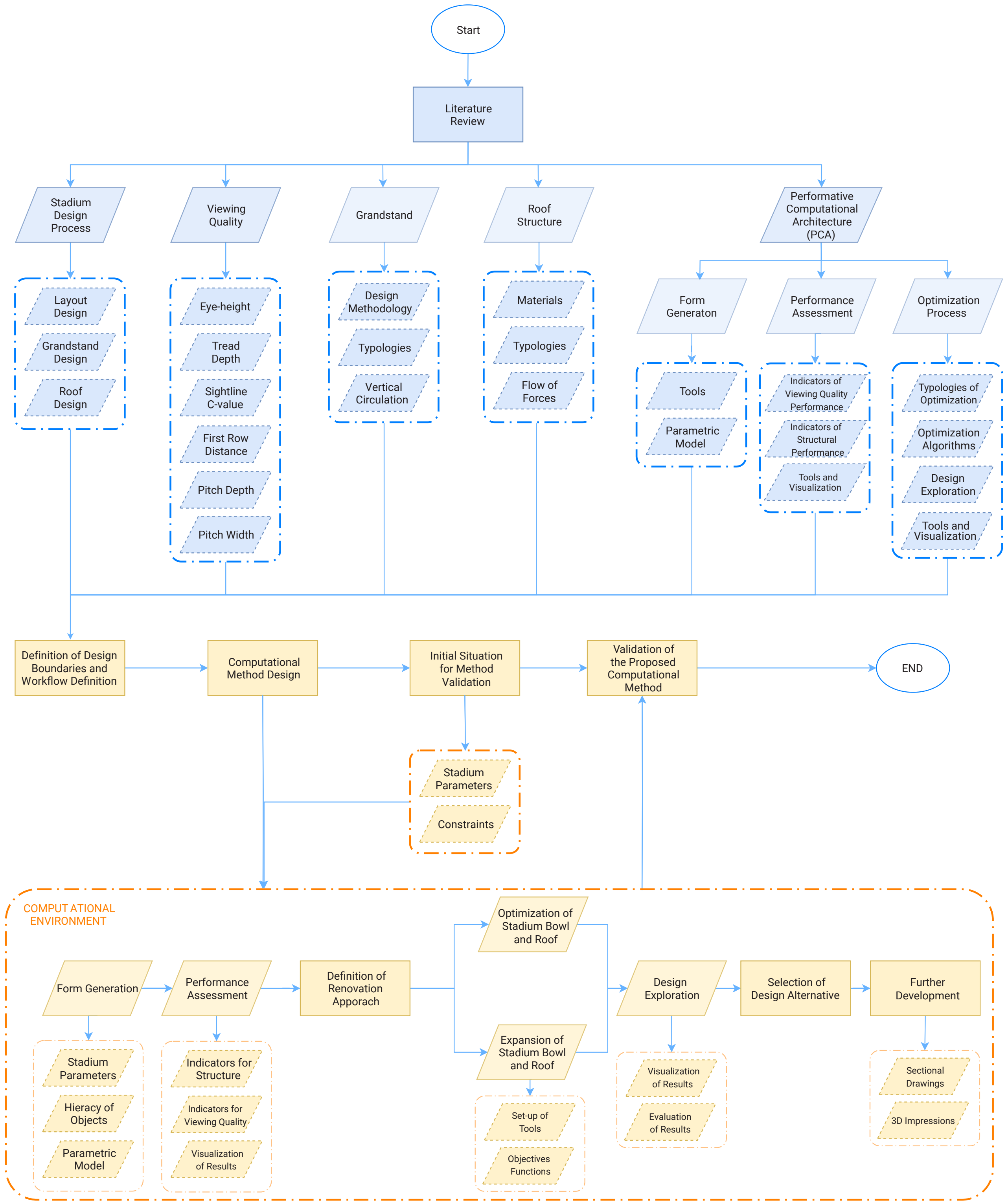


Figure 6. Research Flowchart Overview
(Source: Self-Made)

1.8 Research Planning

Month	November				December			January				February			March				April					May				June				July	
Week	2.1	P1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	P2	2.10	3.1	3.2	3.3	3.4	3.5	3.6	P3	3.8	3.9	3.10	4.1	4.2	4.3	4.4	P4	4.6	4.7	4.8	4.9	4.10	P5	5.1
1 - TOPIC DEFINITION																																	
1.1 Topic Selection																																	
1.2 General Overview																																	
2 - LITERATURE REVIEW																																	
2.1 Stadium Design Process																																	
2.1.1 Stadium Layout																																	
2.1.2 Stadium Grandstand																																	
2.1.3 Stadium Roof																																	
2.2 Viewing Quality																																	
2.2.1 Parameters																																	
2.2.2 Requirements																																	
2.2.3 Evaluation of Performances																																	
2.3 Stadium Structures																																	
2.3.1 Grandstand Design																																	
2.2.2 Roof Typologies																																	
2.2.3 Flow of Forces																																	
2.4 Football Associations Regulations																																	
2.4.1 Stadium Categories																																	
2.4.2 Viewing Quality Requirements																																	
2.4.3 Stadium Requirements																																	
2.5 Performative Computational Architecture																																	
2.5.1 Form Generation																																	
2.5.2 Performance Assesement																																	
2.5.3 Optimization Typologies																																	
2.5.4 Optimization Algorithms																																	
2.5.5 Optimization Tools																																	
2.5.6 Design Exploration																																	
2.6 Initial Definition of Boundaries																																	
3 - FORM GENERATION AND PERFORMANCE ASSESSMENT																																	
3.1 Further Definition of Boundaries																																	
3.2 Form Generation																																	
3.2.1 Model Set-up																																	
3.2.2 Hieracy Definition																																	
3.2.3 Parametric Model																																	
3.3 Performance Assessment																																	
3.3.1 Set-up																																	
3.3.2 Indicators of Viewing Quality Performance																																	
3.3.3 Indicators of Structural Performance																																	
3.3.4 Combination of Indicators																																	
3.3.5 Structural Simulations																																	
3.3.6 Viewing Quality Simulations																																	
4 - OPTIMIZATION PROCESS AND DESIGN EXPLORATION																																	
4.1 Optimization Process																																	
4.1.1 Set-up																																	
4.1.2 Objective(s) function(s)																																	
4.1.3 Optimization Simulation																																	
4.2 Design Exploration																																	
4.2.1 Set-up																																	
4.1.2 User-Interface																																	
4.1.3 Visualization																																	
4.3 Validation																																	
4.3.1 Implementation of the Original Condition																																	
4.3.2 Validation of the Computational Method																																	
4.4 Results Discussion and Evaluation																																	
5 - DETAILED DESIGN																																	
5.1 Production of Detailed Drawings																																	
5.2 Final Report																																	
5.1 Final Presentation																																	

Figure 7. Research Time Table
(Source: Self-Made)

02 | STADIUM BACKGROUND

2.1 Stadium Development

As previously stated, John et al. (1981) provides a definition of stadia:

> *"A stadium can be considered as a pitch or a track for athletics or team competition in an arena surrounded by rising, stepped tiers for the accommodation of standing or seated spectators, with coverings that do not, however, cover the field to enclose the whole building."*

Even though its purpose did not change throughout history, being one of the oldest building typologies, sports and entertainment stadiums experienced an important transformation upon history. Indeed, the development of stadia lived through three main phases.

Firstly, the ancestral prototypes of modern stadium can be traced back to the VIII century BC in ancient Greece (John et al., 2013). Indeed, hippodromes and stadia were built to host the ancient Olympic games. The layout of the stadium was determined based on the practiced sport. Therefore, the Greek stadia were usually U-shaped and provided with a central field surrounded by a track. Viewing quality was also important while designing an ancient stadium. Two main approaches can be described to achieve a solid standard. On the one hand, those stadiums built on flat ground foresaw a playing area slightly carved out in the land to obtain shallow stands around it. On the other hand, ancient Olympic stadia as the Olympia's and Thebes' were dug out from hillsides in order to obtain a series of grandstand with a natural good sightline. Moreover, these ancient stadiums can be compared to modern ones in terms of capacity (maximum 50,000 people), dimensions (192 m long and 32 m wide) and due to the presence of two grandstand tiers.

Secondly, stadia evolved in the Roman era into elliptical arenas known as amphitheaters. Indeed, the venues displayed gladiator combats instead of Olympic sports. Therefore, these ancient stadia were composed of a circular playing field surrounded by series of grandstand, sometimes organized into a maximum of three tiers. The main improvements from the Greek versions are related to the construction method and their structure. Indeed, the stands were no more carved out from hillsides, but a complex structure of arches and vaults established the framework to transfer all the loads to the foundations. Moreover, they were usually realized with stone or a primitive form of concrete. Furthermore, roof systems composed of canvas and ropes were implemented in order to cover the spectators, but without obstructing the view and maintaining a good sightline of the playing area.

Lastly, the building typology of stadia experienced a rebirth in the late XIX century. Indeed, the industrial revolution introduced new materials and technologies that simplified the structures of the stadiums and therefore their construction. Moreover, the establishment of the modern Olympic games in 1896 increased the demand for newly built stadiums. These modern Olympic venues hosted multiple sport activities and their capacity increased to over 100,000 spectators, affecting sometimes security and viewing quality. Thus, the number of sports was reduced in order to obtain smaller arenas with an improved user performance.

Hence, it is notable how the relationship among the playing field, the stadium layout, the grandstand and the viewing quality remained unvaried in history. Indeed, the latest evolution of this building typology is the single-sport stadia which enhance these connections by focusing on the realization of a functional building for one single discipline.

2.2 Stadium Layout

Stadium layout can be described as the arrangement of the seating around the area where the main performance takes place. As stated by UEFA (2011), the design of the stadium bowl is extremely important to assess to success of the overall design since it determines the quality of the spectator's experience in terms of sight quality, atmosphere and the involvement of supporters in the game. In addition to the maximum viewing distances, the preferred viewing locations and the safety requirements have to be taken into account while designing the bowl.

In the case of football, the seating has to be placed on the long side of the playing area in order to provide the spectators with the possibility to follow the motion of the game from both the ends of the pitch. However, more driven supporters have the tradition of observing the matches from behind the goals (John et al., 2013). Indeed, this location is preferred since it enhances the involvement of supporters in the game by opposing themselves to the adversary team.

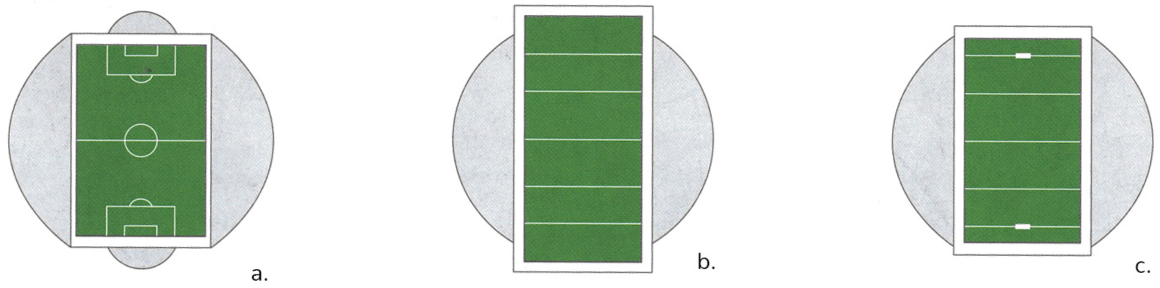


Figure 8. Favorite viewing spots per activity: Football (a), American football (b) and Rugby (c) (Source: John et al., 2013)

Concerning security aspects, UEFA (2011) and FIFA (2011) require that the venues for all the matches must be all-seater. Indeed, in the last fifty years, various accidents that caused the death of numerous spectators drove the football associations to improve the security standards. Indeed, FIFA (2011) and UEFA (2011) specify the safe capacity of a stadium as a necessary requirement to be met. It can be defined as the capacity that grant the safe evacuation of all the spectators from the stadium within a time limit of 8 minute, equivalent to 660 people per hour. However, standing areas are still present in few stadiums around Europe and they are still available for supporters, even though FIFA and UEFA do not include them in the estimation of the overall capacity of the building. It is the case of the Signal Iduna Park stadium in Dortmund, where the 27500 standing places are not considered for the international matches (Nixdorf, 2009).

2.2.1 Viewing distance

In general, EN/DIN 13200-1 divides sports into three categories A, B and C based on the speed of play and the dimension of the object that the spectators have to follow (Nixdorf, 2009). Category C includes sports practiced with a small observable object and an intense playing speed, while category A includes slower sports with a bigger element that the spectators have to follow. In this specific case, football falls within category B, with a medium pace of game and a medium playing object with a diameter of 220 mm. Hence, this parameter can be utilized to determine the maximum allowed viewing distance.

The maximum viewing distance can be defined as the span that can be measured between the spectator and the action. Mills (1976) describes the formula to employ in the measurement as:

$r = 0{,}86 \times s$ [1]

Where: r = viewing distance [m]
s = size of the object [mm]

Considering the diameter of the ball as of 220 mm, the formula can be rewritten as:

$r = 0{,}86 \times 220\ mm = 190\ m$

In the case of football, the maximum viewing distance determined with this formula is of 190m. However, this value is reputed the limit value since it leads to a poor viewing quality for the spectators. Therefore, the formula [1] is improved by a factor of 40%. Hence, the formula is rewritten as:

$r = 0{,}52 \times s$ [2]

$r = 0{,}52 \times 220\ mm = 115\ m$

The maximum viewing distance obtained is of 115m, which leads to an optimal viewing distance for the spectators. However, Nixdorf (2009) implies that a ball can be easily followed from the spectators if the distance that elapses between the furthest seat and the opposite corner flag is of 190m. Hence, the maximum visual acuity angle and the height of an average European player are utilized as the reference values instead of the ball. Therefore, the formula to determine the maximum and recommended viewing distance can be written as:

$Distance = (height\ avg\ player)/(\tan\theta)$ [3]

Considering 1.75m as the height of the average player and 0.7° and 0.53° as the recommended θ values, the formula can be rewritten as:

$Maximum\ distance = (1.75\ m)/(0.53) = 190\ m$ $Recommended\ distance = (1.75\ m)/(0.7°) = 150\ m$

These values are considered as the standard reference distances for the stadium design and they can be useful in the evaluation of the efficiency of the layout of the building.

2.2.2 Optimum Viewing Circle

The maximum and the recommended viewing distances can be utilized to produce the optimum viewing circle. This parameter is extremely useful in the early design process of a stadium to determine the location of the seating and to assess their efficiency in terms of sight (Nixdorf, 2009). Indeed, the optimum viewing circle can be defined as the area beneath which the spectators are provided with a finer viewing quality.

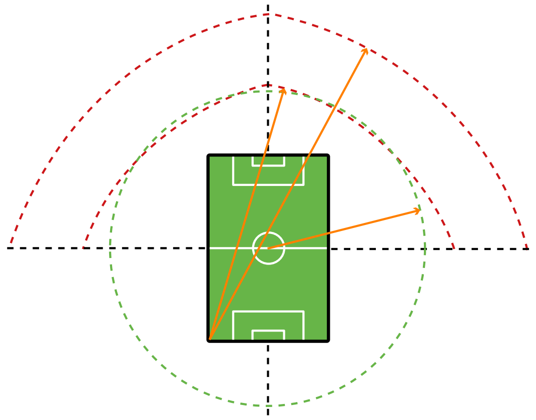


Figure 9. Optimum viewing circle construction for football stadiums (Reference: Nixdorf, 2009)

Since the maximum and the recommended viewing distances for a football stadium are respectively of 190m and 150m, four arches for each distance can be drawn from all the four corner flags of the pitch. The result is a quadrilateral figure that surrounds the playing area representing the zone provided with a finer viewing quality. Usually, the inner figure is substituted with a 90m circle drawn from the center of the pitch, which refines the optimum viewing distance and therefore the efficiency of the evaluation.

The optimum viewing circle exploits clearly the relationship between the performance area and the sight quality provided to the spectators. Therefore, the stadium layout becomes a crucial aspect in stadia design as the disposition of the stands affects greatly the user experience of the venue (figure 7). Indeed, an open rectangular geometry composed of four individual stands (a) does not exploit the corner area, which remains therefore unutilized (Nixdorf, 2009). On the other hand, a continuous bowl (b) increases the number of seating beneath the optimum viewing radius, even though parts of the corner areas remain outside it. John et al. (2013) implies that this layout solution offers the possibility to design more attractive stadiums. Lastly, the optimum geometry (c) and the spectator hub variation (d) manages to provide a very good sightline from all the seating, enhancing the involvement of the spectators with the display (John et al., 2013). Indeed, all the stands lay inside the optimum viewing circle. However, these solutions require a particular design of the grandstand, which is usually the undulation of the upper tier edge.

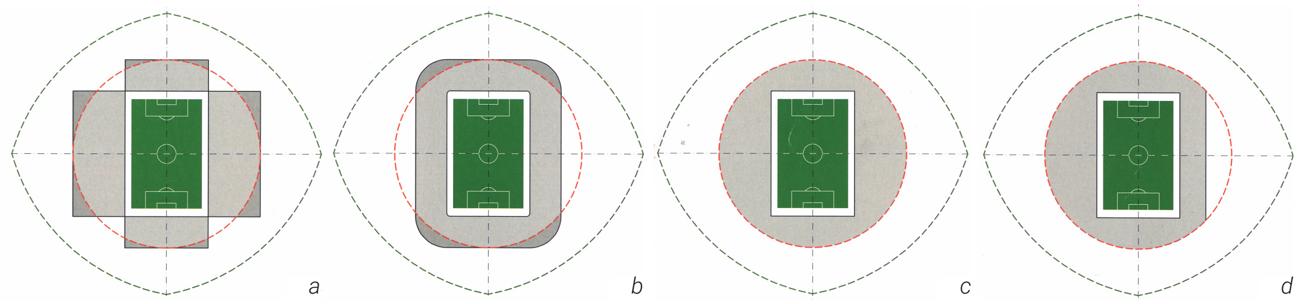


Figure 10. Comparison of the stands positioning of different stadium layouts (Source: Nixdorf, 2009)

2.2.3 Layout Typologies

Nowadays in Europe, two main typologies of layout can be discerned. The first one is the football/athletics geometries, which have specific requirements for the interior of the stadium based on the function. Thus, nine main configurations can be distinguished from this typology. The second one is the asymmetrical derivation, which does not constitute any independent configuration and it is produced from any basic geometry.

In general, it can be said that every layout configuration can be identified as a radical alteration of a rectangular or circular shape. Initially, stadium seating was arranged in a rectangular form as the most logical configuration deriving from the form of the pitch (UEFA, 2011). However, it was notable that the viewing quality was heavily affected from this solution by limiting the sight of those spectators located in the near proximity of the corners. Preferably, the optimal layout configuration should be circular to provide all the spectator with a similar sight quality. However, since the pitch is a rectangle, the viewing distances and the position of the focus points cannot be the same for all observers. Therefore, it is necessary to alter the viewing points in order to achieve a smooth transition from a rectangular to a circular shape.

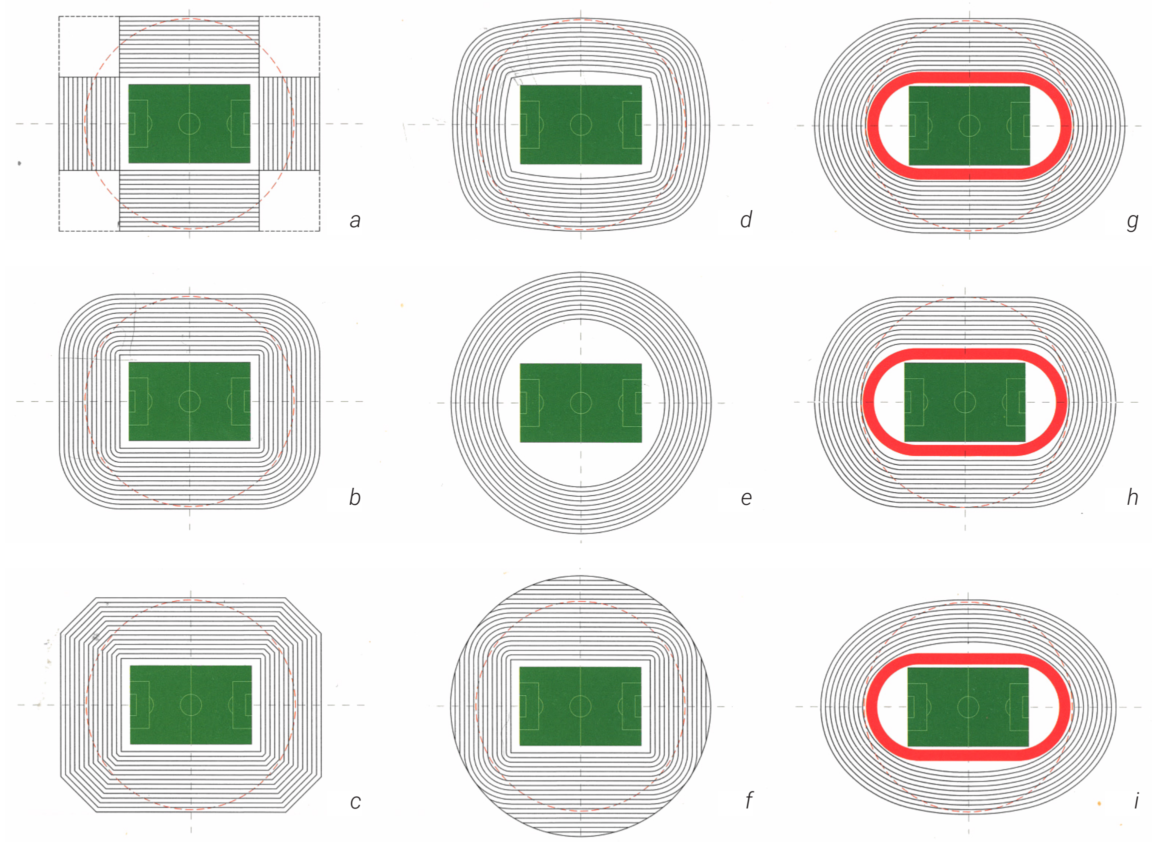


Figure 11. Representation of the layout typologies: geometrically open rectangular geometry (a), rounded polygonal geometry (b), octagonal geometry (c), radial geometry or super ellipse (d), ideal circular geometry (e), undulating geometry (f), semicircular geometry (g), basket arch geometry (h), oval geometry (i) (Source: Nixdorf, 2009)

In general, it can be said that every layout configuration can be identified as a radical alteration of a rectangular or circular shape. Initially, stadium seating was arranged in a rectangular form as the most logical configuration deriving from the form of the pitch (UEFA, 2011). However, it was notable that the viewing quality was heavily affected from this solution by limiting the sight of those spectators located in the near proximity of the corners. Preferably, the optimal layout configuration should be circular to provide all the spectator with a similar sight quality. However, since the pitch is a rectangle, the viewing distances and the position of the focus points cannot be the same for all observers. Therefore, it is necessary to alter the viewing points in order to achieve a smooth transition from a rectangular to a circular shape.

Nixdorf (2009) describes the three main operations that can be utilized to obtain said shift in shape:

- **Layout with equal-height terrace edges:**
  - ♦ **Overlapping/undercutting**: The first approach consists in the alteration of the height offset of the tiers. Indeed, the additional layers are projected or overhang above the stands located at the short sides of the pitch.
  - ♦ **Variations in seating row depth**: The second approach consists in the alteration of the tread depth value of the stands towards the corner areas of the stadium. Hence, the result is an enlarged bowl with an elevation that resembles a wavelike shape. Concerning the viewing quality, the performance is improved since the inclination of the grandstand is modified continually. However, the structure of the bowl is affected, especially the prefabrication process that derives from it.

- **Layout without equal-height terrace edges:**
  - **Undulating upper tier:** The third approach consists in the addition of few seating rows along the central axis of the pitch to the upper tier. This solution creates a wavelike effect upon the edge of the last tier of seating since the central area rises steeply compared to the corner zones. In general, this approach is adopted to implement a feasible roof structure and not only for a formal consideration. Indeed, roof typologies as the tension/compression ring can be applied only on circular layouts.

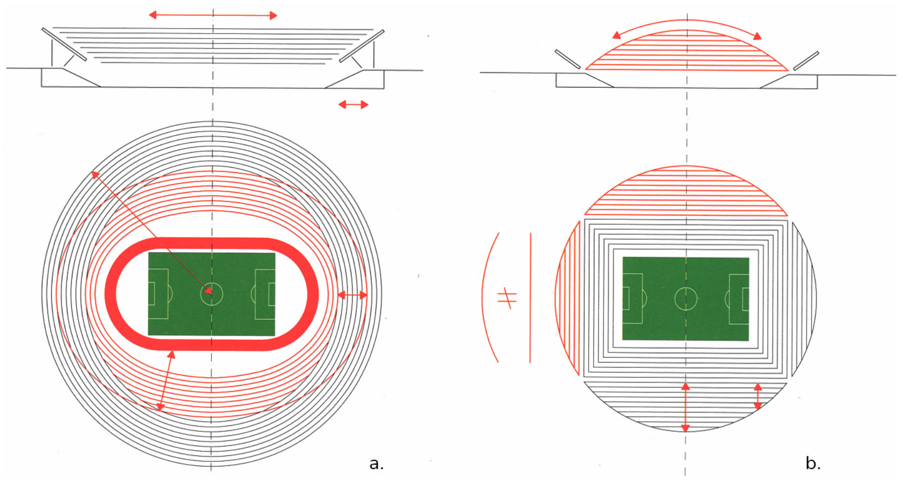


Figure 12. Representation of the transitional approaches: overlapping of the upper tier (a) and undulation of the upper tier (b) (Source: Nixdorf, 2009)

2.3 Grandstand Design

The grandstand in stadium design is the organization of the seating in a rising rows configuration. It constitutes the location that host the spectators of a venue. The grandstand design is the second important step of stadia development. Indeed, once the capacity and the layout are determined, the seating have to be designed accordingly. Mills (1976) describes the main functions of the grandstand. The tribunes must provide a clear and unobstructed view of the playing field, while the structure implemented should be economical and it should require a minimum maintenance. Moreover, the seating must be organized in order to provide safety and comfort to the spectator.

Thereby, the number of tiers and seats of the grandstand are pre-dimensioned based on the planned capacity and the design process is carried out in five main steps, known as the five-step method (Nixdorf, 2009). Firstly, the point of focus of the spectators is determined, which is dependent on the observed sport. Secondly, the sightline and the basic parameters are determined. Thirdly, the grandstand geometry is designed, and the gangways and vomitories are located. Then, the corner areas are inspected to ensure that the sightline quality respects the limitations. Lastly, the calculated configuration is adjusted through the polygonal transformation process to determine how the elements will be pre-fabricated.

2.3.1 Pre-Dimensioning

The pre-dimensioning process of the grandstand is related to the planned capacity of the stadium and it is determined by limitations imposed by the European standards and the country's building regulations. Generally, grandstand can be designed in one tier. However, the maximum viewing distances and the maximum rake of slope constitute further restrictions that can drive designers to consider the implementation of more tiers in order to attain the expected gross capacity (Mills, 1976).

Indeed, for safety reasons, every country has their own regulations regarding the maximum number of rows per tier, which is controlled by the maximum rake of slope, and seats per row. Concerning the rake of slope, the European standard EN/DIN 13200-1 suggests a maximum angle of 35°, consisting in a riser of 20 cm and a tread depth of 25 cm. However, UEFA (2011) and FIFA (2011) recommend a maximum rake of slope of 34° to ensure that a sensation of vertigo is not present, and a maximum of 25-28 seats are allowed per row in order to maintain the safe capacity. The pre-dimensioning process presupposes the determination of the desired capacity in advance. Afterwards, based on the limitations set by the European standards and the layout of the stadium, the number of seats per square meter is determined and utilized to calculate the theoretical dimensions of the stands and the number of rows. Hence, the number of tiers can be determined.

Nixdorf (2009) provides an overview of the number of rows and tiers of a stadium based on the layout, the capacity and the number of seats. In this particular case, 2.2 seats/m2 is utilized as a layout-neutral parameter.

Capacity and theoretical space requirements	Rounded rectangle		Circle-segment geometry		Circular geometry		'Geometrically open' rectangle		
Step 80/50 cm 2.20 seats/m^2	Rows m^2	Tiers	Rows m^2	Tiers	Rows m^2	Tiers	Rows m^2	Tiers	Step 80/50 cm 2.20 seats/m^2
10,000 4,545 m^2	13.07 -> **13** 4,517 m^2		12.99 -> **13** 4,547 m^2		– –	–	14.20 -> **14** 4,480 m^2		**10,000** 4,545 m^2
15,000 6,818 m^2	18.96 -> **19** 6,835 m^2		18.85 -> **19** 6,877 m^2		**15–40** 6,913 m^2		21.30 -> **21** 6,720 m^2		**15,000** 6,818 m^2
20,000 9,090 m^2	24.51 -> **25** 9,299 m^2		24.39 -> **25** 9,350 m^2		**21–46** 9,269 m^2		28.41 -> **29** 9,280 m^2		**20,000** 9,090 m^2
25,000 11,364 m^2	29.77 -> **30** 11,210 m^2		29.64 -> **30** 11,521 m^2		**27–52** 11,524 m^2		35.51 -> **36** 11,520 m^2		**25,000** 11,364 m^2
30,000 13,636 m^2	34.79 -> **35** 13,452 m^2		34.66 -> **35** 13,793 m^2		**32–57** 13,635 m^2		42.62 -> **43** 13,760 m^2		**30,000** 13,636 m^2
35,000 15,909 m^2	39.61 -> **40** 16,100 m^2		39.47 -> **40** 16,166 m^2		**38–63** 16,130 m^2		49,72 -> **50** 16,000 m^2		**35,000** 15,909 m^2
40,000 18,182 m^2	44.23 -> **45** 18,571 m^2		44.09 -> **44** 18,136 m^2		**42–67** 18,159 m^2		56.82 -> **57** 18,240 m^2		**40,000** 18,182 m^2
45,000 20,455 m^2	48.68 -> **49** 20,620 m^2		48.55 -> **49** 20,690 m^2		**47–72** 20,572 m^2		63.92 -> **64** 20,480 m^2		**45,000** 20,455 m^2
50,000 22,727 m^2	52.98 -> **53** 22,736 m^2		52.86 -> **53** 22,805 m^2		**51–76** 22,765 m^2		71.02 -> **71** 22,720 m^2		**50,000** 22,727 m^2
55,000 25,000 m^2	57.15 -> **58** 24,915 m^2		57.03 -> **58** 25,539 m^2		**56–81** 25,036 m^2		78.13 -> **79*** 25,280 m^2		**55,000** 25,000 m^2
60,000 27,273 m^2	61.20 -> **62** 27,731 m^2		61.08 -> **62** 27,780 m^2		**60–85** 27,383 m^2		– –	–	**60,000** 27,273 m^2
65,000 29,545 m^2	65.12 -> **66** 30,062 m^2		65.02 -> **66** 29,356 m^2		**65–90** 29,808 m^2		– –	–	**65,000** 29,545 m^2
70,000 31,818 m^2	68.95 -> **69*** 31,852 m^2		68.85 -> **69** 31,908 m^2		**68–93** 31,947 m^2		– –	–	**70,000** 31,818 m^2

Capacity and theoretical space requirements	Basket arch geometry		Semicircular geometry		Oval geometry		Octagonal geometry		
Step 80/50 cm 2.20 seats/m^2	Rows m^2	Tiers	Rows m^2	Tiers	Rows m^2	Tiers	Rows m^2	Tiers	Step 80/50 cm 2.20 seats/m^2
10,000 4,545 m^2	10.86 -> **11** 4,604 m^2		10.72 -> **11** 4,223 m^2		11.37 -> **12** 4,389 m^2		13.04 -> **13** 4,531 m^2		**10,000** 4,545 m^2
15,000 6,818 m^2	15.91 -> **16** 6,860 m^2		15.71 -> **16** 6,949 m^2		16.61 -> **17** 6,990 m^2		18.88 -> **19** 6,866 m^2		**15,000** 6,818 m^2
20,000 9,090 m^2	20.74 -> **21** 9,215 m^2		20.50 -> **21** 9,332 m^2		21.62 -> **22** 9,266 m^2		24.38 -> **25** 9,352 m^2		**20,000** 9,090 m^2
25,000 11,364 m^2	25.39 -> **26** 11,670 m^2		25.10 -> **25** 11,311 m^2		26.42 -> **27** 11,643 m^2		29.61 -> **30** 11,541 m^2		**25,000** 11,364 m^2
30,000 13,636 m^2	29.86 -> **30** 13,706 m^2		29.54 -> **30** 13,875 m^2		31.03 -> **31** 13,618 m^2		34.57 -> **35** 13,835 m^2		**30,000** 13,636 m^2
35,000 15,909 m^2	34.19 -> **35** 16,343 m^2		33.84 -> **34** 15,998 m^2		35.49 -> **36** 16,176 m^2		39.32 -> **40** 16,241 m^2		**35,000** 15,909 m^2
40,000 18,182 m^2	38.38 -> **39** 18,524 m^2		37.99 -> **38** 18.185 m^2		39.79 -> **40** 18,295 m^2		43.89 -> **44** 18,238 m^2		**40,000** 18,182 m^2
45,000 20,455 m^2	42.45 -> **43** 20,770 m^2		42.03 -> **42** 20,437 m^2		43.96 -> **44** 20,478 m^2		48.29 -> **49** 20,829 m^2		**45,000** 20,455 m^2
50,000 22,727 m^2	46.40 -> **47** 23,080 m^2		45.95 -> **46** 22,754 m^2		**48** 22,726 m^2		52.54 -> **53** 22,980 m^2		**50,000** 22,727 m^2
55,000 25,000 m^2	50.24 -> **51** 25,454 m^2		49.78 -> **50** 25,134 m^2		51.93 -> **52** 25,038 m^2		56.65 -> **57** 25,195 m^2		**55,000** 25,000 m^2
60,000 27,273 m^2	53.99 -> **54** 27,273 m^2		53.51 -> **54** 27,578 m^2		55.77 -> **56** 27,414 m^2		60.64 -> **61** 27,483 m^2		**60,000** 27,273 m^2
65,000 29,545 m^2	57.65 -> **58** 29,763 m^2		–	–	59.50 -> **60** 29,238 m^2		64.51 -> **65** 29,835 m^2		**65,000** 29,545 m^2
70,000 31,818 m^2	61.23 -> **62*** 32,315 m^2		–	–	63.14 -> **63*** 31,732 m^2		–	–	**70,000** 31,818 m^2

Figure 13. Table of theoretical dimensions, rows and tiers of stadiums in relation to desired capacity and layout (Source: Nixdorf, 2009)

2.3.2 Grandstand Calculation

The grandstand geometry is determined by the assessment of the sightline elevation, which is the most important feature of grandstand design, and the riser height. Indeed, the process consists in the construction of the sightline and its transformation in the stand profile. The European standard EN/DIN 13200-1 specifies

The European standard EN/DIN 13200-1 specifies the term as:

> *"The line which connects a spectator's center of the eye to a point of focus in the activity area without obstruction."*

In general, a new grandstand geometry can be calculated with basic principles of trigonometry, for which the point of focus of the spectator and four main parameters have to be defined in order to determine the design.

Firstly, the point of focus varies depending on the observed sport. In the case of football, the perimeter lines of the pitch, thus the sideline, the goal lines and the corners. Besides, the height of the point of focus is considered to be of 0 cm (Nixdorf, 2009). Once the point of focus is determined, the variables are selected, and trigonometry is utilized to calculate the riser height of the stands. The main parameters and their relationship with the grandstand design process are presented by Nixdorf (2009) and they can be described as follows:

A. **Eye-point height.** It is the vertical distance that elapses between the point of focus P and the first spectator's eye-point. This parameter determines the starting point of the sightline construction. Hence, the higher the value is, the steeper the stand will be. On the one hand, a sharper inclination improves the viewing quality and reduces the difference in riser height. Hence, the construction costs are reduced. However, on the other hand, the maximum angle of inclination is reached faster, influencing negatively the capacity of the stadium.

B. **Tread Depth.** It is the horizontal distance between one spectator's eye-point and the eye-point of the spectator seating exactly behind him. Extensively, it represents the depth of the seating/standing step of the grandstand. This parameter determines the seating comfort of the spectators. Therefore, the higher the value is, the more comfortable the user will be. However, its crement leads to the maximum angle of inclination to be reached faster, limiting the capacity of the stadium.

C. **C-Value.** Defined also as eye-point or sightline elevation, it is the vertical distance that elapses between the sightline of two spectators that are sitting one after the other. This parameter constitutes the reference value to evaluate viewing quality in stadium design. UEFA (2011, FIFA (2011) and European standards EN/DIN 13200-1 recommend range of 6 to 12 cm with an admissible tolerance of ±5 mm. Indeed, 12 cm is considered the optimal value for a good viewing quality, while 9 cm is admissible, and 6 cm is accepted only in rare cases. Moreover, John et al. (2013) states that 15 cm is an excellent design value. However, a higher sightline elevation drives a stand to rise steeper, reaching the maximum inclination in advance. Even though various examinations of different grandstand geometries indicate that stadium's capacity and viewing quality are affected by a limited inclination of the stands, security has to be provided to the spectators at the expense of C-value. Indeed, if a grandstand reaches the maximum rake angle before the maximum capacity is achieved, the sightline value will have to be reduced (Nixdorf, 2009). Therefore, it is important to notice that in many cases, the C-value is not always constant and optimal in a stadium.

D. **Distance of the First Row.** It is the horizontal distance that elapses from the point of focus P to the eye-point of the spectator sitting in the first row. This parameter governs the steepness and the viewing quality of the grandstand. On the one hand, the closer the stand is, the higher the involvement of the supporter will be. However, a closer stand causes to reach the maximum inclination angle in advance. On the other hand, if the distance increases, the stand will rise slowly and will be deeper. Hence, the construction will be more costly, even though the viewing quality will be improved. UEFA (2011) and FIFA (2011) require a minimum distance of the first row of 7.5 m behind the goal lines and of 6.0 m from the sidelines.

Once the parameters are set, the riser height of the stand can be calculated with the formula:

$$R_h = \frac{(A+C)}{D} \times B + C \qquad [4]$$

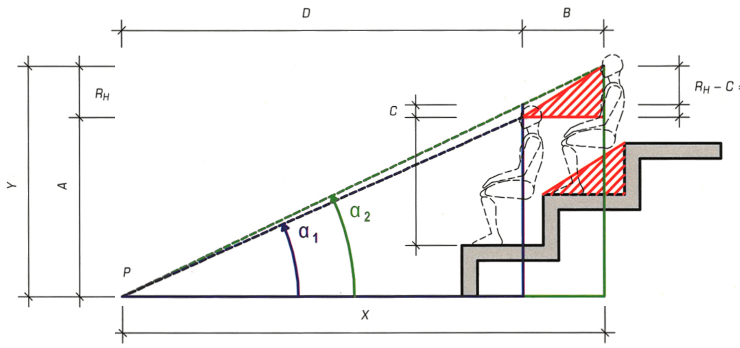


Figure 14. Sightline construction through trigonometry calculations (Source: Nixdorf, 2009)

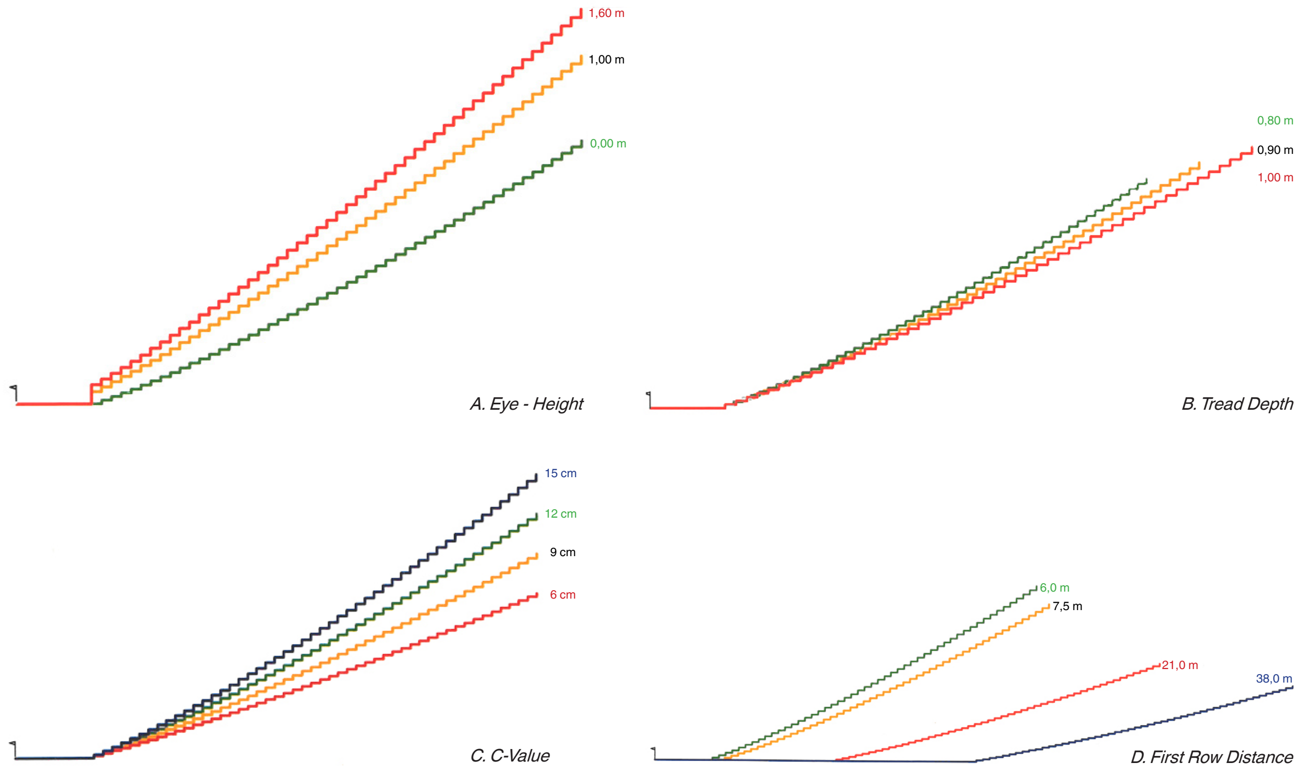


Figure 15. Relation between stand Inclination and grandstand parameters (Source: Nixdorf, 2009)

2.3.3 Polygonal Transformation

Once the riser height is determined, the sightline construction is completed, and the grandstand geometry is finally designed. However, the sightline obtained follows a parabolic curve while rising. Thus, the construction costs of the terrace will increase dramatically. Indeed, a continuous change of the riser height value implies a higher number of prefabricated elements (John et al., 2013).

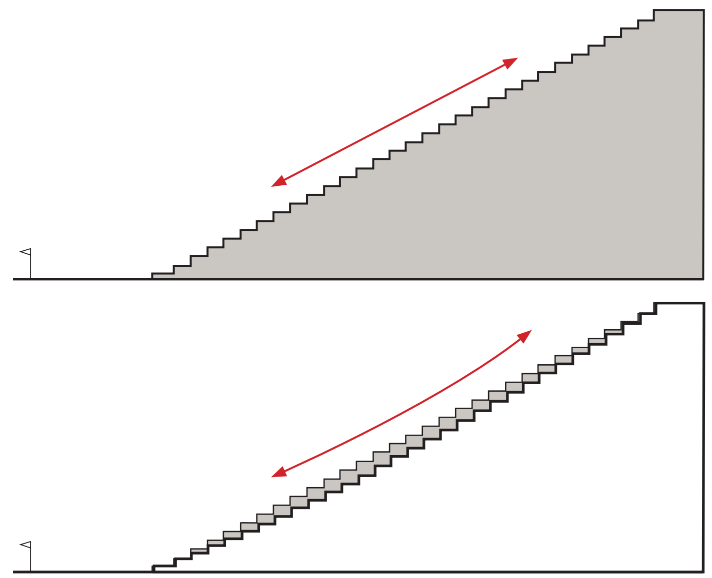


Figure 16. Comparison between a curved stand (black) and the same terrace polygonally transformed (grey) (Reference: Nixdorf, 2009)

Therefore, designers usually perform a polygonal transformation on the preliminary stand in order to reduce the number of prefabricated steps. The process consists in the approximation of the curved sightline into linear risers. Usually, this procedure is performed using the triple steps method, which consists in uniting three risers into one single component. Likewise, the gangways are polygonally transformed as well, while considering the limits of 20 cm as the maximum allowed rise and 25 cm as the maximum allowed depth. In general, the triple steps method is applied since reduces the number of joints of the construction by 1/3, but without affecting the sightline quality of the stadium (Nixdorf, 2009). Indeed, the variation is particularly small and, if it exceeds the tolerance of ±5 mm, the missing height is compensated by adjusting the height of the seats.

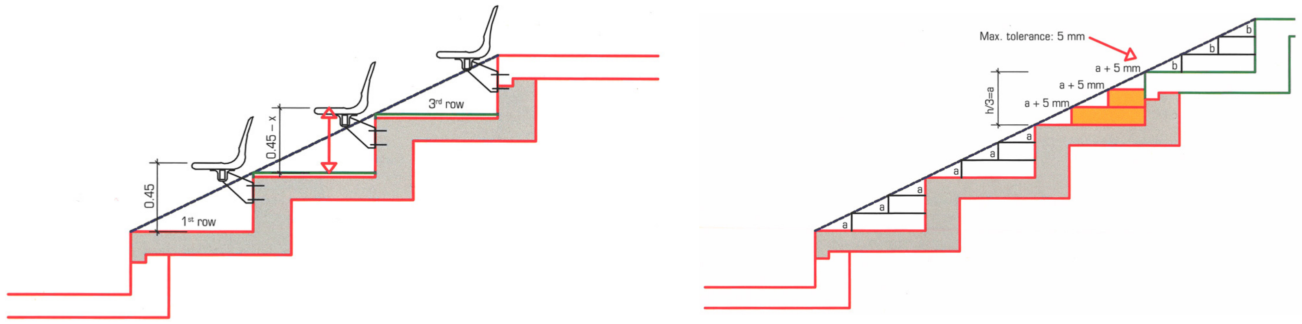


Figure 17. Polygonal Transformation of grandstand (left) and gangways steps (right) (Source: Nixdorf, 2009)

As an alternative, the grandstands are constructed with a constant value for the riser height, which facilitate the prefabrication of the elements. However, this solution affects the viewing quality of the grandstand. Indeed, the C-value decreases at every added row as can be deducted from the formula:

$$C = \frac{(R_h \times D) - (A \times B)}{(D + B)} \qquad [5]$$

For this reason, the grandstand is interrupted when the C-value reaches a minimum value and a new stand is started with a new inclination.

2.3.4 Evaluation of Existing Grandstand

The previous paragraphs described in depth the grandstand design process and the fundamental parameters that governs the geometry. However, in case the viewing quality of a terrace have to be optimized, it is necessary to understand how to evaluate the existing design. Nixdorf (2009) provides useful information, by which the guidelines to perform an analysis can be produced. As a rule, the process consists mainly in reconstructing the sightline curve by utilizing the riser height of the existing terrace. Indeed, after measuring the parameters A, B, D and Rh, the C-value can be calculated with the formula:

$$C = \frac{(R_h \times D) - (A \times B)}{(D + B)} \qquad [5]$$

In general, the approach is different based on the layout typology of the stadium. On the one hand, those configurations that foresees the stands parallel to the pitch can be analyzed exclusively on the central-axis area. In fact, the C-value will remain constant along the entire length of the terraces. On the other hand, in the case of an expanded or a circular layout, the central-axis area of the stands with the furthest distance should be evaluated first. In fact, the sightline elevation reduces towards the edges of the stands. Hence, this approach should be maintained while evaluating the corner areas. Indeed, the terraces get closer to the pitch due to the layout configuration causing a decrement of the C-value. Nixdorf (2009) defines this problem as the corner conflict, advising to apply a minimum value of 9 cm as C-value in order to maintain a good sightline quality.

To conclude, the central-axis area of the longitudinal and transversal stands should be analyzed first, starting always from the terraces with the maximum first row distance. Afterwards, the evaluation should proceed towards the edges of the stands. Lastly, the central-axis area of the corners is evaluated, and the analysis is carried on towards the borders.

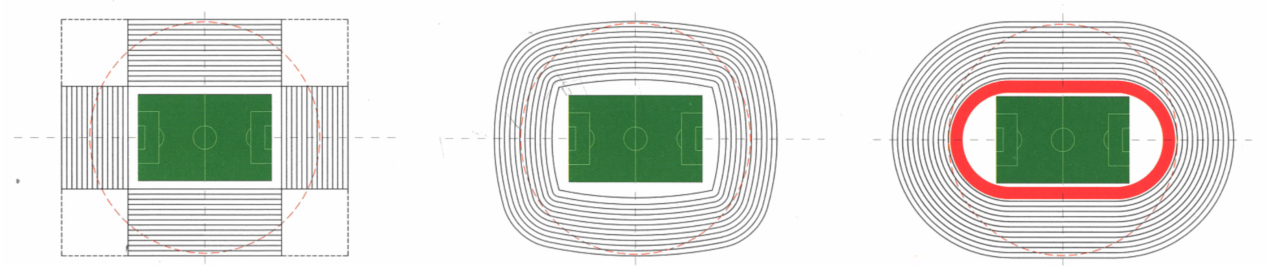


Figure 18. Examples of different layout configurations that foresees different approaches for the evaluation of the C-value) (Source: Nixdorf, 2009)

2.4 Roof Structure

Roof structure in stadium design can be defined as a system that provides cover to the spectators sitting in the stands and, in certain cases based on the activity, that encloses the whole arena. The development of a stadium roof is decisive in determining the appearance, the overall cost of the stadium and the success of the whole design (Nixdorf, 2009). Even though in various countries not covered or partially covered stadiums are present, the implementation of roofs in stadia design is becoming a need. Indeed, spectators request a covering system in order to protect themselves from the weather conditions. Moreover, the combination of the roof structure and the grandstand can enhance the atmosphere and therefore the involvement of supporters in the stadium.

In general, designing a roof for a large-scale building such as a stadium is an extremely complex task, since it is necessary to solve problematics ranging from climate to structural design. In relation to the objective of the thesis, the main focus should be kept on the viewing quality, the unobstructed sight of the pitch and the complete/moderate protection from the weather conditions. All these criteria are governed by the dimensions of the stands, the inclination of the roof and the presence of load-bearing elements between the grandstand and the pitch. Therefore, the review performed on the structural roof typologies aims to furnish a general overview on the available possibilities, the overall advantages and disadvantages and the main features on which is necessary to focus.

Hence, this paragraph defines the systematic families in which the structures can be divided. This organization in based on how the forces are redirected to the ground and the mechanism that affects the flow of forces. Thus, the structures are divided into linear and spatial systems and few types of roofs for each category are explained. Lastly, an overview of the most utilized structural systems is provided and the advantages and disadvantages of each of them is presented. Lastly, it must be said that the general overview is crucial to determine the design boundaries of the digital workflow, intended as the number of feasible structural systems to be explored.

2.4.1 Families of Structural Systems

In building design, the structure has the purpose of redirecting the dead-weight of the facility and the external loads acting on it to the ground. Hence, the structural system can be described as the geometrical organization of the load-bearing elements in order to transfer the forces to the ground and maintain the equilibrium of the building. Overall, structures can be divided into four categories based on the mechanism of force redistribution and the main aspect that affects it. Engel et al. (1997) provides an overview of the systematic families and their mechanics:

- **Form-Active System.** Form-active structures can be defined as the systems that arrange their form to the compression or tension forces acting on them. Hence, flexible materials can be connected to supports and utilized to span large distances. The overall advantage of this systematic family is that the flow of forces creates exclusively normal stress into the load-bearing elements. Therefore, their dimensions are reduced, resulting in the most economical structure typology. Form-active systems are cable structures, tent structures, pneumatic structures and arch structures. The main difference between them relies on the principal structural feature, such as the catenary, the thrust line and the circle. Thus, these are the elements that necessarily need to be analyzed and optimized while designing this structural system.

  On the one hand, the catenary is the ideal shape that a cable assumes under its own weight when it is sustained at its ends. Therefore, it corresponds to the path of the forces towards the supports constituting a suspension cable. A structural system based on a catenary curve transfers the loads by tension forces alone, which are then distributed to the ground through the supports. This principle applies to cable, tent and pneumatic structures. Since these systems are flexible in terms of form, altering the number or the position of the supports will automatically modify the shape of the structure.

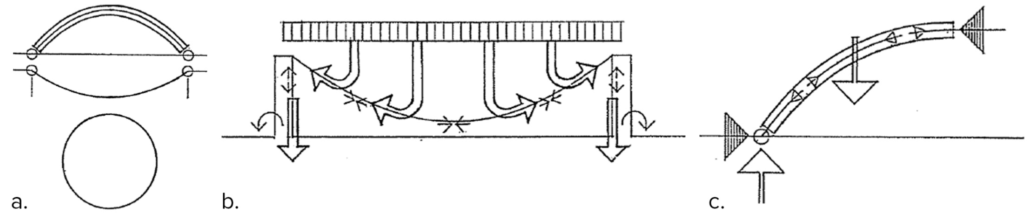


Figure 19. Form-active principle (a) and redistribution of forces (b, c) (Source: Engel et al., 1997)

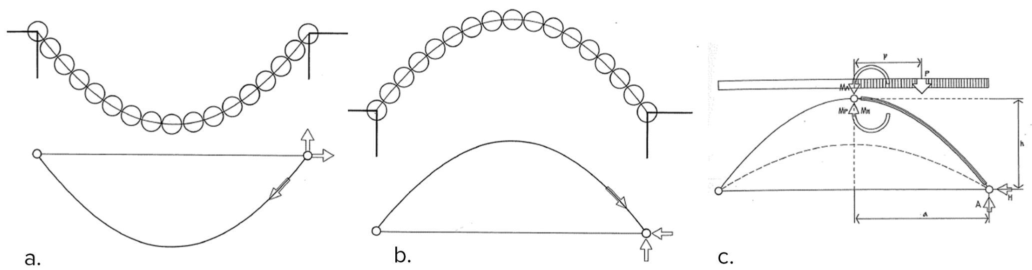


Figure 20. Suspension cable (a), arch (b) and equilibrium(c) (Source: Engel et al., 1997)

On the other hand, the thrust line is the path that the forces follow towards the supports. Ultimately, the thrust line can be obtained by reversing a catenary curve, producing in this way a funicular arch. Hence, a structural system based on a funicular arch transfers the loads by compression forces alone, which are then distributed to the ground through the supports following the thrust line. This principle applies to arch structures. However, unlike the suspension cable, the arch system cannot modify its form freely if the supports are altered in number or position.

- **Vector-Active System.** Vector-active structures can be defined as the systems that redistribute the forces via solid linear elements, identifiable as vectors. Hence, the number and the position of these components compose the geometry and therefore affects the performance of the structure. Due to their reduced dimensions, the members transmit the forces along their length, resulting in normal compression or tension stresses. However, the forces and the loads do not necessarily have to be redirected along one axis or plane, but also in two or three-dimensional directions. Thus, trusses are usually the load-bearing utilized in this structural system, which can result in flat, curved or space trusses.

  In general, the number of vectors and the height of the truss influence the performance of the structure and the redistribution of the forces. Indeed, a higher number of panels or a higher profile increase the load-bearing capacity and allows to cover longer spans. Concerning space structures, the increment of the number of truss elements or directional axis improve the load-bearing capacity of the system.

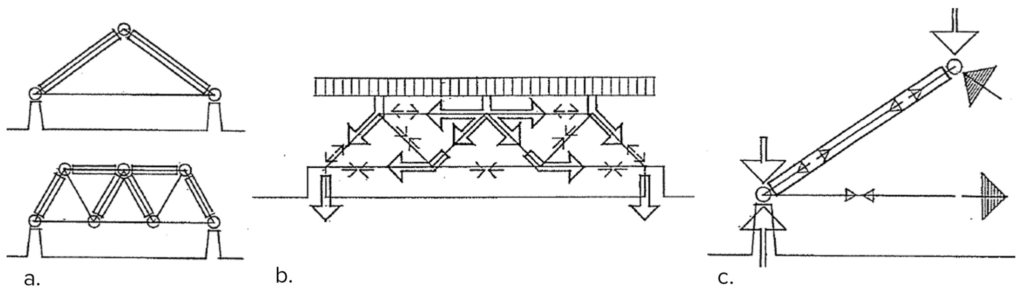


Figure 21. Vector-active Principle (a) and redistribution of forces (b,c) (Source: Engel et al., 1997)

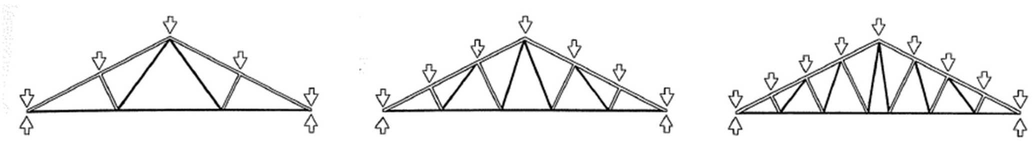


Figure 22. Comparison of Vector-active structures in relation to the number of vectors (Source: Engel et al., 1997)

- **Section-Active structure.** Section-active structures can be defined as the systems that redistribute the forces via solid linear elements through both normal forces and bending. Indeed, these members can withstand vertical stresses, which produces bending stresses. Hence, the geometry and the dimensions of the cross-section affect the load-bearing capacity and the achievable span between the supports. In general, the load-bearing mechanism of section-active systems is obtained by resistance to bending, which causes shear, compressive and tension stresses within the section of the load-bearing elements. Thus, these elements are usually beams, frames or plates, depending on the directions the forces are transferred.

  In general, the external forces cause the load-bearing element to curve along its length. Hence, the bottom part of the member is tensioned, while the upper part results to be compressed. Moreover, the vertical fibers shifts vertically causing shear stress into the section. Therefore, an internal bending moment is created, which counterbalances the rotation moment produced by the external forces acting on the load-bearing element. Thus, equilibrium is achieved.

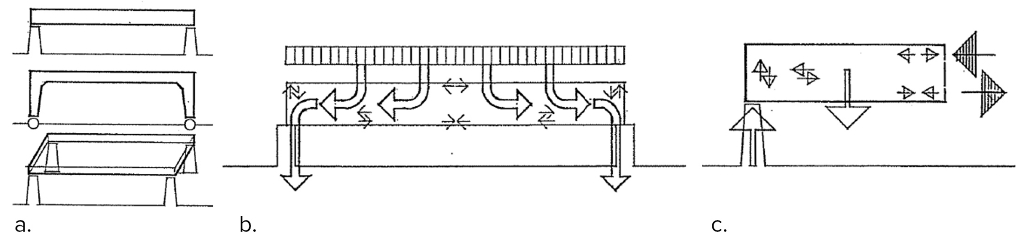


Figure 23. Section-active structures principles (a) and redistribution of forces (b,c) (Source: Engel et al., 1997)

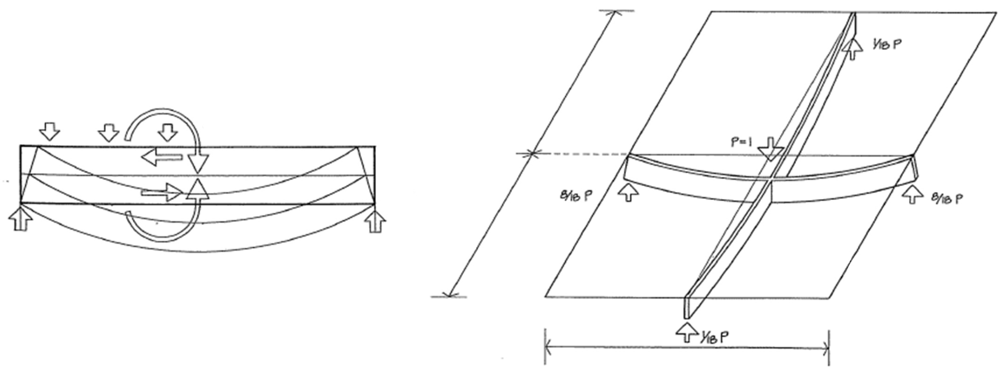


Figure 24. Comparison between a single beam (left) and two-directional beams (right) (Source: Engel et al., 1997)

- **Surface-Active structures.** Surface-active structures can be defined as systems of planes that redistribute in two directions the forces through normal and shear stresses. Hence, the shape of the plane influences the behavior of this typology of structures. In general, surface-active structures perform better in redistributing forces tangential (plates) to the plane and poorly when the force is perpendicular (slabs). Since the shape of the plane determines the performance of the structure and the flow of forces, surface-active structures follow a principle similar to vector-active structures.

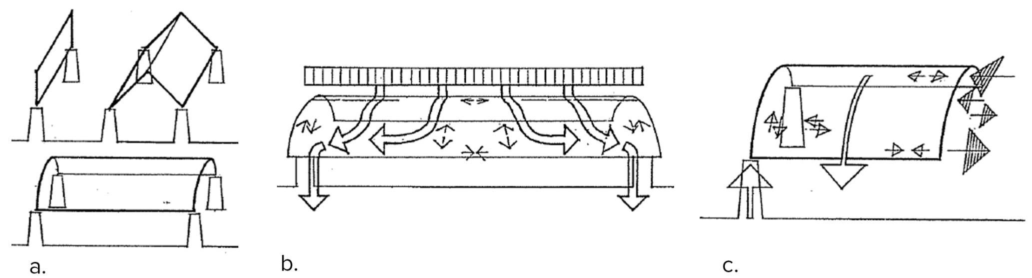


Figure 25. Surface-active structures principles (a) and redistribution of forces (b,c) (Source: Engel et al., 1997)

2.4.1 Families of Stadium Roof Systems

Once the structural families have been discussed, roof stadium typologies can be classified. Nixdorf (2009) divides stadiums roofs systems into primary and secondary structures. Indeed, the first consists in the load-bearing framework that carries the external loads and transfer them to the ground, while the second constitutes the covering system that provides cover to the stands from the weather conditions. Three main systems can be identified.

- **Radial Systems.** The load-bearing structure of these systems is constituted by radial members that spans from the back of the grandstand towards the pitch, covering in this way the entire terraces. Three main types can be distinguished, which are the cantilever systems (type A), the supported cantilever or post and beam structure (type B) and the tie-back or cable restrained cantilever systems (type C).

  In general, the large spans covered by these structures create a large moment in the support, which requires a high height of the load-bearing element to obtain the equilibrium of the forces in the system. If this solution is not achievable, type B or C are applied. Overall, types A and B can be considered as section-active or vector-active systems if beams or two/three dimensional trusses are utilized as load-bearing elements. Concerning type C, tie-back falls within vector-active systems, while cable restrains falls in form-active.

- **Axial Systems.** The load-bearing structure of these systems is constituted by axial members that spans the entire length of the stands. Structural typologies such as goal post structures are part of this category, as well as the catenary cable system. The main characteristic of this typology of systems consists in laying the load-bearing elements parallel to the pitch. Overall, these structures are mainly constituted by vector-active and form-active systems when trusses and cables are implemented.

- **Spatial Systems.** These systems have to be divided into simulated spatial systems and true spatial systems. Indeed, the first group consists of axial typologies laid down in two directions. However, only the visual effect is of a spatial system, while the static principles are identical to the axial systems. In fact, spatial expansions to enhance load-bearing goals is required to define a true spatial system.

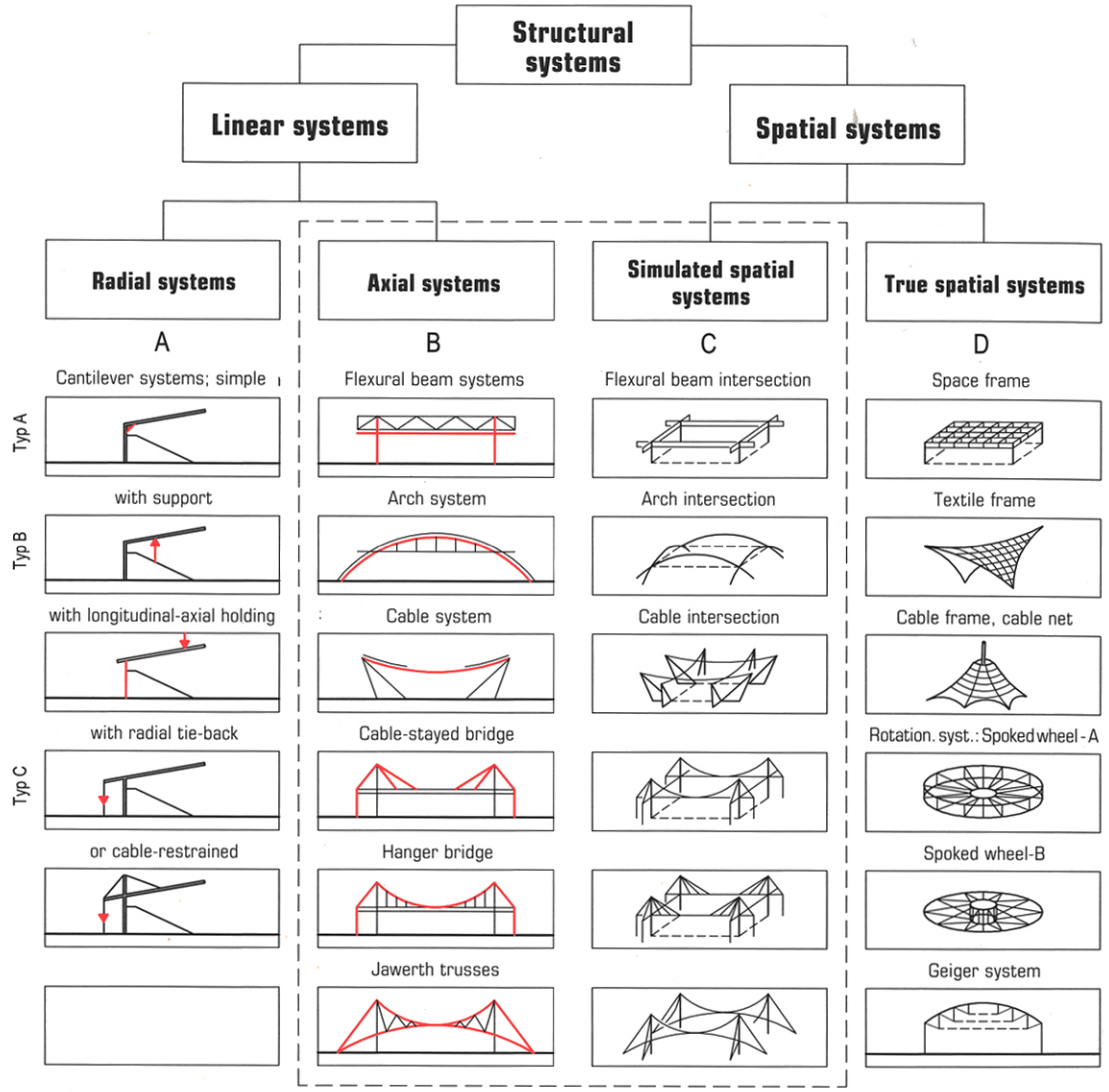


Figure 26. Overview of Structural systems and families (Source: Nixdorf, 2009)

2.4.3 Common Roof Typologies

John et al. (2013) provides a general overview of various roof typologies that are usually implemented in stadium design. In general, all the possibilities presented are dependent on certain types of layout configuration of the building.

- **Post and Beam Structures.** This roof typology is constituted by a series of pillars that sustain the roof, which is composed of sequences of trusses or beams. In general, this structural system is extremely economical since it accounts only from 2% to 4% of the total cost of the stadium. However, the viewing quality from the stands is affected by the presence of the posts. Indeed, the sightline results obstructed by the structural elements. Thus, the only solution to partially overcome the problem is to position the columns as far back as possible, while reducing the price of the affected seats. Hence, this option is not advised to be applied, expect if an existing structure does not allow any other possibility.

- **Advantages:**
  Economic structure

- **Disadvantages:**
  Obstructed view

- **Required Elements:**
  Supports along the edge of the upper tier
  Supports along the pitch on the grandstands
  Multiple beams or trusses spanning between the vertical supports

- **Goal post structure.** This roof typology is similar to the goal and post structure, but in this case the columns are located at the edges of the stand, while the load is carried entirely by one single beam or truss. Even though this structure provides a complete unobstructed view of the pitch from the stands, the single girder must be monitored and maintained constantly to prevent any failure. Thus, the advised ratio between depth and length is of 1/12. Moreover, it is mostly suitable for polygonal layouts, but it is more suitable for independent stands configurations. Overall, the cost results to be moderate.

- **Advantages:**
  Moderate cost
  Large spans are achievable
  Unobstructed view

- **Disadvantages:**
  Maintenance can be problematic
  Restricted application base on the layout

- **Required Elements:**
  Two main support at the ends of the stand (columns)
  One girder spanning above or below the covering

- **Cantilever Structures.** This roof typology consists in supporting the roof from the back of the last tier of stands, while the other edge results free from anchor points. On the one hand, the structure provides the spectators with a complete unobstructed view of the pitch and can cover spans bigger than 45 m. On the other hand, the wind load can cause uplifting, resulting in a heavy structure to overcome the problem. Moreover, over a certain span, the cost becomes prohibitive. Overall, this typology is feasible for all layout configurations, even though circular and oval geometries require a higher number of supports.

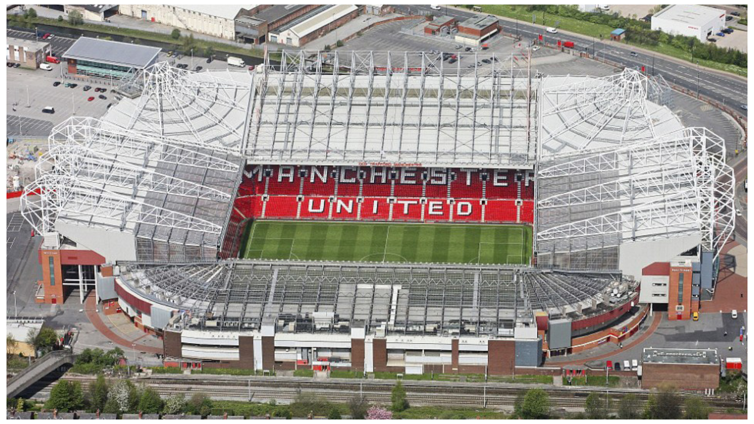


Figure 27. Aerial View of the Old Trafford of Manchester (UK) and its cantilever roof stucture (Source: Dailymail.co.uk, 2016)

- **Advantages:**
  Unobstructed view
  Large spans are achievable
  No restrictions based on the layout

- **Disadvantages:**
  High overall cost
  Susceptible to uplifting effect

- **Required Elements:**
Multiple support along the edge of the upper tier
External support (tie-back)
Multiple beams or trusses spanning from the supports towards the pitch

- **Concrete Shell Structure.** This roof typology consists of a thin concrete surface that distributes the load in multiple directions through compression forces. In general, the effectiveness of the structure depends on the geometric form and the thickness can be extremely reduced. Large spans are achievable, as well as an unobstructed view of the pitch is provided. However, this structural typology encloses completely the arena and it requires an exhaustive design.

- **Advantages:**
Unobstructed view
Large spans are achievable

- **Disadvantages:**
High cost
Extensive design is needed
Limitations to continuous bowl layouts

- **Required Elements:**
Continuous support along the edge of the upper tier
One single surface as load-bearing element

- **Compression/Tension ring.** This roof typology consists of two rings, an inner one working in tension and an outer one working in compression. Thus, radial elements connect the two hoops to maintain the circular shape and transfer the loads between them. This structural system follows the spoked-wheel principle. Hence, no supports are present in the stands, providing a complete unobstructed view of the pitch. Moreover, large spans are achievable, and it is congenial to be implemented in existing stadiums. However, the force distribution requires a circular layout and, depending on the curvature, it can be applied also to elliptical layouts.

- **Advantages:**
Unobstructed view
Large spans are achievable
Suitable for existing stadiums

- **Disadvantages:**
Restricted application based on the layout

- **Required Elements:**
Perimetral support along the upper tier (truss or girder)
Radial beams or trusses to connect the rings

- **Tension structures.** This roof typology consists of elements that transfer the loads merely through tension. Therefore, an advanced design is necessary to avoid unwanted tension within the structural members. Mainly, three sub-typologies are typically utilized in stadium design.

  The catenary cable system, which consists of multiple cables that follow a catenary curve, which are sustained by a single or multiple arches. The **cable-net structure**, which comprises a steel cable web frame arranged in three-dimensions. These two typologies usually necessitate pre or post-tensioning of the cables to perform sufficiently. Moreover, the structural system is separated from the covering, which can be realized with plastic or fabrics. Lastly, the **membrane structures** constitute both the load-bearing system and the covering. The cost and the life-span vary depending on the utilized fabric. Moreover, fire hazards are an issue, as well as maintenance that is needed to prevent the membrane to sag.

- **Advantages:**
No restriction based on the layout

- **Disadvantages:**
Intensive maintenance is needed
Fire hazard is an issue
Extensive design

- **Required Elements:**
Punctual supports on the upper tier edge
External supports
Continuous support along the upper tier edge (membrane)

- **Air-supported structure.** Through the pressure produced by electric fans, a plastic membrane is sustained in order to enclose the entire arena. The structure is constituted by the sheet of material itself or in combination with load-bearing walls. Even though the cost of construction is low, this solution is highly inefficient. Indeed, it is not sustainable since the electric fans have to be powered constantly and the life-span of the system is particularly short.

- **Advantages:**
No restriction based on the layout
Economic structure

- **Disadvantages:**
Short life-span
Vulnerable to damage
Not sustainable

- **Required Elements:**
Load-bearing walls
Cables
Continuous perimetral support

- **Space Frames.** This roof typology consists of a matrix of three-dimensional elements. Hence, the forces are redistributed in two directions, thus limiting the application in stadiums with a rectangular layout. John et al. (2013) indicate a ratio of 1.5:1 for the matrix to achieve an efficient design of the structure. On the one hand, space frames are suitable for spanning large distances. However, the layout application is restricted. On the other hand, this typology of roof structure can result to be expensive since it requires a high amount of material, which is usually steel). Lastly, these types of structures are mostly utilized to cover the entire stadia but may be applied only above the stands. Although, other typologies may result more efficient.

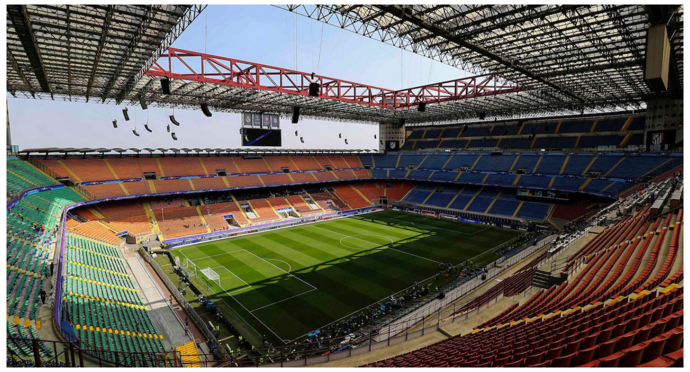


Figure 28. San Siro Stadium in Milan (Italy) and its space frame roof stucture (Source: buildingcue.it, 2018)

- **Advantages:**
Large spans are achievable
Unobstructed view

- **Disadvantages:**
Efficiency is dependent on layout
Efficiency is dependent on 1.5:1 ratio of the matrix
High overall cost

- **Required Elements:**
Continuous punctual or perimetral support
Two-directional load-bearing elements are needed (trusses or beams)

03 | COMPUTATIONAL OPTIMIZATION AND DESIGN EXPLORATION

COMPUTATIONAL OPTIMIZATION AND DESIGN EXPLORATION

As previously mentioned, stadium design is a process that necessitates the analysis of various aspects related to both the architectural and engineering world, together with several themes and high standards. Due to these features and the close interrelation among its parts, a computational method can be identified as the most suitable process to develop an efficient design of a building typology such as stadia, or to enhance the variation of an existing one (Patz et al., 2016). Indeed, computational methods can be utilized to quickly evaluate more proficient designs, to explore suitable options and to optimize the convenient solutions, avoiding investing time in less efficient concepts (Citerne, 2019).

The development of a computational method for stadium renovation falls within the discipline of computational design. Indeed, computational design can be defined as:

> *"Computational tools, methods and techniques, which enable designers to formulate their design needs, requirements and rules, and translate them into algorithms that generate designs for buildings, a design approach which exceeds the use of computation as a representational or drafting tool." (Sariyildiz, 2012)*

Thus, the main advantage of the application of computational design in architecture consists in the possibility to produce and analyze the performances of multiple design concepts. To do so, the elements that compose a building typology have to be hierarchized to determine the dependencies that exist between them. Hence, the parameters that control the elements have to be individuated, as well as the criteria to evaluate the performances. Lastly, the generated elements can be optimized with computational tools and algorithms with the objective of improving the performances (Sariyildiz, 2012). Overall, the steps of a computational process of this kind, usually named performative computational architecture (PCA) can be divided into three main phases: form generation, performance assessment and optimization (Ekici et al., 2018).

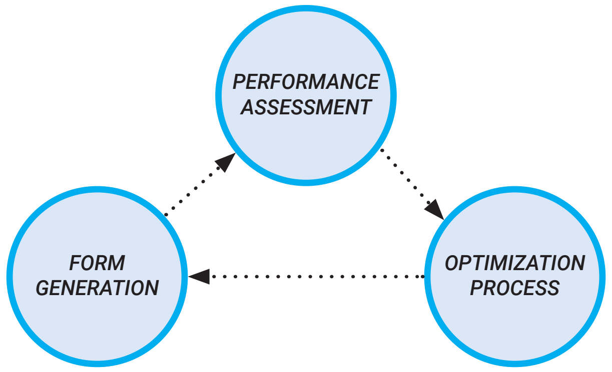


Figure 29. Scheme of the three main phases of PCA (Reference: Ekici et al., 2018)

3.1 Form Generation

The first phase that constitutes a computational method is the form generation. The output of the form generation process is known with the term of parametric model. Parametric modelling can be defined as:

> *"A process of formulating a geometrical representation of a design with parameterized components and attributes" (Pan et al., 2019)*

Indeed, a parametric model consists of a group of objects correlated with each other, which are governed by multiple parameters. Thus, the alteration of the parameters can produce different conformations of the objects, which determine the design space of the parametric model, also known as the solution space (Pan et al., 2019). Rodriguez Garcia (2018) indicates the typologies of parameters that are commonly implemented to control the elements of the parametric model. Said parameters are range of values (continuous parameters), precise values (discrete parameters) or toggles to provide positive or negative responses (binary parameters). The parameters implemented in the model can also be distinguished in independent and dependent parameters. Indeed, the second are defined by the interpolation of the first, therefore relying on them.

The design space constitutes the boundaries within which the design alternatives are explored, and the simulations are performed. Therefore, it constitutes the limits for which the output of the assessment of the performances and the explored alternatives can be considered reliable. Thus, the complexity of the parametric model limits the measurable criteria to assess the performances to analyze and therefore the optimization and variety of the design alternatives (Turrin et al., 2011). Moreover, further limitations can be dependent on the utilized tools to produce the parametric model.

Turrin et al. (2011) explains that a parametric model can be utilized to design multiple objects and to determine how they are correlated together. Hence, a hierarchy of the objects have to be determined before the realization of the parametric model to define the dependencies between them. Thus, on the one hand independent parameters are implemented to define the geometry of the designed objects. On the other hand, the hierarchy of the objects is expressed by the dependent parameters. In this way, the correlation between parameters and objects is established and the alteration of the independent parameters allows for the creation of several alternative geometries of the objects.

3.1.1 Parametric model of a stadium

Computational methods and parametric modelling are usually implemented in the design process of stadiums to generate design alternatives based on multiple measurable criteria, which are related to aspects such as structural design and viewing quality evaluation (Patz et al., 2016). Although, the objects and the complexity of the parametric model define the design space within which the performance assessment and the optimization process can be performed.

Considering the objective of the envisioned method, it is notable that various parametric models and tools have been developed to design complex roof structures and seating bowls of stadium. In this context, Hudson (2010) produced a parametric model for the Aviva stadium based on the stadium bowl generator (SBM) developed by Populous. The generated model included a bowl layout, roof structure in relation with the constraints of an existing stadium building. Miller (2009) describes the generation of multiple stadium bowl configurations in relation to a single shell structural typology by using an in-house developed bowl generator realized in Rhinoceros and Grasshopper. Similarly, Pan et al. (2019) realized a parametric model for a multi-purpose arena with the same tools to include various conventional and unconventional bowl configurations and three typologies of space frame structures for the roof. Lastly, Yang et al. (2018) developed a parametric model of an indoor sports building with Rhinoceros and Grasshopper. The produced model based on the preliminary phase of a selected case study, included a single layout configuration of the grandstand of the arena, a single typology of roof structure and the envelope of the building. Joseph et al. (2015) developed a single seating bowl configuration in Rhinoceros and Grasshopper to evaluate the viewing quality of the grandstand on a micro-scale level. Patz et al. (2016) developed a parametric model within Rhino and Grasshopper consisting in various stadium bowl layouts to implement virtual reality evaluation of the viewing quality of the grandstand.

In general, Rhinoceros and its plug-in Grasshopper are mainly utilized to produce parametric models of stadium. Indeed, its user-friendly interface facilitates the exploration of different complex geometries and it can be integrated with multiple plug-ins for the assessment of various performances related to the built environment (Yang et al., 2018). Multiple plug-ins towards stadium design generations, such as TORO or Bowlbuilder have been developed recently. These tools can be utilized to produce multiple layout configurations of the seating bowl for multiple activities and to evaluate the viewing quality of the grandstand. However, considering that roof structures can be neither realized nor evaluated jointly with the viewing quality with these tools, the possibility to relate them with Grasshopper should be considered before including them in the computational method.

Overall, considering the objective of this master thesis, emphasis should be given to the components of the stadium towards the performance assessment of the viewing quality of the grandstand and the structural performance of the roof. Thus, the seating bowl, which comprises the playing area and the stands, and the roof structure of the stadium should be implemented in the parametric model. Moreover, in order to enhance the design space, multiple layout configurations of the bowl and different structural roof typologies should be considered. Lastly, Rhinoceros and Grasshopper, considered its versatility towards tools for the evaluation of building performances and its intuitive interface, will be implemented in the computational method as the standard computational environment.

3.1.2 Example of parametric model of a stadium

Pan et al. (2019) describe in detail the realization of a parametric model of a stadium to perform a multi-objective optimization based on a framework of interdisciplinary assessment criteria. More specifically, the focus is on multi-purpose arenas, the performance assessment of the viewing quality of the spectators, the structure of the building and the acoustics and the multi-objective optimization with post-processing tools. In this case, the parametric model is produced to allow for flexibility of the stadium and to provide a broader solution space. Thus, multiple layout configurations and three long-span structural roofs have been implemented in the model.

Thus, the complexity of the parametric model and the boundaries of the design space are determined in this phase. The parametric model was realized in the parametric environment of Rhinoceros and Grasshopper in four steps described as follows:

1. The bowl and the playing area are designed. In detail, the dimensions of the playing area are defined based on the activity to be observed, while the geometry of the bowl is determined by the sightline construction method (see section 2.3.2).

2. A variable layout of the arena is defined and utilized to produce the final bowl. In detail, a curve is utilized to define the configuration of the arena. To allow flexibility of the design space, the curve is dependent on control points, which can be altered by modifying discrete and continuous parameters. Thus, their alterations enhance the creation of multiple configurations of the seating bowl. Lastly, the dependency of the number of seats upon the height of the bowl is determined.

3. The roof structure is defined and inserted in the parametric model. Hence, control points are located on the perimeter of the seating bowl to govern the quadrangular grids representing the roof structure. Limits upon the heights of the control points are set, while their position is left free to vary along the perimeter of the bowl. Thus, the boundary of the roof structure is established. An upper and lower single-layer grids are designed to produce multiple geometries of the roof. In detail, various parameters controlling the spacing of the grids, the height upon the playing area and the inclination of the curves in x and y directions are implemented. Furthermore, curves or polylines controlled with two discrete parameters are utilized as grid components in both x and y directions.

4. The three structural typologies are implemented in the parametric model by defining topological patterns. Firstly, quadrangular pattern is utilized to generate grid-shell geometries, while the lower grid produced in step 3 is used as the axes for the load-bearing elements. Secondly, two-layer grids controlled by two discrete parameters are implemented to generate space frame and truss-beam structures. Hence, an inverted triangular shape is determined as the cross-section of the truss-beams and the diagonal members connecting the main members are realized. Lastly, the materials and the cross-section shape of the structural members are defined. Thus, three steel types are utilized for all the structural elements and systems, while a hollow circle is chosen as the cross-section form. The shape is controlled with discrete parameters, while providing a range to limit the variety.

The final result is a parametric model with an extensive design space to include multiple configurations of the bowl and the roof. Thus, the objective of realizing a parametric model for a multi-purpose arena for the performance assessment of the viewing quality of the spectators, the structure of the building and the acoustics for a multi-objective optimization is fulfilled.

3.2 Performance Assessment

The second phase that constitutes a computational method is the performance assessment. This process can be described as the evaluation of the design to determine to what extent it fulfills the set standards for one or multiple subjects (Ekici et al., 2018). On the one hand, these requirements can differ based on the discipline of the assessment, as for example architectural design, climate design, facade design or structural design. On the other hand, the standards may differ according to the aspects to be evaluated within the discipline. As an example, within the discipline of structural design, the evaluation can be performed on aspects as for example the stresses of the structure, its deformation or its weight. In general, the term performance can be described as:

> *"The manner in which or the efficiency with which something reacts or fulfils its intended purpose. Dealing with performance leads therefore to consider both the identification of the intended purposes of the subject and the capacity the subject has to accomplish such expected tasks" - Stein (Turrin, 2014)*

Ekici et al. (2018) state that the process of performance assessment of multiple disciplines can be implemented in the architectural design process to predict and evaluate numerically their efficiency. This is due to the progress made in developing computational tools and in the overall digital industry. Moreover, this process can be integrated in every design phase of a project. However, it should be necessary to exploit the advantages of this possibility towards the early conceptual phase of the design process, which influences greatly the overall efficiency of the project. Indeed, a computational process oriented towards the design performances of a building can increase the amount of disciplines and aspects to be evaluated. Furthermore, the assessment can be performed on the basis of measurable evaluation criteria (Turrin et al., 2011).

Thus, the complexity of the computational model, the accuracy of the geometries and the degree of cross-disciplinarily defining the design space have a great influence on the performance assessment process (Eciki et al., 2018).

Therefore, on the one hand, the development of a computational method should give particular attention to the initial form-generation in terms of parameters, geometries and hierarchy of the objects. On the other hand, the form-generation should be developed towards the performance assessment in terms of disciplines, their aspects and the range of measurable and non-measurable criteria (Turrin et al., 2011). Concerning the objective of this thesis, particular focus should be kept on the viewing quality performance of the grandstand and the structural performance of the roof. Indeed, it is necessary to understand which may be the criteria for the evaluation and how they may influence each other. Concerning this aspect, Pan et al. (2019) states that the relationship between the roof structure and the aspects related to stadiums have not been investigated deeply, which causes a lack of exhaustive assessment criteria.

3.2.1 Viewing Quality Performance Assessment

In general, viewing quality can be described as the comfortness of the spectator in following the activity held in the stadium. As explained in chapter 2, multiple factors can influence the viewing quality of the spectators seating in the grandstand. Examples of these factors are the viewing distance, the sightline or C-value and the unobstructed view. In addition to these, the field of view of the playing area and the horizontal/vertical viewing angles can be considered factors as well. In this regard, Nixdorf (2009) provides an overview of the recommended values in relation to the proximity of the spectator to the pitch.

In general, the performance assessment of the viewing quality of stadiums have been the focus of multiple papers, articles and reports. In these regards, Pan et al. (2019) evaluated the viewing quality of the spectators of a multi-purpose stadium based on five indicators, such as the average and maximum viewing distance, the ratio of sightline obstruction, the ratio of seats for stage performance and the horizontal viewing angle. The performance was assessed within the computational environment of Grasshopper. Joseph et al. (2015) evaluated the viewing quality on a microscale utilizing the ratio of obstructed view as indicator. The parametric environment of Grasshopper was used in relation to its plug-in Horster to create the point-of-view of each seat. Patz et al. (2016) evaluated the viewing quality of multiple layout configurations of stadiums using multiple indicators, such as field of view, horizontal/vertical viewing angles, C-value, proximity to sideline and proximity to the center point of the playing area.

Figure 30. Examples of performance indicators for the viewing quality assessment (Source: Patz et al., 2016)

Concerning the objective of this master thesis, indicators such as the field of view, the horizontal/vertical angles and the C-value seems promising. Considering the relationship between the structural performance of the roof and the viewing quality of the grandstand of an existing stadium, further indicators might be identified for implementation. As for example, these indicators can be the ratio of obstructed view produced by the roof, the vertical distance between the lowest point of the roof structure and the highest sightline (which can be defined as vertical roof structure distance, VRSD) or the clear vertical distance between the eye-point height of the spectator in the last row and the playing area (which can be defined as the clear vertical distance, CVD). Another option is to consider the relation among the grandtsands and the roof structure as constraint of the existing stadium. As an example, an existing roof that spans the entire length of the stands must cover the whole grandstands after the optimization is performed. Hence, the quality of the two components will not be affected after the optimization process. This aspect will have to be checked along the design phase of the computational method.

3.2.2 Structural performance assessment

As explained in section 2.4, the roof structure of a stadium can be distinguished in load-bearing framework and coverings. Respectively, the purpose of the first is to transfer the dead-weight and the external loads to the ground, while the second serves mainly to provide protection from the weather conditions to the spectators (Nixdorf, 2009). In general, the performance assessment of the roof structure of a stadium is performed to evaluate criteria such as the weight, the embodied energy or the strain energy.

Meanwhile, constraints such as for example the stresses within the structure, the deformation, the deflection, the Ultimate Limit State (ULS) and the Service Limit State (SLS) are estimated to ensure structural safety. Mainly, these aspects are part of the performance assessment since roof structures influence greatly the overall cost of the design (Nixdorf, 2009; John et al., 2013).

The performance assessment of the roof structure of stadiums have been the focus of multiple papers, articles and reports. Yang et al. (2018) evaluated the ULS and SLS of a roof structure of an indoor sports arena using a plug-in of Grasshopper, Karamba. Pan et al. (2019) evaluated the dead-weight and the strain energy of the roof structure for a multi-purpose stadium using Karamba and Grasshopper. The roof structure of the Emirates Stadium (UK) was analyzed to evaluate the buckling capacity of the load-bearing framework (Shepherd, 2015). Göppert et al. (2007) describe the structural analysis of the convertible roof of the New Commerzbank Arena in Frankfurt, Germany. The spoked wheel structure was analyzed to evaluate the stresses and the deflection of the load-bearing elements to ensure security. Lastly, a buckling check was performed on the overall structure.

Concerning the objective of this thesis, the structural performance assessment should evaluate aspects as for example the stresses, the deformation, the deflection, ULS or SLS to ensure structural safety. Moreover, indicators such as for example the weight, the volume, the embodied energy or the strain energy should be checked to assess the performance of the roof structure. Considering the computational tools, Karamba seems to constitute the most suitable plug-in to perform the structural analysis of the stadium roof structure.

3.3 Optimization Process

The third phase that constitutes a computational method is the optimization process. Computational optimization can be defined as the generation through optimization tools of multiple design variants within the solution space via the definition of continuous or discrete parameters to achieve a set objective (Bradner et al., 2014). Hence, optimization tools can be defined as:

> *"Creation tools that use parametric modeling, performance simulation and mathematical optimization to systematically generate and evaluate design alternatives" (Bradner et al., 2014)*

Hence, a computational method including optimization and design exploration allows to explore a higher number of alternatives compared to the usual design method. Moreover, computational methods focus on performative solutions based on one or multiple measurable design criteria. In general, computational optimization and design exploration can be utilized to support designers and engineers in the decision-making process or to extract useful information on specific design scenarios. However, concerning the objective of this master thesis, the focus is set on the first described approach.

The implementation of computational optimization within the architectural practice has been rising in recent years due to the increment of accessible tools and information on the topic. Wortmann et al. (2017) provide an overview of computational optimization, such as available tools, typologies and algorithms, which is explained more in depth in the next subsections. In general, the optimization process is based on the resolution of defined mathematical functions. Indeed, an optimization problem consists in the identification of two main elements, which are the collection of parameters and constraints, and a mathematical expression to express them. However, the firsts are difficult to determine, while the definition of the mathematical expression may result in an impossible task. Although, computational tools can get around the problem. Indeed, once the parameters and the constraints are individuated, they can be implemented in the tools which can simulate the conditions and provide solutions to the optimization problem. Hence, it is necessary to introduce the term black-box optimization, which can be defined as:

> *"The solution of optimization problems in which some of the functions describing the objective and constraints of the problem can be computed but are not available in analytical form, i.e. their mathematical expression is unknown." (Wortmann et al., 2017)*

3.3.1 Optimization Typologies

As previously explained, computational optimization consists in performing a numerical simulation on a parametric model. Thus, a collection of parameters and constraints serves as the inputs to run the simulation via computational tools. Therefore, the output is the evaluation of the performance towards the set objective of the function (Wortmann et al., 2017). Based on the number of the objectives, the disciplines and the aspects related to the disciplines involved, three main typologies of optimization processes can be distinguished: single-objective optimization, multi-objective optimization (MOO) and multi-disciplinary optimization (MDO).

A. **Single-Objective Optimization (SOO).** As the name suggests, this typology of optimization consists in performing a single simulation towards a single objective. Hence, the aim of this type of optimization consists in maximizing or minimizing the output of the single expressed function (Wortmann et al., 2017). As an example, a single-objective optimization can be utilized to minimize the weight of a structure or to maximize the c-value of a grandstand. The main advantage of this typology is that the solution of the optimization problem is mathematically specified. Indeed, the scope is to determine a solution in the design space to minimize or maximize the output of a single objective function f(x).

B. **Multi-Objective Optimization (MOO).** As stated by Wortmann et al. (2017), unlike the single-objective optimization which aims to find a single solution within the design space to maximize or minimize the output of a single objective function f(x), a multi-objective optimization examines more objective functions at the same time. These objective functions may be conflictual, meaning that it is nearly impossible to maximize or minimize the output of the objective functions together. In general, a multi-objective optimization function can be described as the combination of multiple single-objective functions.

As mentioned, the solution of the multi-objective function would not be fully determined. Indeed, a multi-objective optimization provides a range of solutions within the design space that fulfill the objectives, but none of them is dominant compared to the other.

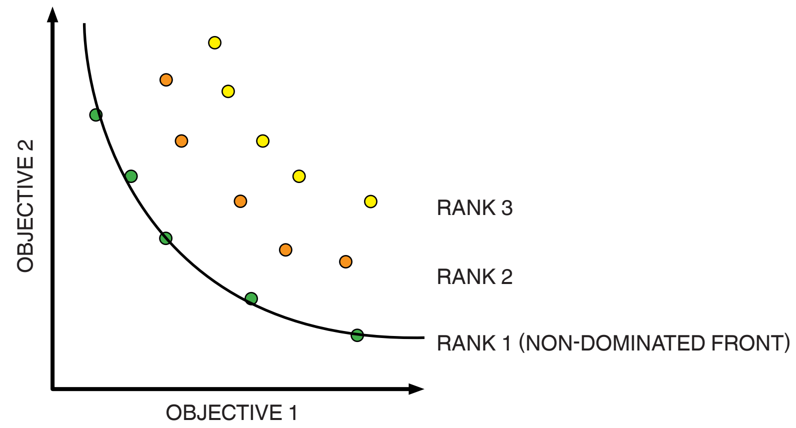


Figure 31. Scheme of Pareto-Front solutions (Source: Self-Made)

In general, the range of non-dominant solutions is known with the term Pareto Front. This term can be defined as:

> *"A Pareto front — which for two objectives is often drawn as a curve — represents the trade-offs between conflicting objectives." (Wortmann et al., 2017)*

Hence, if the multi-objectives are conflictual, the output of the optimization process is a range of non-dominant solutions, also known as Pareto front. Therefore, a Pareto-based optimization aims to find solutions for a single meta objective to approximate the Pareto front (Figure. 31). Concerning the objective of this master thesis, Wortmann et al. (2017) suggests considering few architectural or engineering criteria as constraints instead of the objectives of the optimization. As an example, the structural stresses and the deflection may be considered as limits not to be overcome while defining the multi-objectives of the optimization.

C. **Multi-Disciplinary Optimization (MDO).** As stated by Yang et al. (2015), multi-disciplinary optimization (MDO) is strictly related to multi-objective optimization. Indeed, MOO focuses on multi-objectives which may be related to a single or multiple discipline, while MDO focuses on multiple disciplines, disregarding the number of objectives. Hence, defining the main advantage of MDO:

> *"It allows designers to decompose a complex system into smaller subsystems (solved separately) and coordinate subsystem solutions towards an optimal system design. Thus, the MDO facilitates the incorporation of various interacting engineering disciplines involved in building design optimization." (Yang et al., 2015)*

Hence, MDO has started to spread in building design recently. Nevertheless, Yang et al. (2015) state that little research about MDO within the building design process is available.

Concerning the objective of this master thesis, single-objective optimization is discarded since two main disciplines will be involved. In general, multi-disciplinary MOO and multi-objective MDO can be feasible to develop a computational method as the envisioned one since they allow for more objectives and more disciplines. In general, Pan et al. (2019) states that little focus is given to the integration of multi-purpose space and the structure of stadiums. Joseph et al. (2015) explained how primary structure of the roof of the Aviva stadium was optimized with MOO to not obstruct the view from the grandstand. Pan et al. (2019) optimized with MOO the weight of the roof structure in relation to the reverberation time of sound and the average viewing distance for multi-purpose stadiums. The developed method was therefore applied on different case studies.

3.3.2 Optimization Algorithms

Wortmann et al. (2017) provides an overview of black-box optimization algorithms, which are mainly distinct into iterative methods and metaheuristics. Iterative methods are furtherly distinguished in direct search methods and model-based methods. Hence, the overview is presented.

A. **Metaheuristics Algorithms.** This typology of algorithms includes simulated annealing, particle swarm optimization (PSO) and genetic algorithms (GAs). The latter are the most implemented group within architecture and engineering optimization. GAs consists in improving a cluster of solutions, usually known as population, following mechanisms that imitates natural evolution. In general, metaheuristics is described by Wortmann et al. (2017) as a high-level procedure to produce a heuristic for a computational problem. Hence, these algorithms can be utilized to find an approximated optimal solution based on previous experience. Indeed, these methods preserve a population of solutions at every loop cycle, which results in a continuous improvement of the approximated produced results. Another characteristic of metaheuristics algorithm is their randomness, meaning that the algorithms generate the solutions arbitrarily. Indeed, these algorithms are defined as stochastics.

   Overall, on the one hand, metaheuristics algorithms have the advantage of a simple concept and a broad spectrum of application. On the other hand, the continuous iterations loop needed to improve the population is often excessively time-consuming for both generation and evaluations. However, this process is appropriate for Pareto-based optimization. Indeed, this type of optimization usually implement GAs or PSO. The main advantage is that, since Pareto-based are multi-objective optimization processes, a higher number of solutions is required, but there is no method to assess which is the best performing solution (Wortmann et al., 2017).

B. **Direct Search Algorithms.** Wortmann et al. (2017) explains how, unlike metaheuristics that produces a population of multiple solutions, direct search methods explore a series of individual solutions on the basis of the single previous iterations.

   On the one hand, local direct search algorithms, starting from a set solution, evaluates various directions towards the objective by altering the variables of the model (polling step). At every iteration, the previous produced solution becomes the new starting point. Hence, every produced solution consists of an improved previous solution towards the objective of the optimization. Therefore, local direct search algorithms can be represented as a path line connecting various alternative solutions within the design space that converges towards an optimal solution to solve the objective function. Even though applications of local direct search algorithms in MOO are available, this typology is most suitable for single-objective optimization.

   On the other hand, global direct search algorithms subdivide the design space into smaller clusters in which the optimal solution can eventually be found. At every iteration, the clusters become smaller and smaller until the optimal solution to solve the objective function is found. However, the number of variables have to be significantly reduced to utilize this typology of algorithms.

C. **Model-Based Algorithms.** Wortmann et al. (2017) defines model-based as algorithms that produce an approximation or a derivation of the objective function as a surrogate model to instruct and guide the optimization process. Consequently, the mathematical expression of the approximated objective function is known by the algorithm. On the one hand, the solutions result more precise in relation to the approximated objective, hence improving the optimization process. On the other hand, since the objective function is approximated, it becomes risky to rely on the single surrogate model. Indeed, this can lead to poorly optimized solutions. Therefore, it is suggested to train the surrogate model with a reduced cluster of solutions and afterwards substitute the original model with it.

   In general, these typologies rely on the accuracy of the surrogate model. Indeed, a not accurate model can lead to poor optimizations or to limited solutions. Even though the accuracy can be increased by the analysis of a larger number of solutions, the evaluation will result to be more time-consuming. Hence, a right balance between these two aspects must be found.

Concerning the objective of this thesis, on the one hand, GAs have been successfully implemented in MOO in regards of structural design and climate or architectural design for stadium buildings (Wartmann et al., 2017). Indeed, on the one hand, Pan et al. (2019) utilized metaheuristics algorithms to perform MOO in relation to viewing quality and acoustics of a multi-purpose stadium and the roof structure. Yang et al. (2018) utilized metaheuristics algorithms (NSGA-II) within ModeFRONTIER to optimize an indoor sports arena towards structure, daylight and energy. On the other hand, surrogate models have also been implemented in the optimization process of stadiums. However, the complexity of the parametric model may affect the suitability of model-based algorithms. In general, the choice of the algorithm may be reduced to metaheuristics and model-based. Hence, the computational tools to perform the optimization process should include these typologies of algorithms and able to be implemented with the parametric environment of Rhinoceros and Grasshopper.

Computational Tool	Plug-in of Rhino + Grasshopper	External Tool	Optimization Algorithm	Optimization of Structure	Optimization of Viewing Quality
Opossum	X		Model-Based	X	X
Octopus	X		Metaheuristics	X	X
Optimus	X		Metaheuristics	X	X
ModeFRONTIER		X	Metaheuristics	X	X
Wallacei	X		Metaheuristics	X	X

Figure 32. Available tools to perform the optimization process (Source: Self-Made)

3.3.3 Design Exploration

As previously mentioned, the optimization process constitutes the last phase of a computational method. However, the optimization process aims only to find single optimal solution or a population of sub-optimal solutions towards a single or multiple objective function, while design exploration constitutes a further phase within a computational method. Indeed, design exploration can be defined as a process that allows designers and engineers to evaluate the sub-optimal solutions produced via optimization in order to support them into making decisions. Therefore, the objective of the design exploration can be described as the visualization and benchmarking of the output of the optimization to facilitate the decision-making process of designers (Turrin, 2014).

Wortmann et al. (2017) states that MOO provides an advantage towards the decision-making process of designers, especially in the case of Pareto-based applications. In these regards, Patz et al. (2016) proposed a visualization of the results within a Self-Organized Map (SOM). Hence, the map has a color gradient and different heights indicating how well the solutions fulfil the multiple objectives. Therefore, the solutions are organized on the map to clearly show their performances in relation to the objectives. Thus, designers are facilitated in evaluating the produced solutions and in making decisions.
Concerning the objective of this master thesis, design exploration will constitute a crucial step of the envisioned method in order to support the decision-making process. Therefore, the visualization method and the user interface to be implemented will have to be determined based on the clearness and the intuitiveness.

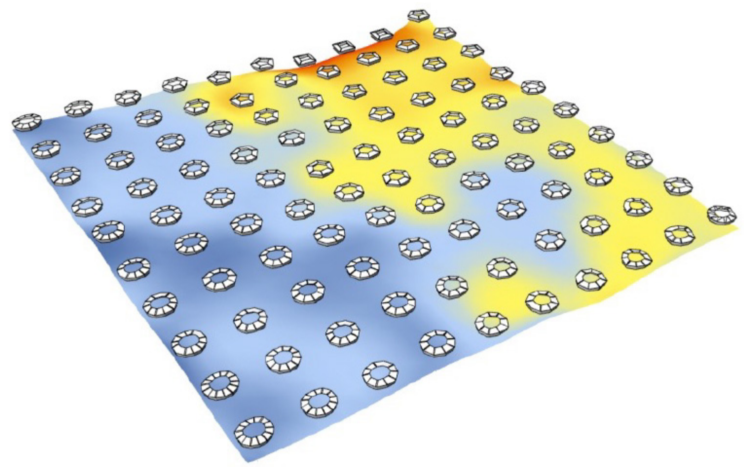


Figure 33. Example of Self-Organizing Map (SOM) (Source: Patz et al., 2016)

04 | STRUCTURE OF THE COMPUTATIONAL METHOD

STRUCTURE OF THE COMPUTATIONAL METHOD

Based on the knowledge acquired during the literature review, the structure of the proposed computational method was outlined. The design boundaries were determined in relation to the complexity of the parametric model, the performances to evaluate and the optimization process. Thus, the components of the stadium, the indicators individuated to asses the performances and the objectives of the optimization implemented within the computational method are described in this chapter. The workflow followed to include these features in the method is determined during the design phase, along with the different included typologies. A description of the workflow is provided in the following chapters.

Lastly, it is notable that the determined design boundaries will limit the number of existing stadiums on which the computational method can be applied. Therefore, its validation will also be restricted to the following design boundaries.

4.1 Design Boundaries

The design boundaries were determined in relation to the complexity of the parametric model, the performances to evaluate and the optimization process. Furthermore, the implementation of the following features within the computational workflow rose problematics related to the data to be processed. Hence, further restrictions to the boundaries were added during the design phase. A general overview of the design boundaries and restrictions is provided in this section, while a more detailed explanation on the workflow followed for the implementation is provided in the following chapters.

4.1.1 Complexity of the Parametric Model

As previously mentioned, the proposed computational method approaches the problem statement from a general perspective, rather than focusing on a specific existing stadium. Since the stadium components can be blended together in an endless amount of possibilities, the number of implemented features were reduced considering primarily the elements that are strictly related to the performances to evaluate. For this reason, all the stadium facilities such as the benches and the hospitality and media areas were excluded from the parametric model. Instead, the playing area, the grandstand and the primary roof structures were included. Indeed, these features have a bigger impact on the performances to be assessed. In fact, the relation between the playing area and the grandstand influence the viewing quality of a stadium, while the stand geometries and the roof structure affect the structural performance. Lastly, the vertical circulation was included to consider the block division of the grandstand. However, the vomitories, which constitutes the exits from the stands, were excluded in order to simplify the parametric model. Indeed, these elements are treated differently in every stadium, while the vertical circulation can be generalized in relation to their number and position. A hierarchy of the implemented objects was established in the parametric model by determining the dependencies among the design variables.

Hence, the playing area was the first stadium component to be implemented, which constitutes the focus point for the assessment of the viewing quality. Subsequently, the grandstands were included in the parametric model. Firstly, the layouts describing the organization of the stands around the pitch were inserted. Nine common layout typologies were individuated during the literature review, but the undulated and octagonal geometries were excluded from the parametric model. Indeed, the undulated and octagonal geometries required to solve the intersection of a significant number of curves. This process was increasing the computational time needed to produce the geometries, therefore slowing down the entire workflow. Moreover, the control over the data to be processed for these typologies was troublesome and affected the results of the viewing quality assessment and the implementation of the roof structures.

The general configuration of the grandstands was established by determining the number, the position and the typology of the stands. Therefore, the layouts were divided into eight sections in accordance to the cardinal points and the possibility to choose the number of tiers per section and the stand typology per tier was provided. This choice was taken to increase the flexibility of the computational model and to enlarge the design space. However, few limitations were added during the design phase. Indeed, the number of tiers is restricted to a maximum of three, while only the stand typologies with a linear ascent were considered. On the one hand, the parabolic stand required a continuous reiteration of data that resulted to be problematic to handle accurately in grasshopper. On the other hand, the linear stand typologies allowed to have a better control over the C-value for the evaluation of the viewing quality, which is a crucial output for the performance assessment. Lastly, the vertical circulation was implemented in the parametric model. This feature was necessary to divide the stands into seating sections and to provide a more accurate approximation of the capacity of the stadium.

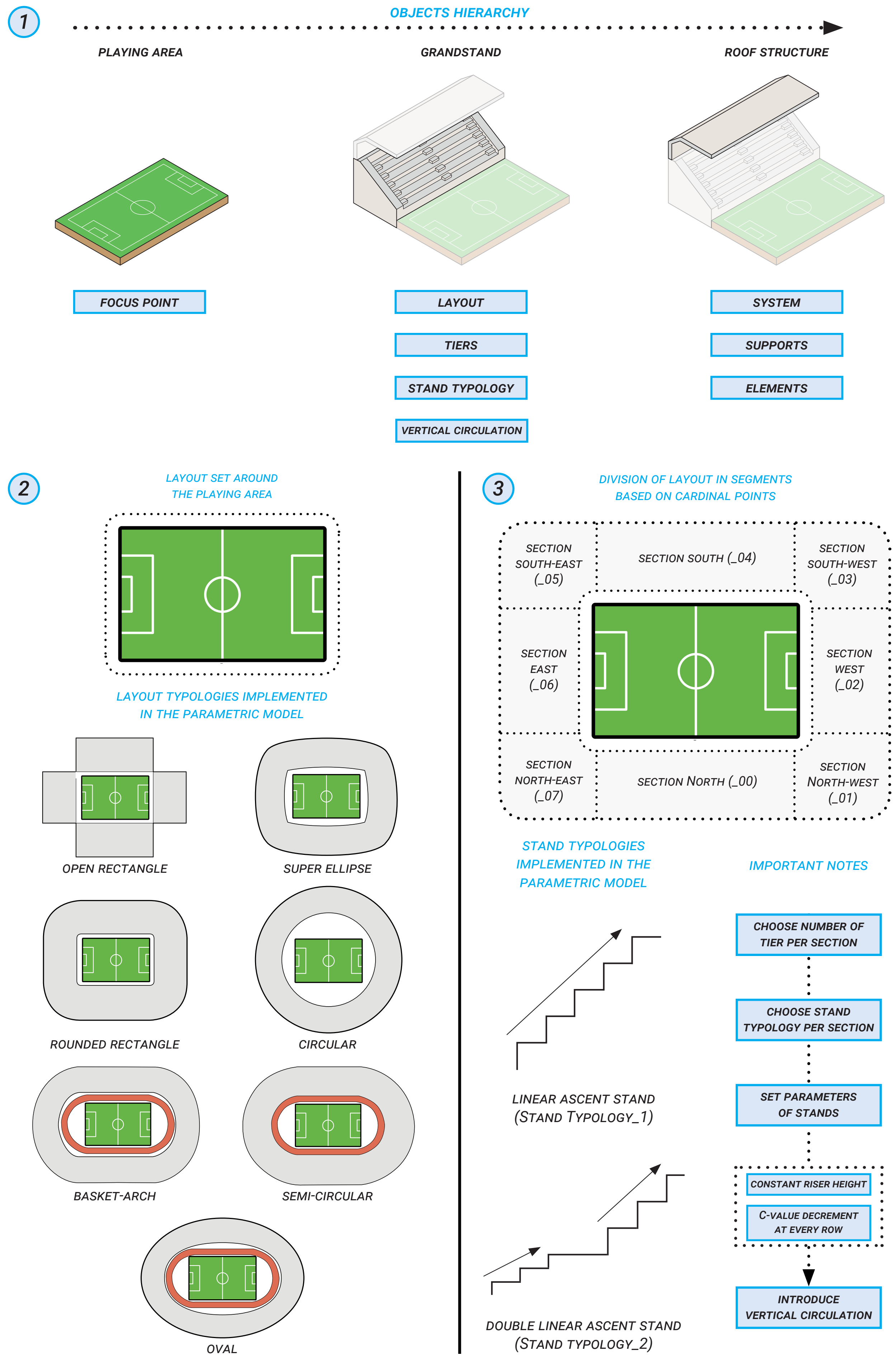


Figure 34. Design Boundaries scheme of the computational method: Hierarchy (1), Layout (2) and Grandstands (3) (Source: Self-made)

4.1.2 Roof Structures

The roof structure typologies included in the parametric model were reduced to the simple cantilevers, the tie-back structures and the restrained cantilever structures. Indeed, these structural systems allow surely an unobstructed view from the stands and they can be applied without limitations in relation to the implemented layout typologies. The elements that constitutes these systems can be divided in two main categories, which are the primary and secondary structure. Further structural boundaries were included in relation to the support conditions, the structural elements implemented, and the materials considered.

Considering the simple cantilever system, the primary structure is constituted by a pillar and a beam, while the secondary structure is composed of a series of bracing elements that connects the cantilever beams together. Concerning the tie-back system, the primary structure is constituted by a pillar, a beam and a restraining element, while the secondary structure is composed of a series of bracing elements that connects the cantilever beams together. Lastly, the restrained cantilever system is constituted by a pillar, a beam and three restraining elements, while the secondary structure is composed of a series of bracing elements that connects the cantilever beams together. In all three systems, the connection between the bracings and the cantilever beams is considered as a hinge. Indeed, a degree of freedom is released at both ends and the rotation along the y-axis is allowed.

Three sets of support conditions were implemented in the parametric model for all the structural systems:

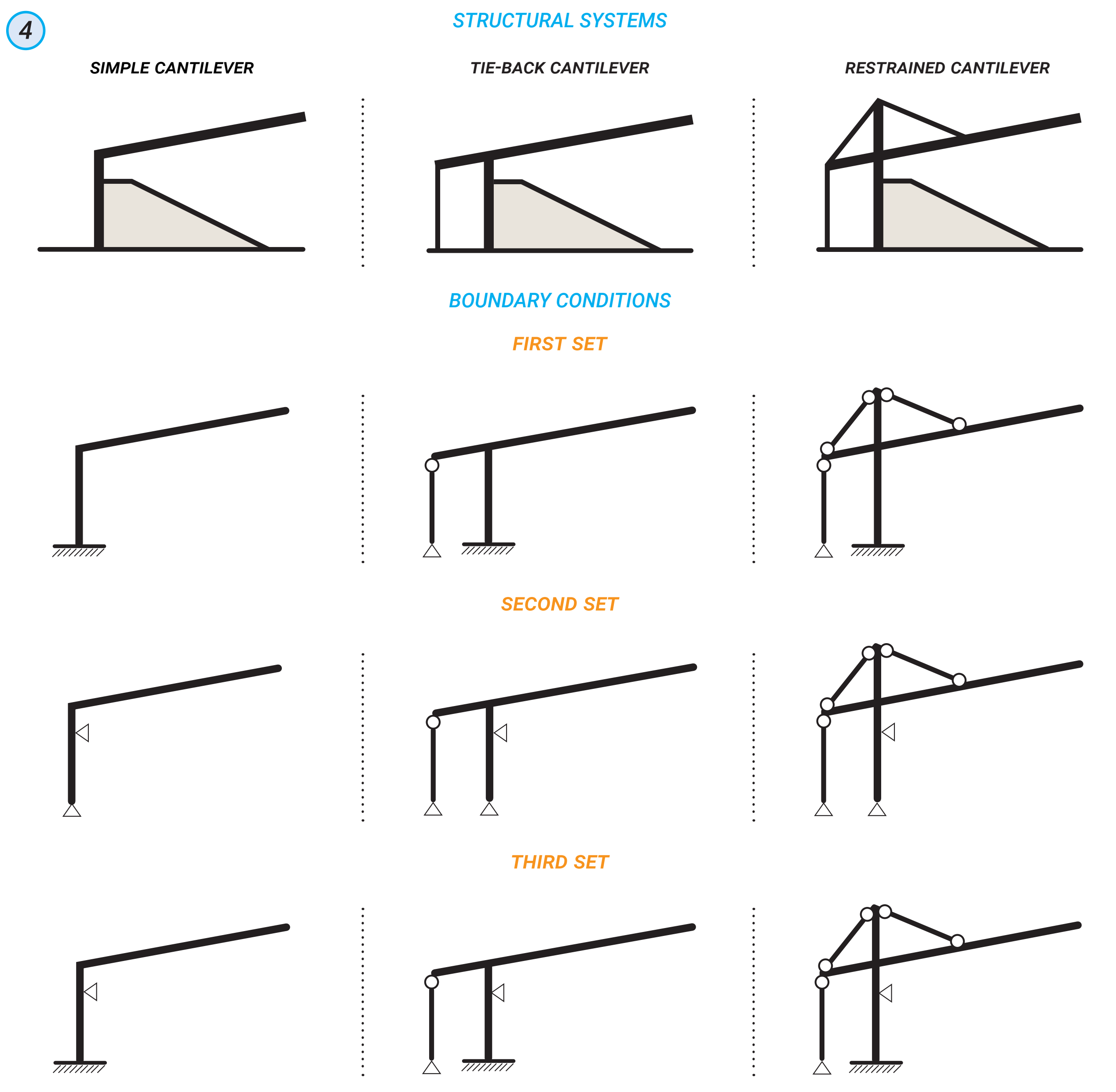
- The **first set** consists in a fixed support at the base of the pillar to consider its connection to the ground.
- The **second set** consists in a hinge support at the base of the pillar to consider its connection to the ground and a hinge support for the pillar where it is connected to the last tier of the stands.
- The **third set** consists in a fixed support at the base of the pillar to consider its connection to the ground and a hinge support for the pillar where it is connected to the last tier of the stands.

Concerning the tie-back and the restrained cantilever systems, a hinge support is added at the base of the restraining element to consider its connection to the ground. Moreover, a degree of freedom is released at both ends of all the restraining elements and the rotation along the y-axis is allowed.

For all the structural elements implemented in the parametric model, the cross-section typologies considered are the European HEA beams and the UK CHSC circular hollow beams. Due to the large spans to be covered and the high bending moments and deflections to withstand, parallel trusses were implemented in the parametric model as an option for the pillar and the cantilever beam. Indeed, these structural elements are highly effective solutions to reduce stresses and deflection of large-span structures. However, these elements will be simplified as solid rectangular cross-sections in the parametric model to maintain a better control on the workflow for the implementation within Karamba 3D, the Grasshopper plug-in that will be utilized to evaluate the performance of the roof structure.

Similarly to the grandstands, the roof structure is divided into eight section in accordance to the cardinal points. This choice is taken to provide more flexibility and enlarge the design space for the structural solutions. Indeed, this option allows the roof structure of every section to work independently or as a whole based on the continuity of the bowl geometry, therefore allowing to explore different alternatives.

Considering that the roof structure is divided into eight sections and that the structural elements of the three structural systems will be grouped in categories (the pillars, the cantilever elements, the bracings and the three restraining elements), it should be necessary to provide different cross-section typologies for the different parts of the structure. However, this solution provided multiple problematics during the evaluation of the structural performance of the roof. Indeed, Karamba did not considered the roof structure as a whole, but as a eight different structures. In order to solve this problematic, an extensive process to manage the data within grasshopper was evaluated as a solution, which was however not possible to be applied due to the limited time frame available. Hence, the structural elements of the three structural systems are divided in groups (pillars, cantilevers, bracings and the three restraining elements), but a single cross-section typology is provided for every category. Further information is provided in the sub-section 9.2.



STRUCTURAL ELEMENTS

Structural Elements	Simple Cantilever	Tie-back Cantilever	Restrained Cantilever	Released Rotation Y-axis at Start-Point	Released Rotation Y-axis at End-Point
Pillar	x	x	x		
Cantilever	x	x	x		
Bracing	x	x	x	x	x
1- Restrain		x	x		x
2- Restrain			x	x	x
3- Restrain			x	x	x

ELEMENT TYPOLOGY AND CROSS-SECTION

Structural Elements	Beam Option	Truss Option	Circular Hollow Profile (UK CHSC)	I - Profile (EU HEA)
Pillar	x	x	x	x
Cantilever		x	x	x
Bracing	x		x	x
1- Restrain	x		x	x
2- Restrain	x		x	x
3- Restrain	x		x	x

Figure 35. Design Boundaries scheme of the computational method: Roof Structure (4) (Source: Self-made)

4.1.3 Performance Indicators of the Viewing Quality

The viewing quality of the grandstand of a stadium was defined as the comfort of the spectators into following the activity held in the stadium. In this regard, two main aspects can be distinguished. On the one hand, a spectator should not have the view obstructed by any objects. On the other hand, the spectators should be able to follow the activity while comfortably seating in the stands. Hence, the performance indicators were selected based on these features. Moreover, it should be notable that the evaluation of the viewing quality will be considered valid exclusively in relation to the components included in the parametric model and described in sub-section 4.1.1. The selected performance indicators are:

- **C-value.** As explained in sub-section 2.3.2, the c-value is the vertical distance that elapses between the sightline of two spectators that are sitting one after the other. The European standards EN/DIN 13200-1 recommend range of 6 to 12 cm with an admissible tolerance of ±5 mm. Indeed, 12 cm is considered the optimal value for a good viewing quality, while 9 cm is admissible, and a c-value below 6 cm is considered as not acceptable.

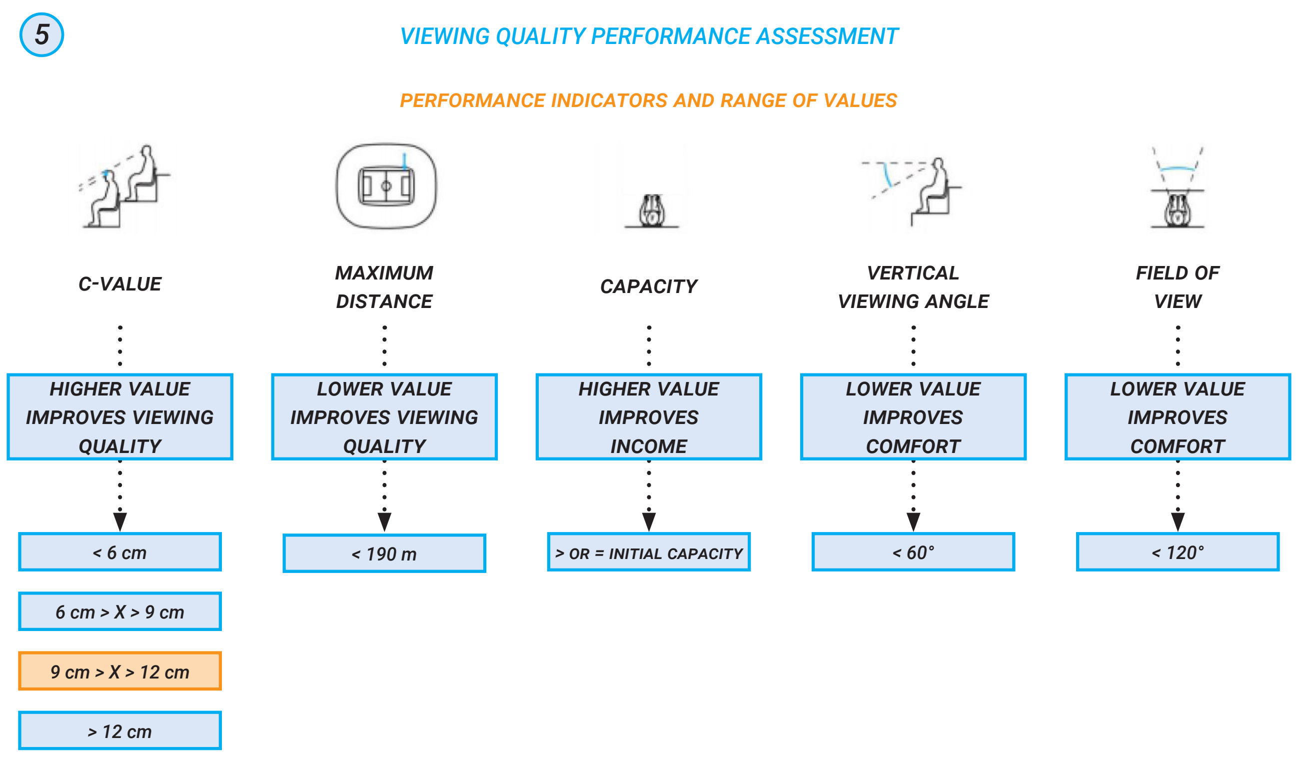
  Concerning the objective of this thesis, the c-value will be evaluated by taking these three values into consideration. Hence, the results will be grouped in four different branches. Values above 12 cm will be considered excellent, while value above 9 cm will be considered as recommended. Lastly, values between 9 cm and 6 cm will be considered acceptable, while values lower than 6 cm will be considered poor, meaning that the sightline will be obstructed by other spectators' heads. The evaluation will be focused on all the seats and in relation to the whole stadium. Moreover, the percentage of the spectators with a recommended c-value (> 9 cm) will be calculated for all the tiers of the stadium to provide a more accurate evaluation and to support the decision-making.

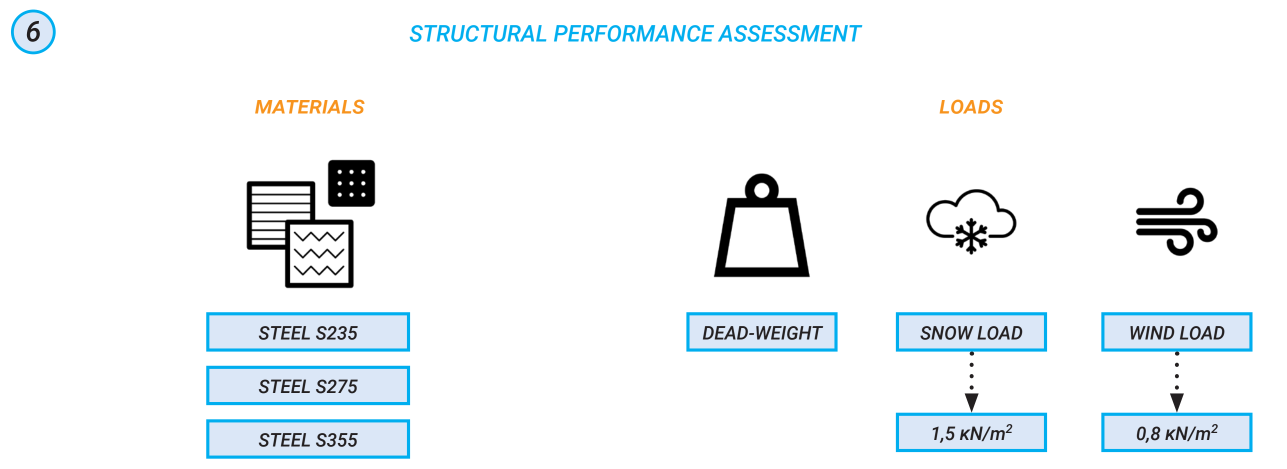
- **Maximum Viewing Distance.** The maximum viewing distance can be defined as the horizontal distance that can be measured between the spectator and the action. In general, a smaller distance improves the viewing quality by bringing the spectators closer to the pitch and by enhancing the atmosphere of the stadium (UEFA, 2011). Two different aspects of the maximum viewing distance will be evaluated. On the one hand, the distance between the spectators and the touchline will be analysed for the whole stadium. The output will provide the range of distances of the spectators from the pitch. On the other hand, the concept of the optimum viewing circle (seb-section 2.2.2) will be utilized to determine how many spectators are provided with a finer viewing quality. As a limit, 95% of the spectators should be located within a maximum radius of 190 m.

- **Vertical Viewing Angle.** The vertical viewing angle is the vertical angle between the horizontal sightline of a spectator and the immaginary line that connects the spectator's eye and the touchline. This performance indicator can be utilized to evaluate the comfort of the spectator into following the activity. Indeed, a smaller angle requires less movement of the head to follow the action on the pitch. The vertical viewing angle will be analysed for the whole stadium. The output will provide the range of angles of the spectators in relation to the touchline. Lastly, 60° is considered as a limit value, which constitutes the vertical field vision of a person (Nixdorf, 2009).

- **Field of View.** The field of view indicates the comfort of the spectators into following the activity. A person standard field of view is up to 150°, with 120° as an angle that requires a slight movement of the head (Nixdorf, 2009). The field of view will be analysed for the whole stadium. The output will provide the range of angles of the spectators in relation to the touchline. Lastly, 120° is considered as a limit value for good comfort. However, it should be noticed that, for few layouts, the spectators located near the half line of the pitch will not be able to have a field of view lower than 120° due to the proximity to the pitch. In these cases, the field of view will not be considered as a constraint because the activity is considered as performed in only half of the pitch.

- **Capacity.** The capacity does not represent a performance indicator for the viewing quality, but it is however a crucial aspect to be evaluated. Indeed, it represents the number of tickets that can be sold for the venues, therefore providing an insight on the income of the stadium. To evaluate the design alternatives, the capacity of the initial situation should be calculated and utilized to determine if the value will increase or decrease after the renovation. Therefore, the capacity of the initial situation is considered as a limit that should not be reduced.





MATERIAL PROPERTIES

Structural Elements	Density (kg/m³)	Unit Weight (kN/m³)	Young's Modulus (Mpa)	Yield Strength (Mpa)
STEEL S235	7850	78,5	210000	235
STEEL S275	7850	78,5	210000	275
STEEL S355	7850	78,5	210000	355

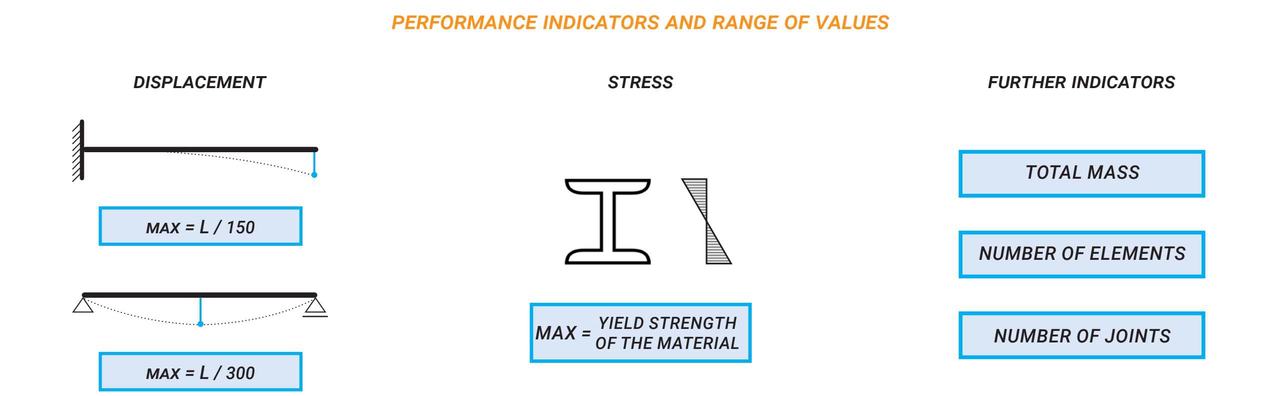


Figure 36. Design Boundaries scheme of the computational method: Viewing quality (5) and structural performance (6) (Source: Self-made)

4.1.4 Performance Indicators of the Roof Structure

As explained in section 2.4, the roof structure of a stadium can be distinguished in load-bearing framework and coverings. Respectively, the purpose of the first is to transfer the dead-weight and the external loads to the ground, while the second serves mainly to provide protection from the weather conditions to the spectators (Nixdorf, 2009). Concerning the objective of this thesis, few performance indicators are considered to evaluate the roof structure. It should be notable that the evaluation of the viewing quality will be considered valid exclusively in relation to the components included in the parametric model and described in sub-section 4.1.2.

In addition, the material considered are restricted to steel S235, S275 and S355. Moreover, the loads considered are the dead-weight of the structure, the snow load as 1,5 kN/m^2 and the wind load as 0,8 kN/m^2. In this case, the wind load is considered for uplift effect on the roof. Hence, it is considered as acting perpendicularly to the roof surface towards the ground, therefore increasing the deflection of the roof structure. Hence, the structure will be evaluated in the worst case scenario to ensure its stability. The selected performance indicators are:

- **Displacement.** The displacement will be evaluated to ensure the stability of the structure. For all the elements, the deflection will be calculated and confronted with a limit value. Considering the structural systems implemented, the limit values are set with a rule of thumbs of L/150 for cantilever elements and L/300 for the elements simply supported at both ends (Raven W. J., 2008)
- **Strees.** The stress within the structural elements will be evaluated to ensure the stability of the structure. For all the elements, the stress will be calculated and confronted with the yield strength value of the selected material.
- **Mass.** The mass value provides an insight on the cost of the material to construct the roof structure. Indeed, since the roof structure influences greatly the overall cost of a stadium (Nixdorf, 2009), it constitutes a useful indicator to evaluate the structural performance. To evaluate the design alternatives, the mass of the initial roof structure should be calculated and utilized to determine if the value will increase or decrease after the renovation.
- **Number of Elements and Joints.** An evaluation of the number of elements and joints present in the roof structure provides an insight on the labour work necessary to construct the roof structure. This is based on the assumption that a renovation process should be performed as quickly as possible to avoid a delay in the venues scheduled for a stadium. To evaluate the design alternatives, the number of elements and joints of the initial roof structure should be calculated and utilized to determine if the value will increase or decrease after the renovation.

4.1.5 Stadium Constraints

As explained in section 1.2, nowadays there is a tendency to renovate existing stadiums, instead of building new grounds. Indeed, the refurbishment of a stadium can provide benefits to the revenues by expanding the capacity, by improving the experience of the supporters and by enhancing the security of both spectators and players, while preserving the history of the existing stadium and containing the overall costs of the operation (Figure. 36).

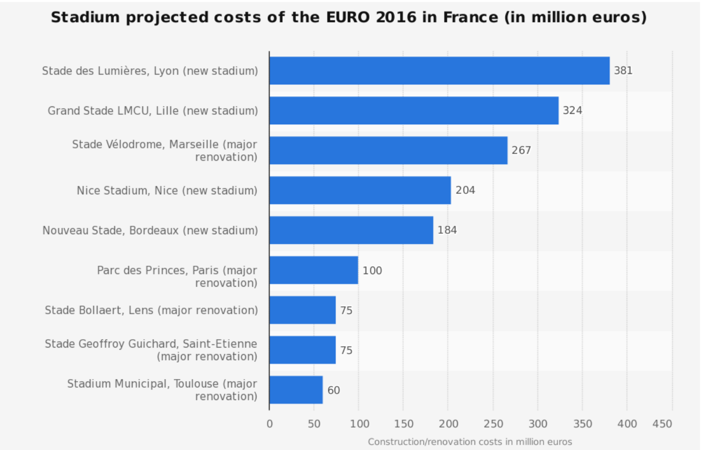


Figure 36. Confrontation between renovation and construction costs of major French stadiums for EURO 2016 (Source: Statista, 2018)

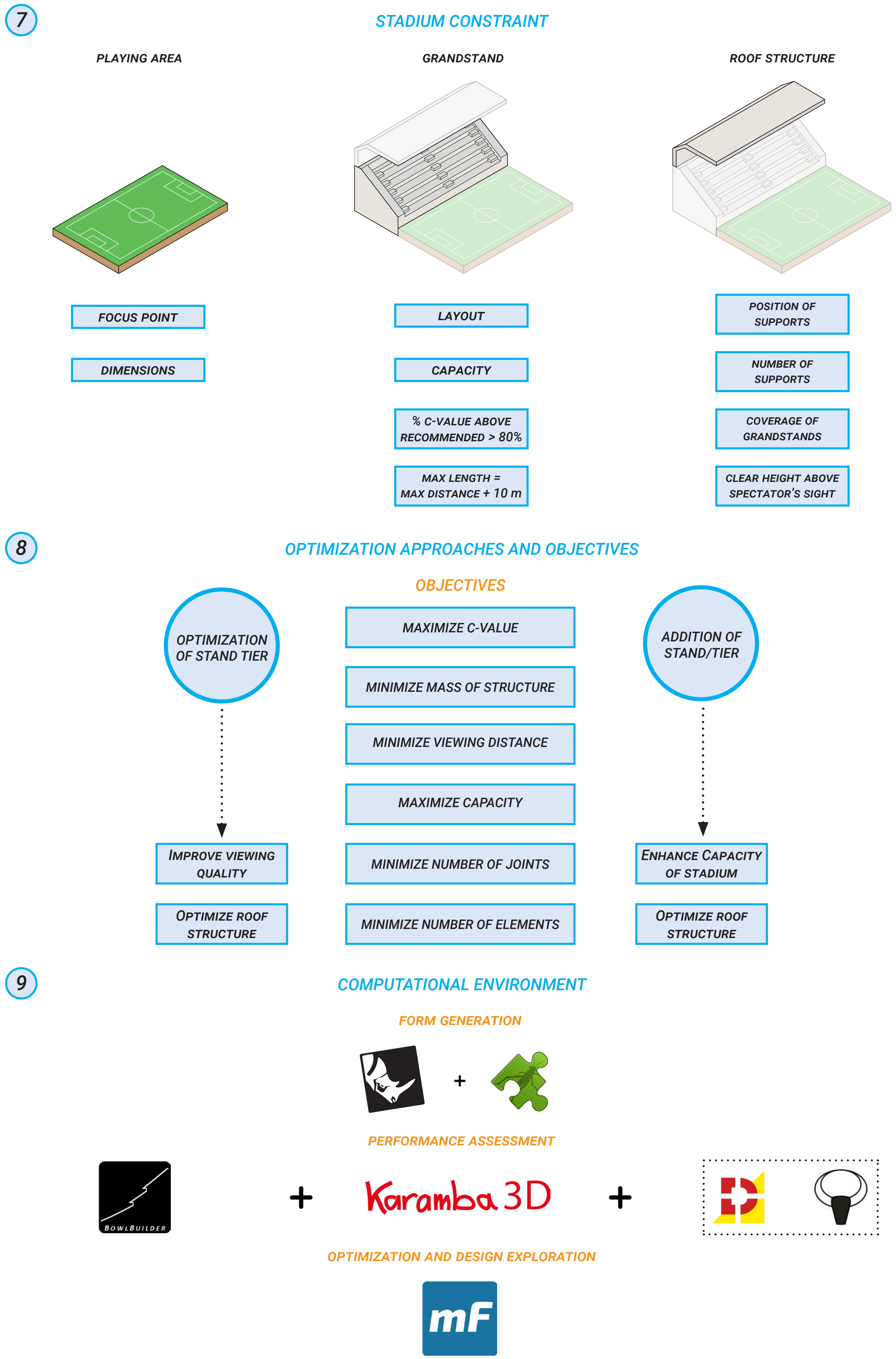


Figure 37. Design Boundaries scheme of the computational method: Stadium constraints (7), Optimization (8) and Computational environment (9) (Source: Self-made)

The concept of renovation and stadium constraints must be defined. Concerning the objective of this thesis, an existing stadium will be analysed in relation to the viewing quality and the structural performance of the roof to determine which parts are worth to be kept and which portions should be redeveloped. Hence, a state-of-the-art of the two performances is evaluated to define an approach, which can be the refurbishment of the bad performing parts or the expansion of the stadium whether its portions perform well. Moreover, the design alternatives for renovation should not worsen the initial performances.

Hence, the pitch is considered to remain unaltered, as well as the layout. Furthermore, the grandstands are considered as well performing whether more than 80% of the seats provides a minimum C-value of 9 cm and no seats have a C-value lower than 6 cm. In addition, the capacity will not have to be affected by the renovation. Likewise, 95% of the stadium will have to respect the limit of 190 m of the optimum viewing circle, while, in case of refurbishment, the maximum distance from the touchline should not increase more than 10 m.

Concerning the roof, the number and the position of the supports should not be modified to avoid a complete alteration of the structure from the initial situation in case of renovation. However, in case of an expansion, the alteration of their position and/or their number will be evaluated in relation to aesthetic criteria. Hence, in case of renovation, these parameters will be kept constant. Moreover, since the roof has the main function of covering the spectators from the weather conditions, the produced design alternatives will have to shelter at least the same area of the grandstands of the initial situation. Lastly, in order to avoid any obstruction to the spectator's view towards the pitch and the opposite section of the stadium, the roof structure will be constrained above the last spectator's horizontal sightline.

In the computational method, the constraints will be dealt in two steps. Firstly, the parameters will be implemented as inputs in the parametric model in order to control these features independently. Secondly, the constraints inputs will be excluded from the optimization to avoid alteration. In addition, the calculated values as for example the capacity and the maximum viewing distance will be considered as limit values for the optimization.

4.1.6 Objectives of Optimization

As explained in section 3.3, computational optimization can be defined as the generation through optimization tools of multiple design variants within the solution space via the definition of continuous or discrete parameters to achieve a set objective (Bradner et al., 2014). Concerning the objective of this thesis, two main approaches for the optimization are individuated. On the one hand, design alternatives for the renovation of the grandstands and the roof structure will be produced whether the viewing quality is poor. On the other hand, design alternatives to expand the stadium will be produced by modifying the grandstands and the roof structure. The designer can freely follow one of the approaches based on the results of the performance assessment of the initial situation of the stadium.

Independently from the followed approach, few objectives have been individuated for the optimization process. In these regards, the percentage of c-values above the recommended value of 9 cm will have to be maximized over at least 80%, which is considered in this thesis as a solid value to provide a successful solution for the optimization problem. Concerning the roof structure the mass value will be minimized, as well as the number of joints and elements to reduce the overall costs and labor work to construct the structure. Moreover, the capacity will constitute and objective to be maximized, and the maximum distance will constitute and objective to be minimized.

Lastly, few constraints will be inserted to respect the requirements of the European standards and the football associations. In these regards, the stands inclination will be kept lower than 35°, while the stresses and deflections within the structure should respect the limits described in sub-section 4.1.2.

4.1.7 Parametric tools

The parametric environment of Rhinoceros and Grasshopper is utilized as the basis of the computational method. Indeed, its user-friendly interface facilitates the exploration of different complex geometries and it can be integrated with multiple plug-ins for the assessment of various performances related to the built environment (Yang et al., 2018).

Concerning the viewing quality, the Grasshopper plug-in "Bowlbuilder" (mmarschall, 2018) will be implemented to assess the C-value and the field of view of the spectators. A grasshopper script was initially evaluated to be included instead of the plug-in. However, the computational time to assess the two performances was slowing down the whole process since it required to solve the intersection of multiple lines.

On the other hand, Bowlbuilder provides two components coded with Phyton that reduce greatly the computational time needed for the evaluation. Concerning the roof structure, Karamba 3D (Preisinger, 2018) will be utilized to perform the structural analysis of the structures. Indeed, this plug-in can be utilized to parametrically control structural inputs and outputs continuously, while providing live feedbacks on the performance assessment. On the other hand, Diana FEA (TNO, 2003) will be utilized for an initial analysis to explore the behaviour of the structural systems and to individuate the most stressed and deflected portions.

Lastly, the computational tools to perform the optimization process necessitated to include metaheuristics or model-based algorithms. Moreover, it needed to be implemented with the parametric environment of Rhinoceros and Grasshopper. For these reasons, ModeFRONTIER will be utilized to perform the optimization. Indeed, it provides multiple metaheuristics algorithms for MOO and MDO, as well as multiple analysis tools to evaluate the produced data and to facilitate the trade-off of the produced design alternatives. Moreover, the optimization process requires a minimal set-up before starting, which allows to select inputs, outputs, objectives and constraints and to easily control the range of values for the exploration.

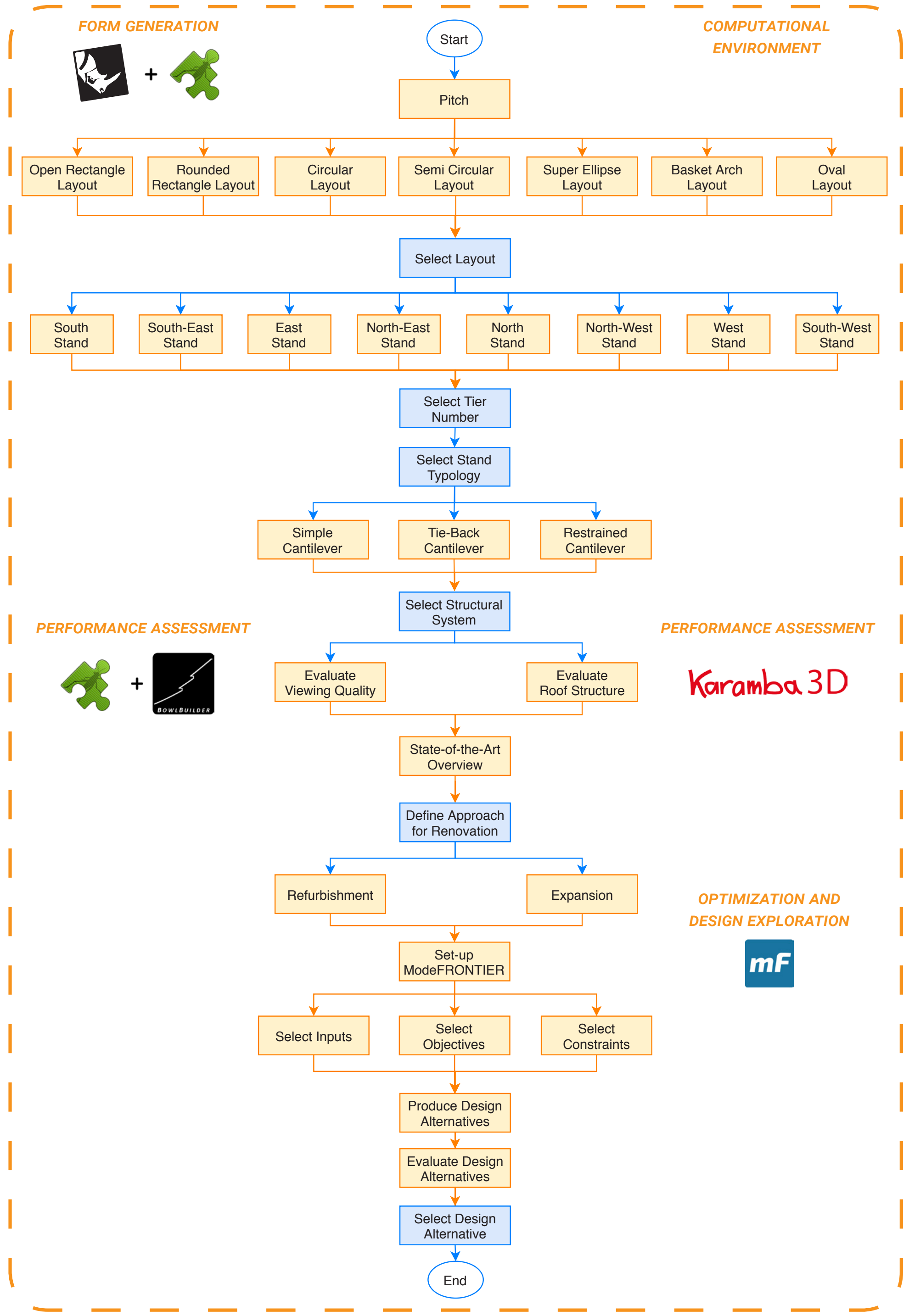


Figure 38. Overview of the Steps of the proposed Computational Method (Source: Self-made)

05 | FORM GENERATION

FORM GENERATION

The first phase of the computational method consists in the form generation. As previously stressed in section 3.1, the form generation consists in the realization of the parametric model. This phase results crucial since it determines the design space. Indeed, the output of the performance assessment can be considered valid exclusively within its boundaries. Likewise, the design alternatives that can be produced and explored in the optimization and design exploration phase will be limited to the design space (Patz et al., 2019).

5.1 Set-up

The parametric environment of Rhinoceros and Grasshopper is utilized as the basis of the computational method. The complexity of the parametric model and the hierarchy of the objects is established and explained in sub-section 4.1.1. Therefore, the envisioned computational method includes the pitch, seven layout typologies, two grandstand geometries, the vertical circulation, the spectators and three main structural systems for the roof.

Each element is parametrized, meaning that its geometry is determined by a various number of input parameters. In this case, discrete parameters (sliders) are utilized. This choice is due to the further optimization process that will be performed with ModeFRONTIER. Indeed, this computational tool can import from Grasshopper exclusively these typologies of input parameters. Lastly, the hierarchy of the objects is implemented by the creation of a dependancy among the objects, meaning that an high rank element has control over a lower rank object. Hence, the output of a high rank object constitutes the input for the next object in the hierarchy. Therefore, an alteration of the first element will automatically modify the subsequent ones.

Firstly, the parametric model is initialized by modelling the pitch as a polyline, which constitutes an input for the layout. Secondly, the layout typologies are shaped and divided into sections based on the cardinal points. Hence, the sections are utilized to produce the grandstand geometries of the stadium. Lastly, the roof structures are shaped using as inputs the first and last curve of the grandstands.

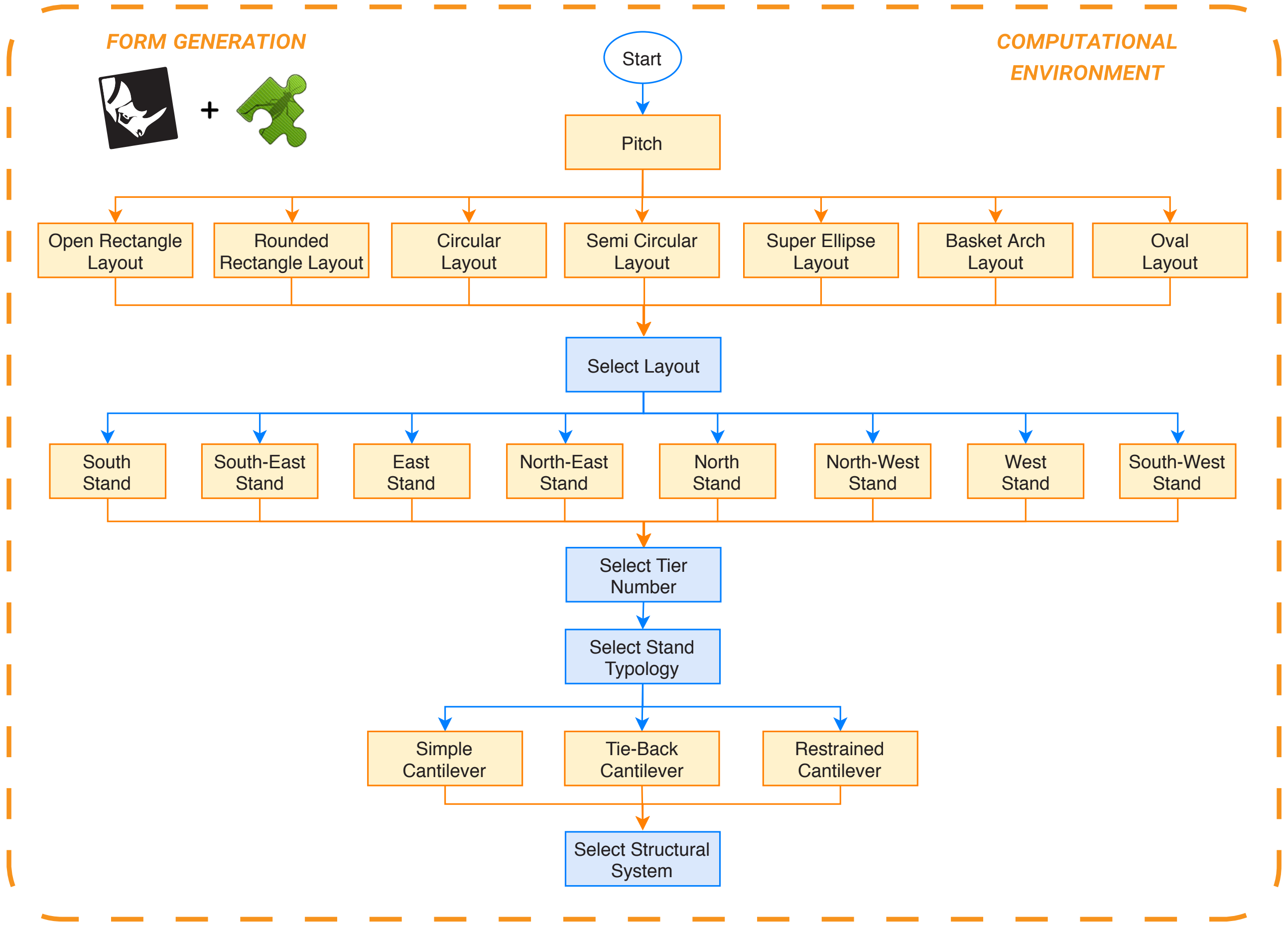


Figure 39. Overview of the Steps of the Form Generatio Phase (Source: Self-made)

5.2 Playing Area and Layout

The playing area included in the parametric model is constituted by the football pitch. In this instance, the playing area is modelled as a closed rectangle dependent on four control points. Discrete parameters are utilized to set the dimension of the pitch. Furthermore, the half line, the boxes and the centre circle are modeled utlizing discrete parameters to control their shape. Hence, the main output provided is the touchline, which is utilized to perform the viewing quality evaluation. Further outputs are the center of the pitch, the half line and the boxes. Indeed, these are the areas of major interest during a game and they can be utilized to detail further the assessment of the viewing quality. Lastly, a standard athletic track that surrounds the football pitch is modelled. Indeed, three of the implemented layouts require its implementation.

Concerning the layout typologies, the touchline is provided as the main input curve. Similarly, to the pitch, closed curves dependent on control points are shaped. Each curve is dominated by various parameters, two of which determines the distance between the layout curve and the touchline. The range of values of these two parameters are limited to the minimum safe distance set by FIFA (2011) and UEFA (2011), which corresponds to 7.5m behind the goals and 6.0 m from the sides of the pitch. However, the range of values can be altered in case of stadiums with a lower first row distance. Hence, the output of the layout typologies consist of closed curves for all layouts, with the only exception for the open rectangular geometry. In this case, the output is constituted by four lines.

Subsequently, the layout curves are divided into sections based on cardinal points. Hence, the curves are exploded and the generated sections are ordered counter-clockwise considering the South section as the first item. As a result a list of the sections for all the layout typologies is constructed. These lists are then entwined in a tree structure, with every branch representing a layout typology. An option to select which layout to utilize for the next phase is provided by selecting the correct tree branch with a list item component.

Lastly, an expression component and a stream gate component are utilized to separate the layouts into two groups based on the number of sections present in the lists. This choice was necessary to set-up the next phase of the form generation, which is the grandstand design. Indeed, the data management without this option would have reduced drastically the control over the geometries and the parameters of the objects.

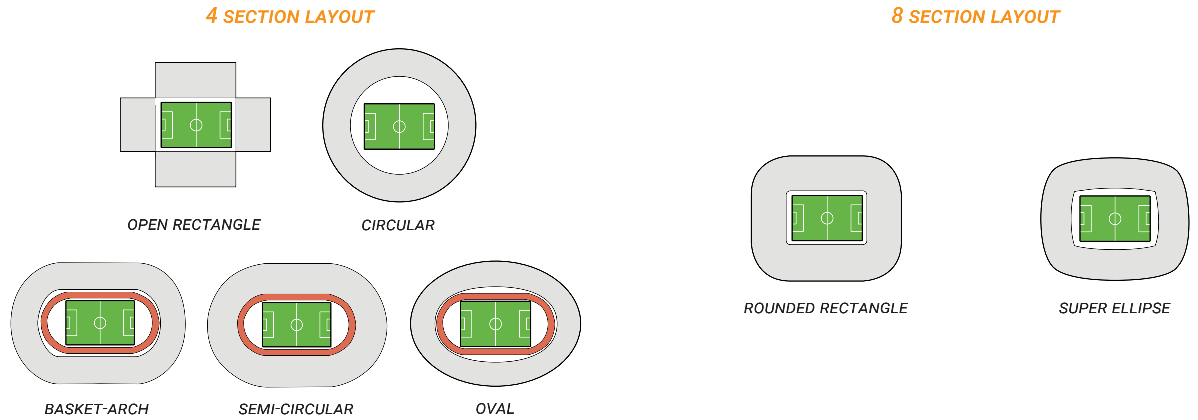


Figure 39. Groups of Layout Typologies (Source: Self-made)

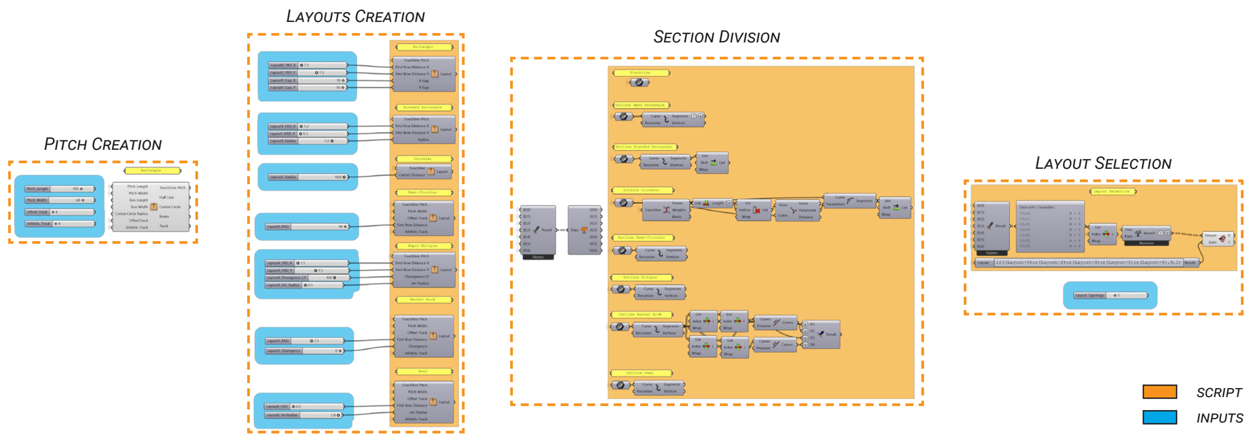


Figure 40. Grasshopper Script utilized to create the Pitch, Layouts, Section division and Layout Selection (Source: Self-made)

5.3 Grandstands

Three main aspects had to be considered to design the grandstands within the parametric model. Firstly, it was necessary to define the number of tiers for every section of the stadium. Secondly, which stand typology to apply had to be determined. Lastly, the stand typology had to be parametrized. Therefore, the data stream had to be organized in order to respect the set hierarchy and to maintain control over the input parameters. Hence, a script to produce the stand typologies was firstly designed and the data stream was controlled by redirecting the sections of the layout to the assigned script. Furthermore, a switch is provided to control the number of tiers of every section. Thus, 2 scripts for each stand typologies and for each section of the layout were designed, for a total of 16 scripts. Therefore, in order to determine the number of tiers per section, the scripts are divided in three portions, which is the maximum considered number of tiers. Concerning the stand typologies, the script for the two types are divided in three parts, each one controlling one tier. Hence, the grandstands are determined with a total of 48 scripts, 6 scripts for each layout section. Then, the outputs are grouped in a tree structure as in first, second and third tier for every layout section. The workflow followed to produce the parts of the stand typologies' scripts are identical.

Hence, the section curves constitute the main input for the first part of the scripts. Considering the linear typology, the first row of seats is produced to provide the basis for the stands. Hence, an offset component is utilized to dispose the curves on the ground level. The offset value corresponds to the tread depth value and it is set with a discrete parameter. Afterwards, the height of the curves is adjusted to the correct elevation. For the first curve, an initial riser value is selected, while for the other curves, a riser height value is determined. For both values, discrete parameters are utilized. Subsequently, a series component is implemented to determine the number of rows of the stand. In the end, the curves representing the eye points of the spectators were produced from the stand curves. In this case, 1,25 m is utilized as an additional height to consider the seats, while 1/3 of the tread depth is the value utilized to move the curve upfront. At this step of the script, the first tier is produced. Therefore, the script is repeated after designing the first row of the second tier as a basis. Once the second tier is concluded, the operation is replicated to produce the third tier of stands.

Considering the double linear typology, the workflow followed is identical to the one for the linear type. However, in this case the input parameters are doubled since the stands are considered as two parts dependent on each other. Moreover, the distance between the end of the first part of the stands and the starting point of the second part is parametrized with a discrete parameter.

Once the two stand typologies had been designed, the data stream had to be controlled to provide the choice for the number of tiers and the stand typology to apply to the layout sections. Three main components have been utilized to achieve this objective. As a main workflow, the tree structure containing the layout sections was exploded with an explode tree component. As a result, a series of tree branches containing the layout curves was obtained. Hence, the data of every tree branch was connected to two stream gate components. Here, two discrete parameters were utilized to determine whether a tier is wanted and which stand typology have to be applied. Then, the section curve was fed to the selected script for the stand typology. Lastly, the stand geometry produced was connected to an entwine component. As a result, the tree structure was reconstructed with each branch containing the correct stand geometry. Moreover, a second tree structure was realised following the same principle to group the curves of the eye-points of the spectators.

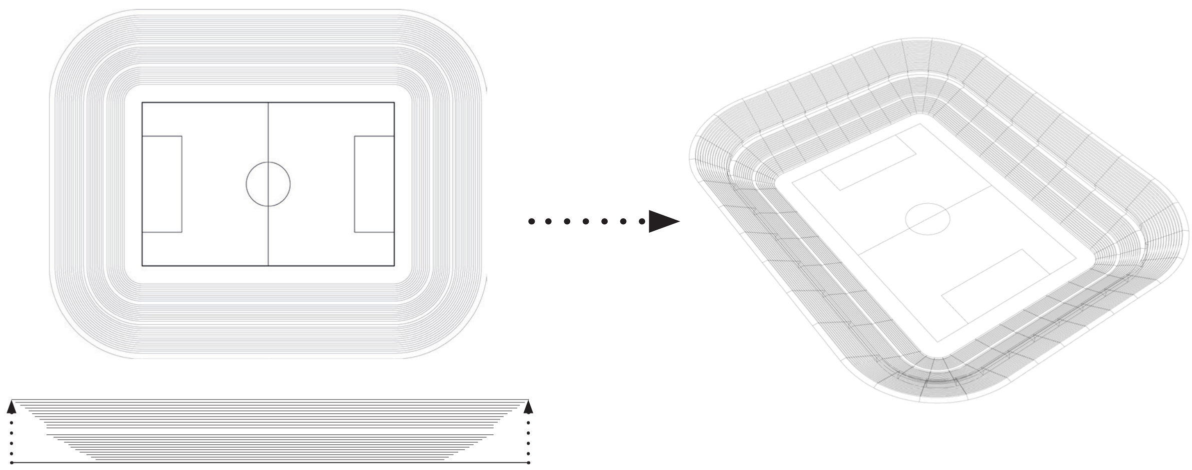


Figure 41. Visualization of the Workflow followed to model the grandstands within Grasshopper (Source: Self-made)

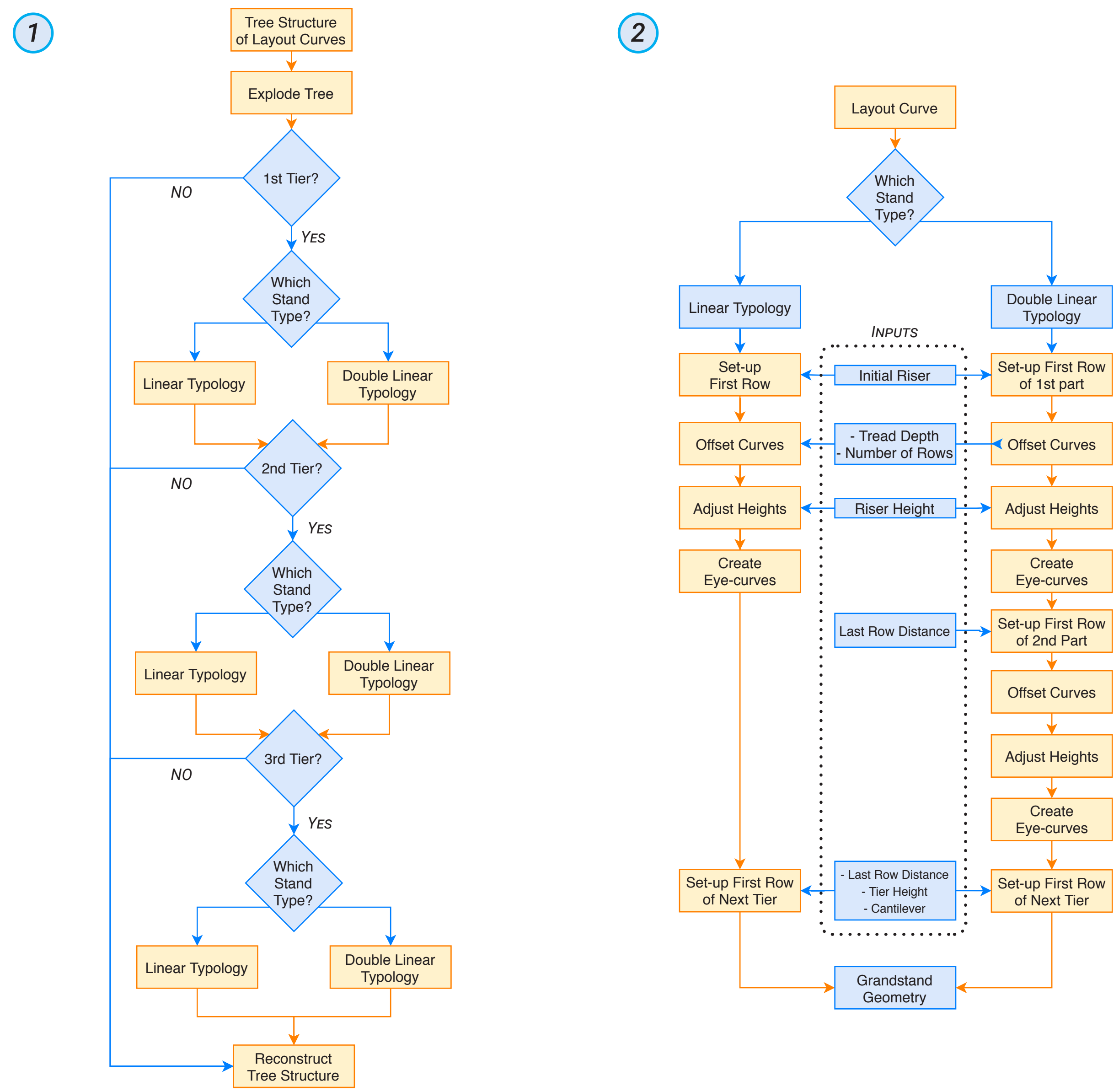


Figure 42. Flowchart of workflow for Grandstand geometry design (1) and stand stypology design (2) (Source: Self-made)

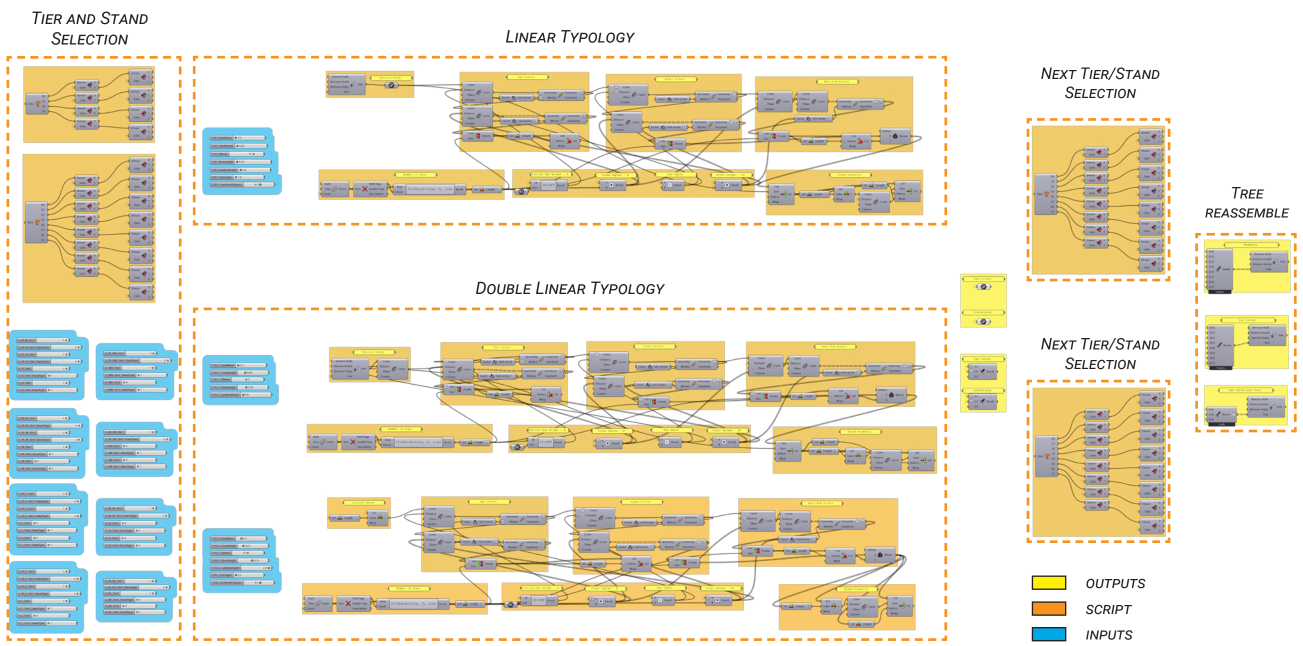


Figure 43. Script utilized to model the grandstands within Grasshopper (Source: Self-made)

5.4 Spectators

The workflow followed to produce the grandstands provided as an output two tree structures organized in three branches and eight sub-branches each. The sub-branches indicate the layout section of the stadium, while the branches represent the tiers. The two trees contain the curves composing the grandstands and the curves representing the eye points of the spectators. Hence, this last tree structure is utilized in this step to produce the eye points of the spectators based on the dimensions of the seats and the distance between them. Furthermore, the gangways are produced to erase the eye points that intersects them. This solution allows to replicate the block division of the spectators within the stadium. Therefore, the final output will be a tree structure containing the eye points of the spectator, which is organized in branches representing the blocks of the stadium.

Initially, the two tree structures are connected to a "clean tree" component to erase the empty items that were produced within the scripts of the two stand typologies. Hence, the tree structures were exploded to extrapolate the eye curves and the grandstand curves. Concerning the gangways, the first and the last grandstand curves of every stand were utilized. As a first step, the curves are divided with a "divide curve" component. Hence, a slider is utilized to determine how many gangways are needed for every section of the stadium. Then, the gangways are produced as rectangles and their width can be controlled with a discrete parameter. As an output, a list of rectangles representing the gangways is produced.

Similarly, the eye curves were divided with a "divide curve" component. Hence, the slider utilized to determine the number of gangways is utilized to create the block division of the stands. Then, the resulting curves were divided further using as inputs the width of the seats and the distance between them. As an output, a tree structure containing the eye points of the spectators was obtained. Lastly, the eye points intersecting the gangways were eliminated from the list. Therefore, the final output of this step is a tree structure containing the filtered eye points of the spectators, which is organized in branches representing the block division of the stadium.

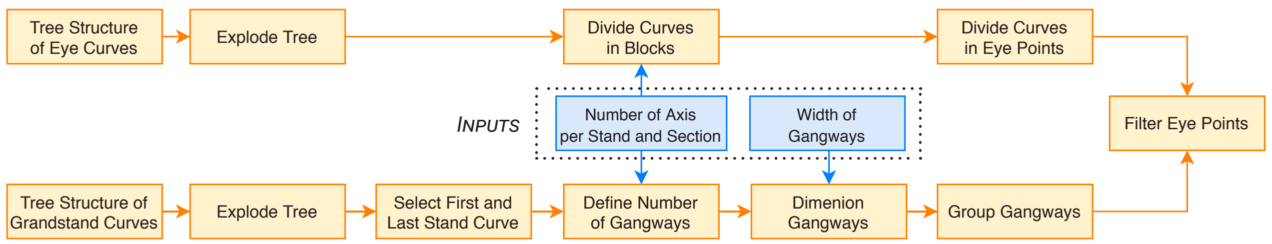


Figure 44. Flowchart of the Workflow followed to implement the spectators (Source: Self-made)

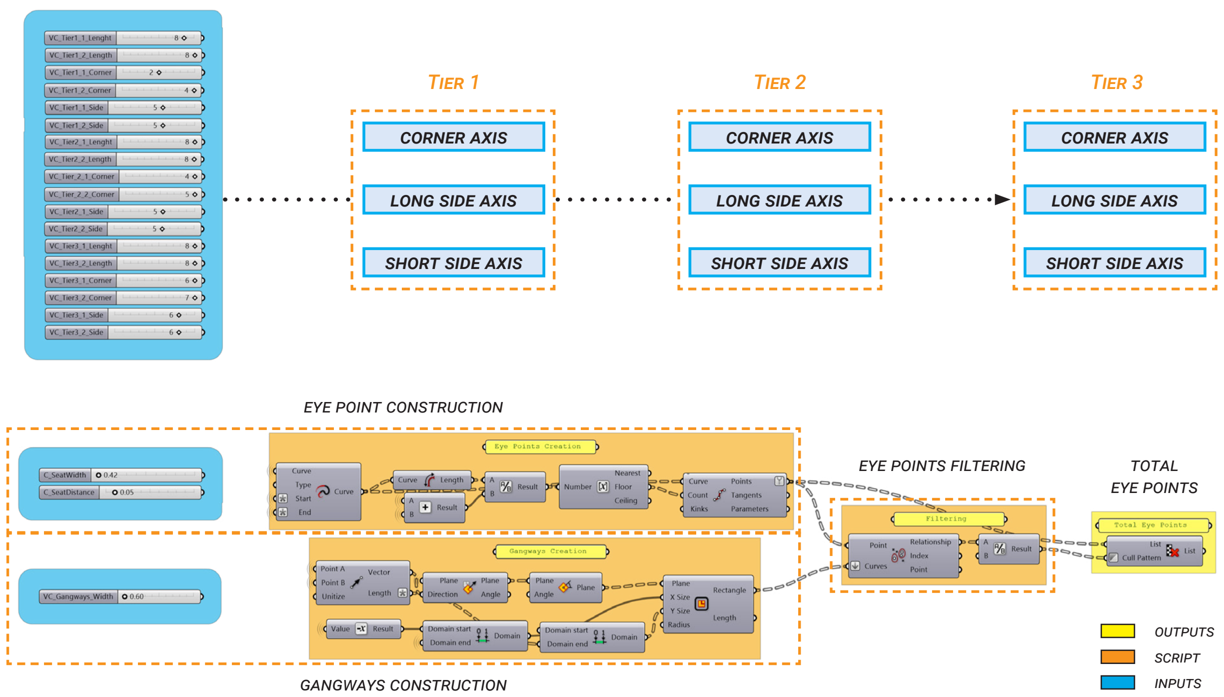


Figure 45. Schemes and scripts for the implementation of the gangways and the eye points of the spectators (Source: Self-made)

5.5 Roof Structure

As explained in sub-section 4.1.2, three structural systems have been selected to be implemented in the parametric model. The workflow is divided in two main steps. Firstly, the outline of the three systems is produced. Secondly, the cross sections, the materials, the loads and the support boundaries are introduced with Karamba 3D. Indeed, this Grasshopper"s plug-in provides useful components to implement these features within the computational method for the structural analysis. In this section, the workflow followed to produce the outline and the structural elements is presented, while the definitions of the materials, the support boundaries and the loads are presented in section 6.4.

5.5.1 Structural Systems

The three structural systems implemented are the simple cantilever, the tie-back cantilever and the restrained cantilever. Initially, the outline of the systems is produced. Hence, the structural elements are grouped and fed to a "line to beam" component to obtain the structural elements for the analysis. It is notable that Karamba 3D can read exclusively lines and not curve. Hence, the outlines of the structures are reconstructed as polylines and exploded into segments at their intersections.

All the structural systems were outlined starting from three main groups of points, which are the external ground support points, the grandstands support points and the end points of the cantilever elements. In order to create these groups of points, the tree structure of the grandstand curves was utilized. Indeed, the tree structure was exploded into the branches of the stadium sections. Then, the first and last curve of the grandstands were extrapolated with a "list item" component. Then, the two sets of curves were divided with a "divide curve" component. Three sliders were utilized as input for the division. The first one indicates the division of the corner sections of the stadium, the second one indicates the division for the long side sections of the stadium and the last one indicates the division for the short side sections of the stadium. As a result, two tree structures were obtained, one containing the grandstands support points for every section of the stadium, and one containing a series of points for every section of the stadium.

Afterwards, this last tree structure of points was utilized to produce the end points of the cantilever elements and to create the external ground support points. On the one hand, the points were copied and their height adjusted based on the height of the grandstand's sections to create the end points of the cantilever points. On the other hand, the points were copied and translated outwards to produce the external ground support points of the structure. In this case, a slider component for every stadium section is utilized to determine the length of the translation. In the end, three tree structures were obtained, each divided in branches related to the stadium sections. One tree contains the end points of the cantilever elements, while the other two trees contain the external ground support points and the grandstand support points.

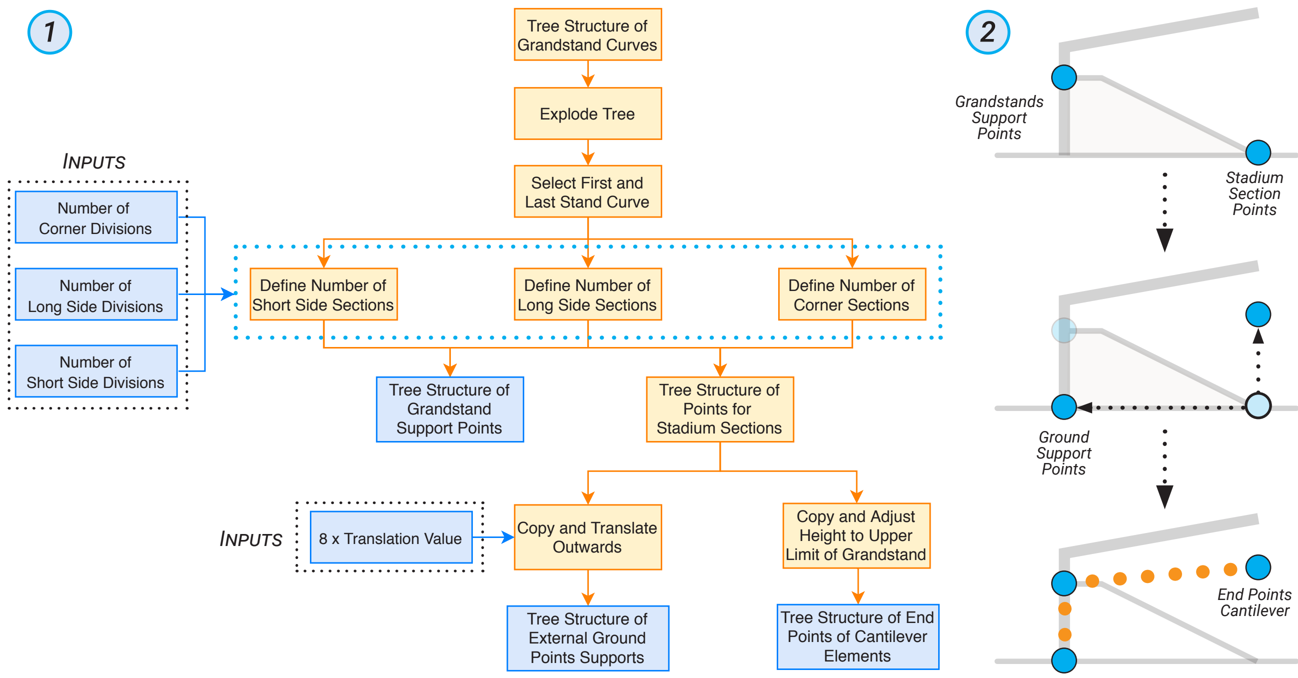


Figure 46. Flowchart of workflow for the base points of the roof structure (1) and scheme of process (2) (Source: Self-made)

The three tree structure of points were utilized as a basis to outline the structural systems. Firstly, the simple cantilever system was implemented. Then, the tie-back and the restrained cantilever systems were implemented by adding elements to the simple cantilever system. Afterwards, once the lines were transformed into beam elements, the structural components were grouped into one list per structural system and entwined together. Then, a slider input is provided to select which structural system will be utilized for the analysis. Lastly, it is notable that a hierarchy to connect the points was established. On the one hand, the elements spanning vertically were created by connecting the lowest points to the highest points. On the other hand, the elements spanning horizontally were created by connecting the outward points to the inward points. Moreover, the tree structures of the structural elements are ordered counter-clockwise starting from the South section of the stadium and proceed upwards and inwards. Indeed, this hierarchy was necessary to facilitate the extrapolation of the results within Karamba 3D. The workflow followed to implement the structural systems is described as follows:

- **Simple Cantilever System.** As explained in sub-section 4.1.2, the structural elements that compose the simple cantilever system are the pillars, the cantilevers and the bracing elements. Since Karamba 3D requires all the elements to be divided at their intersections to perform the analysis, the three groups are sub-divided.

  Hence, the pillar were divided in two lines. Firstly, the ground support points and the grandstand support points were connected to obtain the first group of pillars. Secondly, the grandstand support points were copied and translated upwards to create the starting points of the cantilever elements. In this case, a slider component is utilized to determine the length of the elements. The range of values is limited between 2,5 m and 10 m to provide a minimal clear height above the grandstands. Moreover, a “two point vector” component was utilized to provide the direction for the translation. Indeed, it was necessary to maintain the same direction for the lines of the second group of pillars. Therefore, the grandstand support points and the starting points of the cantilever elements were connected to realize the second group of pillars.

  Considering the Cantilevers, the lines were created by connecting the starting and the end points of the cantilever elements. In this case, Hence, the tree structure containing the lines was fed to a “divide curve” component. A slider input was utilized to determine the number of bracing elements. As an output, two tree structures containing the bracing lines and the cantilever lines were obtained. Lastly, the lines were shattered at their intersections to obtain all the structural elements.

- **Tie-Back Cantilever System.** As explained in sub-section 4.1.2, the structural elements that compose the tie-back cantilever system are the pillars, the cantilevers, the bracing elements and a first restraining element.

  Starting from the tree structures of the elements created for the simple cantilever system, the strating points of the cantilevers were copied and translated outwards to obtain the extension points for the cantilevers. In this case, a slider component was utilized to determine the length of these additional elements. Then, the two structure of points were connected with a line representing the extension of the cantilevers.

  Following the same workflow to create the external ground support points, the tie-back supports were produced. In this case a new set of slider components was utilized to determine the position of the points, one for each section of the stadium. Lastly, the tie-back support points were connected to the extension points of the cantilevers to obtain the lines of the first restraining elements.

- **Restrained Cantilever System.** As explained in sub-section 4.1.2, the structural elements that compose the tie-back cantilever system are the pillars, the cantilevers, the bracing elements and three sets of restraining elements.

  Starting from the tree structures of the elements created for the tie-back cantilever system, the starting points of the cantilevers were copied and translated upwards to obtain the extension points for the pillars. In this case, a slider component was utilized to determine the length of these additional elements. Then, the two structure of points were connected with a line representing the extension of the pillars.

  Therefore, the extension points for the cantilevers and the pillars were connected to create the second set of restraining elements. Similarly, the extension points of the pillars were connected to the cantilevers to obtain the third set of restraining elements. In this case, the elements can be connected to the cantilevers at different locations. Thus, a slider component was included to determine which intersection points have to be utilized.

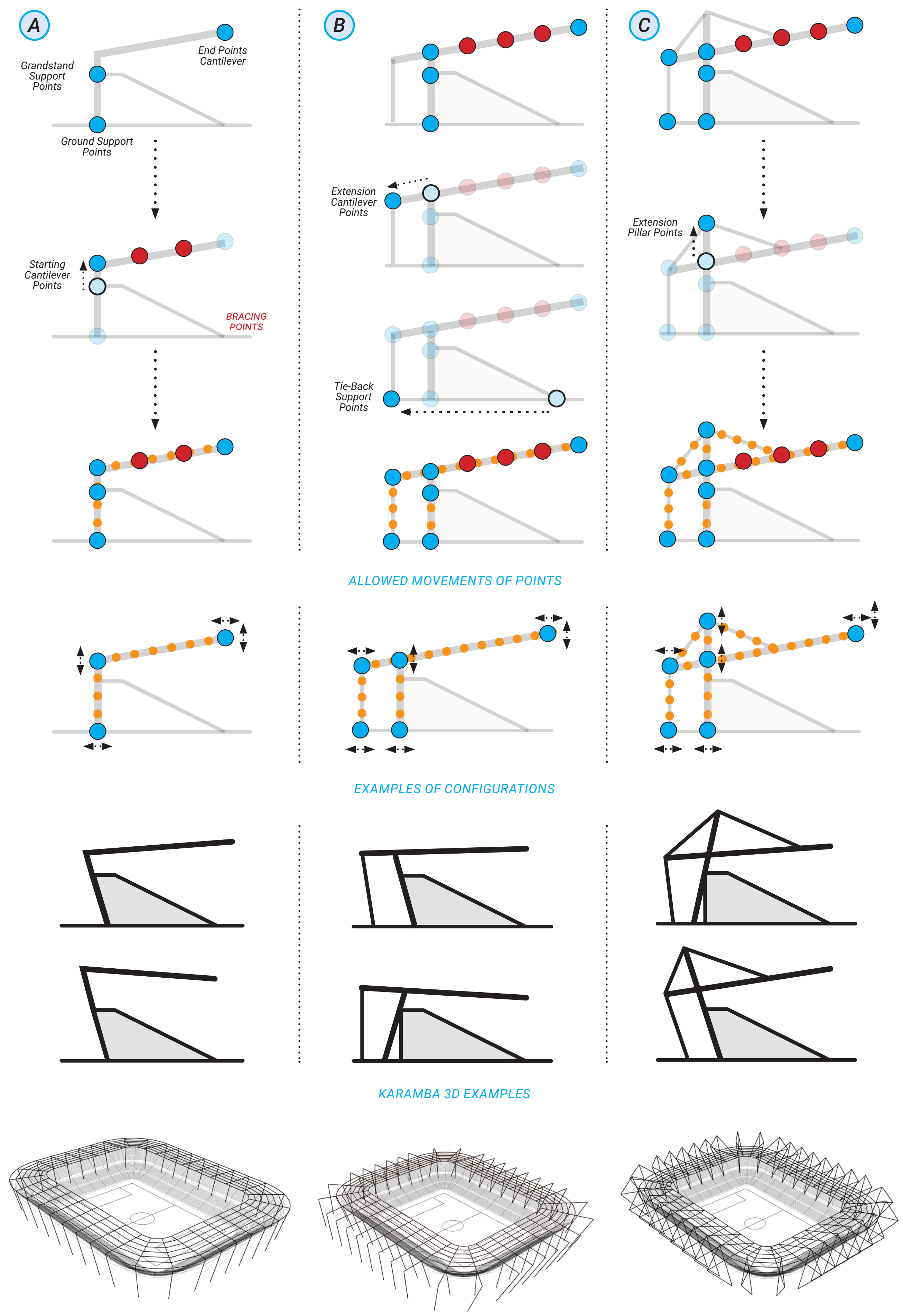


Figure 47. Scheme of construction of the three structural systems: Simple Cantilever (A), Tie-Back (B) and Restrained (C) (Source: Self-made)

5.5.2 Simplification of the Model

Once the outline of the three structural systems were defined, all the lines were grouped in different categories in order to transform them into the right stuctural element within Karamba 3D. Hence, the structural elements were divided into pillars and extension pillars, cantilevers and tie-backs, bracings, first restraining set, second restraining set and third restraining set. This solution was necessary to assign the correct cross-sections to the elements and to calculate the correct dead-weight of the structure. Afterwards, for all the groups is possible to determine which cross section to utilize choosing between UK CHSC circular hollow profiles and EU HEA I Profiles. In this case, the UK CHSC profiles considered were reduced by taking all the diameters available, but considering exclusively the largest thickness for every profile.

Concerning the pillars and the cantilever, a further step is implemented. Indeed, since these two structural elements have a bigger impact on the performance of the structure and considering the long spans to be covered, trusses elements were implemented. On the one hand, a choice between beam or truss is provided for the pillars. On the other hand, the cantilevers are considered as only truss elements. In this case, only 2D parallel trusses were considered and the elements were simplified for the implementation. Indeed, the diagonals of the trusses were neglected and the two chords implemented as a solid rectangular beam.

The simplification is performed by applying the rule of Steiner, known also as the parallel axis theorem (Gere et al., 2012). Hence, after choosing which cross section typology to apply, the second moment of area I_x and I_y of the truss were calculated with the formulas:

$$I_{x\,truss} = \sum (I_x + Ad^2) \quad [6] \qquad\qquad I_{y\,truss} = \sum (I_y + Ad^2) \quad [7]$$

Since the trusses considered are parallel and symmetric because the same cross section is applied to both chords, the formula can be rewritten as:

$$I_{x\,truss} = 2{*}I_x + 2{*}(Ad^2) \quad [8] \qquad\qquad I_{y\,truss} = 2{*}I_y \quad [9]$$

Where: A = Area of selected cross section [m^2]
d = Distance between centroid of cross section and centroid of Truss [m]
I_x = *Second moment of area of the cross section along x-axis [m^4]*
I_y = *Second moment of area of the cross section along y-axis [m^4]*
$I_{x\,truss}$ = *Second moment of area of the truss along x-axis [m^4]*
$I_{y\,truss}$ = *Second moment of area of the truss along y-axis [m^4]*

Hence, within Karamba 3D, the selected cross section for the chords was exploded and its parameters were utilized to determine the second moment of area of the x-axis and the y-axis of the truss. Afterwards, a solid rectangular cross section was created by matching the total height of the truss and the second moments of area. To determine the base of the truss, the formula for the second moment of area of a rectangular section was reversed and utilized as follows:

$$I_{x\,simplified\,truss} = \frac{b{*}H^3}{12} \quad \cdots\cdots\cdots\blacktriangleright \quad b = \frac{12{*}I_{x\,simplified\,truss}}{H^3}$$

Where: b = Base of the rectangular cross section [m]
H = Height of the truss = Height of the rectangular cross section [m]
$I_{x\,simplified\,truss}$ = *Second moment of area of the truss along x-axis [m^4]*

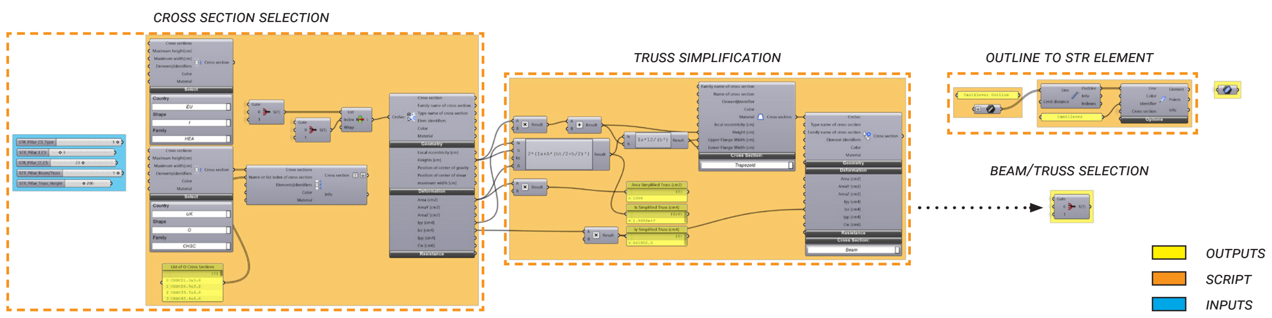


Figure 48. Example of a script for cross section selection (Pillar), with a choice between truss and beam element (Source: Self-made)

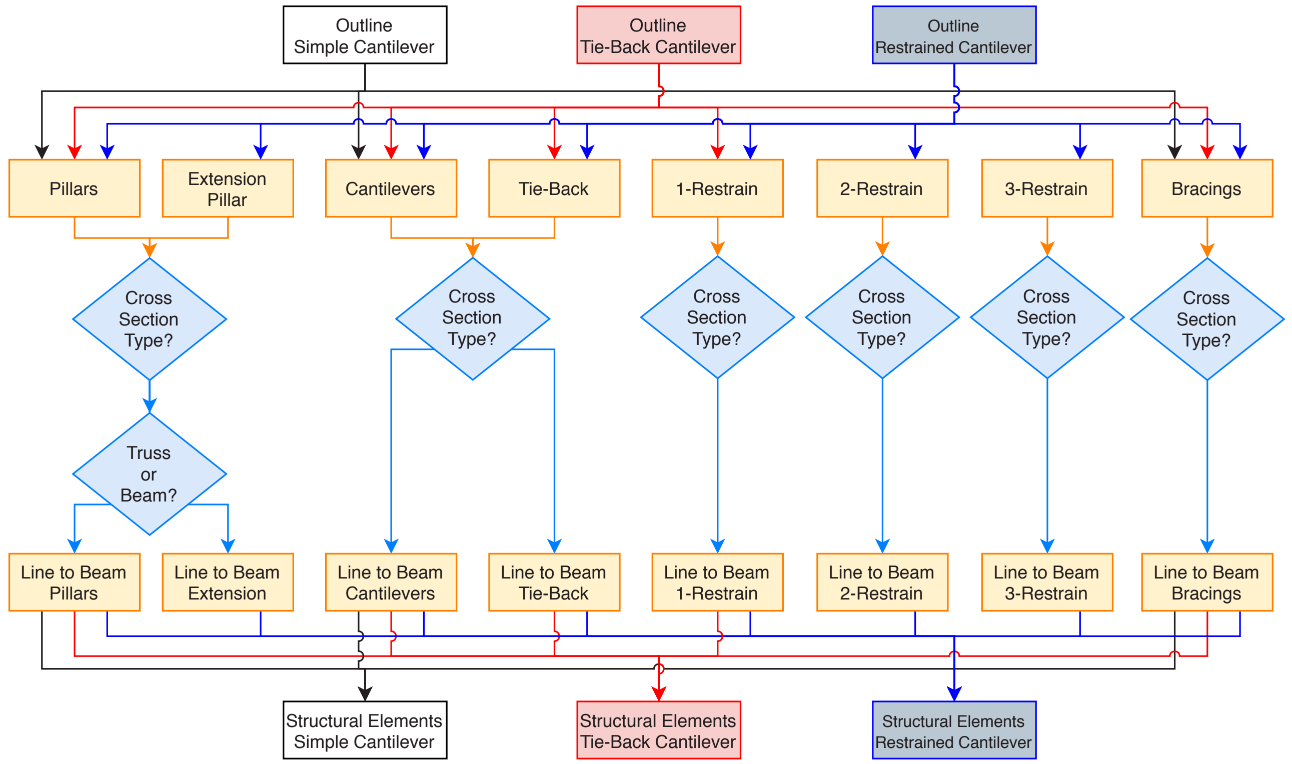


Figure 49. Flowchart of the workflow followed to implement the structural elements within Karamba 3D (Source: Self-made)

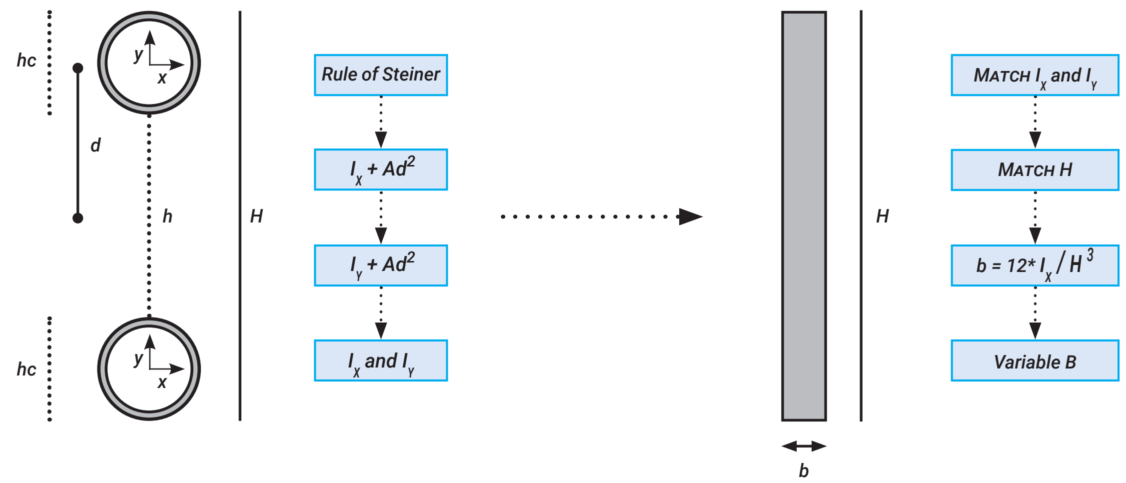


Figure 50. Scheme of Simplification of the trusses (Source: Self-made)

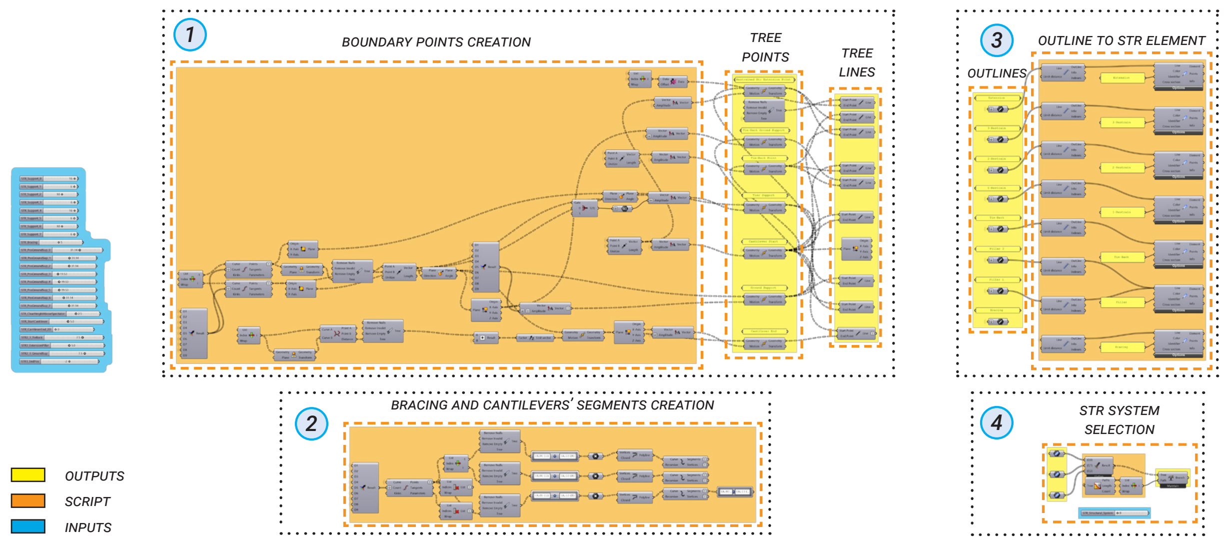


Figure 51. Script utilized to model the roof structure within Grasshopper (Source: Self-made)

06 | PERFORMANCE ASSESSMENT

PERFORMANCE ASSESSMENT

The second phase of the computational method consists in the performance assessment. As stated in section 3.2, the performance assessment consists in the evaluation of the design to determine to what extent it fulfill the set standards for one or multiple subjects. In this case, the viewing quality of the grandstands and structural performance of the roof were evaluated. In order to perform the assessment, measurable evaluation criteria and indicators had to be individuated. The performance indicators and the workflow followed to implement these features in the computational method are presented in this chapter.

6.1 Set-up

On the one hand, the viewing quality of the grandstands was defined as the comfort of the spectators into following the activity held in the stadium. On the other hand, the objective of the roof structure is to transfer the dead-weight and the external loads to the ground. Few indicators have been individuated to evaluate both performances. Concerning the computational tools, the evaluation was performed with Grasshopper and BowlBuilder (mmarschall, 2018), while the structural performance was performed within Karamba 3D (Preisinger, 2018) after an initial evaluation of the structural systems within DIANA FEA (TNO, 2003) to gain an insight on their behaviours.

Concerning the viewing quality, the tree structure of the eye-points of the spectators is utilized as the main input for the evaluation. Indeed, the eye-points represent the spectators seating in the stands. In this case, the c-value, the proximity to the pitch, the field of view and the vertical viewing angle were utilized as main indicators. More in depth, the performances based on the indicators are related to the overall stadium and, in few cases, to the tiers of stands. Indeed, this categorization is necessary to individuate the portions of the stadium that are worth to be kept and those that necessitate a refurbishment. Lastly, the results are displayed by utilizing a color gradient map to provide a graphic visualization of the data, while the values are listed in panels.

Concerning the roof structure, an initial evaluation of the behaviour of the structural system was performed in DIANA FEA. This step was necessary to gain an insight on aspects as the bending moment within the structures and to understand the global vertical deflection of the systems. Afterwards, the outline of the structural systems are utilized as the main input for the evaluation. In this case, the outline has to be transformed into structural elements to be read by Karamba 3D. Moreover, the supports, the loads, the joints and the cross sections have to be defined from the outline of the structural systems. Regarding the measurable criteria, the bending moments for the groups of structural elements are calculated to determine the stresses, as well as their vertical deflections. In addition, the mass of the structural systems are calculated, along with the number of elements and the number of joints within the structure. Furthermore, to check the stability of the structures, the stresses and the deflections are confronted with their limits (sub-section 4.1.4) for all the structural elements. Hence, the values are grouped and the maximum values are extrapolated. Lastly, the results are displayed by utilizing the "model view" and the "beam view" components of Karamba, while the values are listed in panels. Moreover, for every group of structural elements a solution is provided to individuate the element with the maximum deflection and stress to serve as a decision-making support system.

Laslty, in order to support the decision-making process of the designer for the evaluation of the performances and to set-up the optimization, two solutions are provided. On the one hand, the sections of the grandstands are produced and shown in 2D. On the other hand, the camera of Rhinoceros is set to the eye-points of the spectators to provide a simulated view of their sight from the stands. In this case, "Horster camera control for Grasshopper" (Fraguada, 2016) is utilized.

6.2 Viewing Quality

The viewing quality of the grandstands is defined as the level of comfort of the spectators in following the activity hold in the playing area. Few indicators had to be individuated to assess the performance. In this case, the indicators were selected in relation to two main aspects. On the one hand, the vertical viewing angle and the field of view were chosen to investigate the comfort of the spectators. Indeed, lower values indicate that the spectators can follow the activity without or with a slight movement of both head and torso. On the other hand, the C-value was chosen to investigate the obstruction of the view provided by the other spectators. Indeed, below a certain value (6 cm), the sighline of a spectator results to be obstructed. Lastly, proximity to the touchline was chosen to investigate how close the spectators are to the action. In fact, a lower distance enhances the atmosphere of a stadium. Except for the C-value and the field of view, which were analyzed with two components of "BowlBuilder", a Grasshopper script was produced to evaluate the proximity to the touchline and the vertical viewing angle.

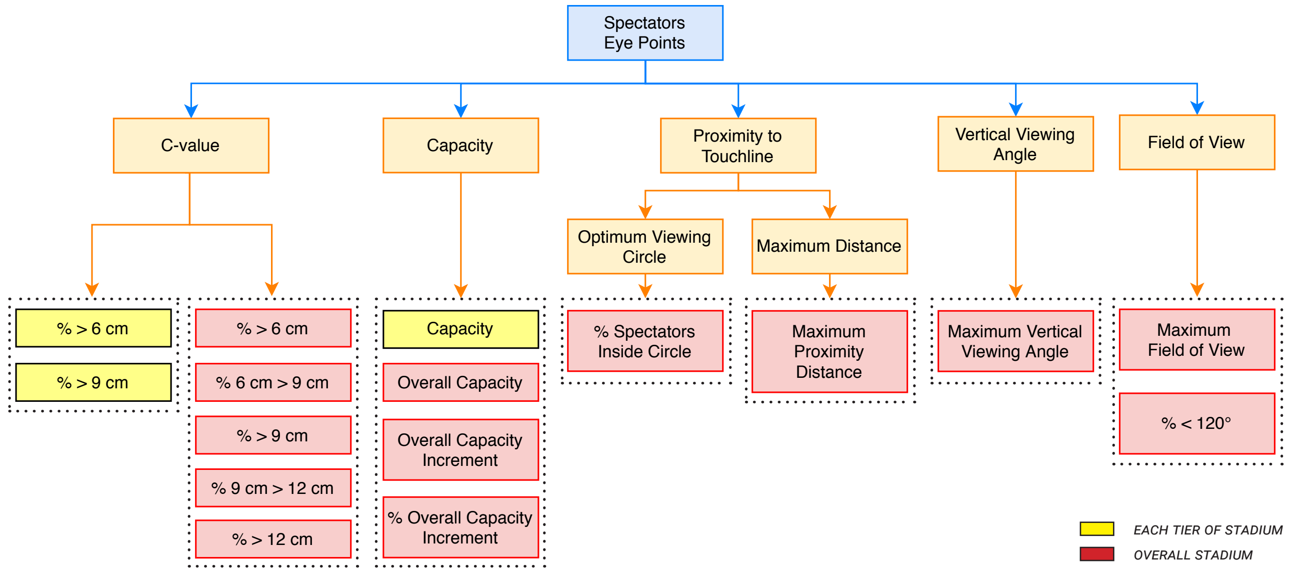


Figure 52. Flowchart of the evaluation for the viewing quality of the grandstands (Source: Self-made)

Concerning the objective of this thesis, a special focus was kept on the C-value, which is mainly utilized by FIFA (2011) and UEFA (2011) to evaluate the viewing quality of the grandstands. Hence, multiple data related to it were calculated to better assess this aspect in relation to both the overall stadium and each tier. In contrast, the other indicators were analysed only in relation to the whole stadium.

6.2.1 C-value

The tree structure of the filtered eye points of the spectators constituted the main input to evaluate the C-value the spectators. In this case, the BowlBuilder component "C-value" was utilized to calculate it. This component is realized with a phyton script that reduces the computational time needed to evaluate the performances compared to a Grasshopper script. Indeed, on the one hand a Grasshopper script would have required to individuate the focus point for all the spectators, to construct all the sightlines and to solve the intersection between them and two new sets of vertical and horizontal lines. Expecially this last step resulted to be time consuming and was slowing down the workflow. On the other hand, the "C-value" component evaluates the focus point for all the spectators and automatically calculates the vertical distance between the sequence of the sightlines.

Therefore, the tree structure of the eye points of the spectator was re-organized. Indeed, the points were re-ordered counter-clockwise and per stadium rows from the first tier to the last tier. Afterwards, the tree structure was fed to the "C-value" component to provide the spectators point of view, as well as the touchline curve to provide the focus of the sight. Hence, the output provided is a tree structure with the calculated C-value for the spectators. Once the values were calculated, the assessment was performed by taking into consideration the range of values individuated during the literature review phase. Indeed, as explained in sub-section 2.3.2, the European standards EN/DIN 13200-1 recommend range of 6 to 12 cm. Indeed, 12 cm is considered the optimal value for a good viewing quality, while 9 cm is the recommended value, and a c-value below 6 cm is considered as not acceptable.

Hence, the results were grouped in five different branches. The values higher than 12 cm were considered as excellent, while the values higher than 9 cm were considered as good and the values lower than 6 cm were considered poor. Moreover, intermediate values were taken into account. Indeed, the values between 9 cm and 12 cm were considered optimal, while the values in the range of 6 cm to 9 cm were considered acceptable.

Concerning the topic of renovation, it was necessary to evaluate the C-value for the overall stadium and for each tier of stands. Indeed, as explained in sub-section 4.1.5, the C-value plays a key role in determining which portion of the stadium is worth to be kept in case of renovation. Indeed, in relation to the set limits, a grandstand does not require renovation when:

% C-value recommended (> 9 cm) > 80%   % C-value poor (< 6 cm) = 0%

Whenever one of the two conditions is not matched, then the grandstands is considered to need a refurbishment. Lastly, it notable that the limit of 80% is set for this thesis, but a designer can determine his own limit based on the necessities of the project to be evaluated.

Lastly, the visualization of the results was realized with a color gradient in relation to the overall stadium. Indeed, this solution allows the designer to locate the areas of the stadium where the c-value is critical, therefore supporting the decision-making process. A lower limit of 6 cm was set and it was displayed in red, while 12 cm was selected as the upper limit and it was displayed in green. Considering the stand typologies included in the parametric model, the c-value is expected to decrease at every row of the tiers, with the maximum values located in the first row and the minimum values located at the last rows. Moreover, the first row of every tier is expected to have a C-value higher than 12 cm and therefore displayed in green. To conclude, the C-values of all the spectators and the explained percentages were grouped in panels to read the data, while the visualization can be switched on and off within Grasshopper.

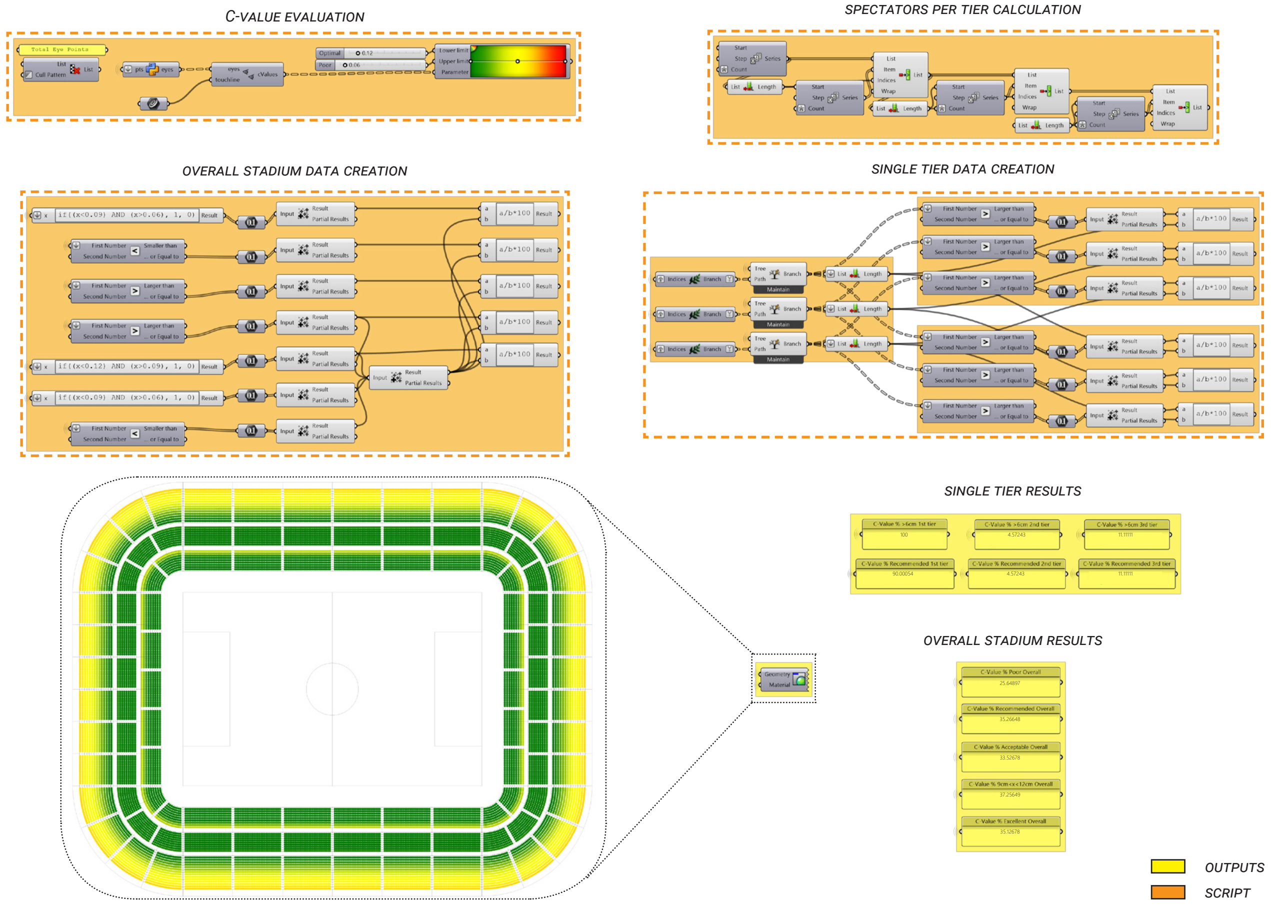


Figure 53. Visualization of the C-value and the script utilized to perform the evaluation (Source: Self-made)

6.2.2 Field of view

The tree structure of the filtered eye points of the spectators constituted the main input to evaluate the field of view of the spectators. In this case, the BowlBuilder component "field of view" was utilized to calculate it. This component is realized with a phyton script that reduces the computational time needed to evaluate the performances compared to a Grasshopper script. Indeed, on the one hand a Grasshopper script would have required to individuate the focus point for all the spectators, to construct all the lines connected to the corners of the touchlines and to calculate the angles between them. This last step would have required a greater manipulation of the data by furtherly subdivide the tree structure and cross referencing the eye points to the correct corners of the field. On the other hand, the "field of view" component of "BowlBuilder" does not necessitates this step, but exclusively the eye points of the spectators and the touchline curve to calculate the data.

Therefore, the tree structure of the eye points and the touchline were fed to the component to evaluate the field of view of the spectators. The output is a tree structure containing all the values for each spectator. Hence, the visualization of the results was realized with a color gradient in relation to the overall stadium. Indeed, this solution allows the designer to have an insight in the comfort of the spectators in the different areas of the stadium. Indeed, the field of view indicates the comfort of the spectators into following the activity, considering that a person standard field of view is up to 150°, with 120° as an angle that requires a slight movement of the head.
In this case, the upper limit is set to 120° and it is displayed in red, while the minimum value is taken from the results' list and it is displayed in green. The field of view is expected to increase towards the corners of the stadium and to the furthest seats from the touchline. Lastly, it should be noticed that, for few layouts (i.e. rounded rectangle geometry), the spectators located near the half line of the pitch will not be able to have a field of view lower than 120° due to the proximity to the pitch. In these cases, the field of view will not be selected as a constraint because the activity is considered as performed in only half of the pitch. To conclude, the values of all the spectators were grouped in panels to read the data, as well as the maximum and minimum and the percentage of the spectators with a field of view lower than 120°, while the visualization can be switched on and off within Grasshopper.

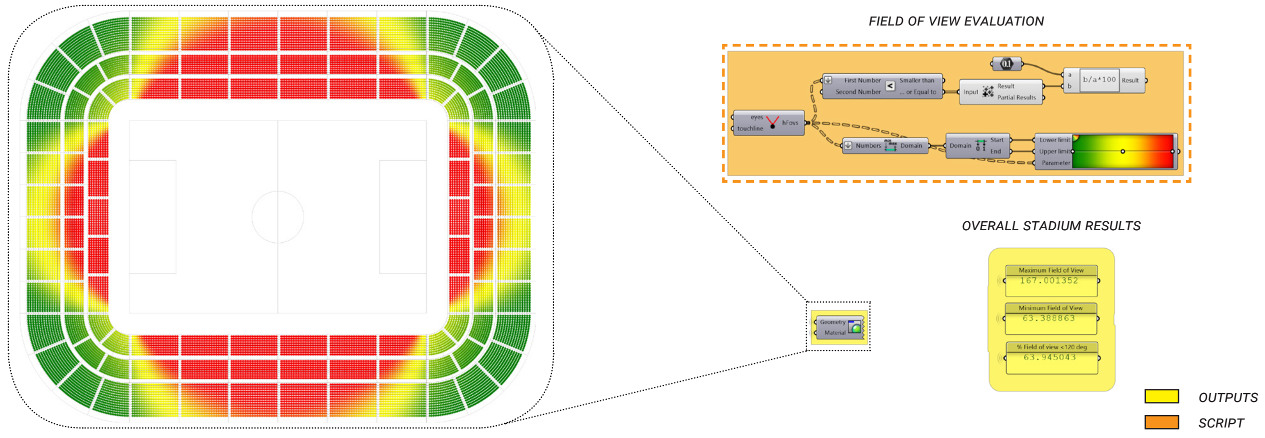


Figure 54. Visualization of the Field of View of the spectators and the script utilized to perform the evaluation (Source: Self-made)

6.2.3 Vertical Viewing Angle

The tree structure of the filtered eye points of the spectators constituted the main input to evaluate the vertical viewing angle of the spectators. In this case, a Grasshopper script was produced to calculate it. Therefore, the tree structure of the eye points and the touchline constituted the main inputs for the evaluation. Hence, the focus points for each spectator were individuated and two vectors were constructed. Firstly, a vector connecting the eye points and the focus points was created. Secondly, the horizontal sightline was constructed. Thus, the angle between the two vectors was calculated.

The visualization of the results was realized with a color gradient in relation to the overall stadium. Indeed, this solution allows the designer to have an insight in the comfort of the spectators in the different areas of the stadium. Indeed, the vertical viewing angle is the vertical angle between the horizontal sightline of a spectator and the line that connects the spectator's eye and the touchline. This performance indicator can be utilized to evaluate the comfort of the spectator into following the activity. Indeed, a smaller angle requires less movement of the head to follow the action on the pitch.

In this case, the upper limit is set to 60° and it is displayed in red, while the minimum value is taken from the results' list and it is displayed in green. The vertical viewing angle is expected to increase with the height of the seats. Therefore, the lower values should be located in the first row of the stadium, while the higher values should be located in the last row of the stadium. To conclude, the values of all the spectators were grouped in panels to read the data, as well as the maximum and minimum, while the visualization can be switched on and off within Grasshopper.

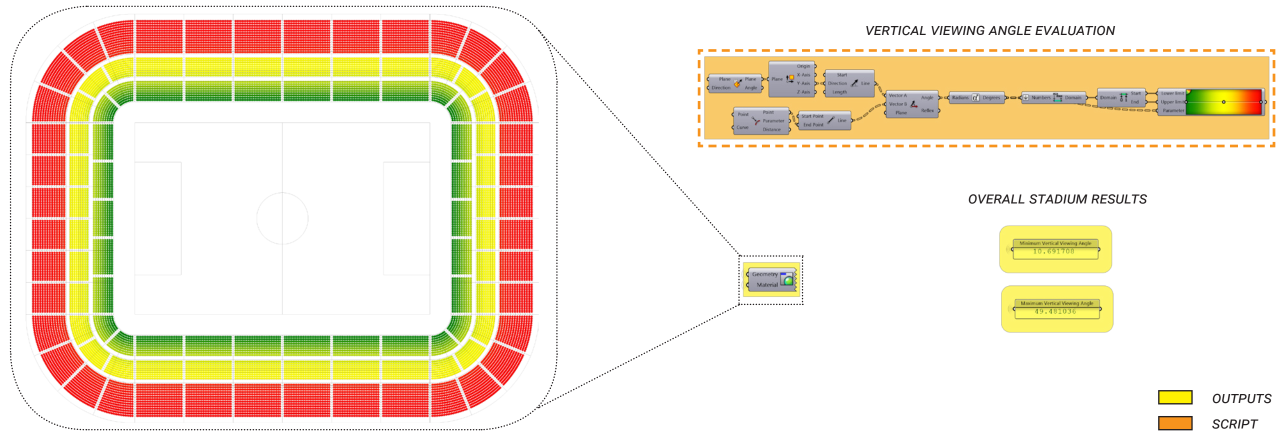


Figure 55. Visualization method and script utilized to perform the evaluation of the Field of View of the spectators (Source: Self-made)

6.2.4 Maximum distance

Two main aspects were analysed in relation to the maximum viewing distance. On the one hand, the proximity of the spectators to the touchline was analysed for the whole stadium, where the output provides the range of distances of the spectators from the pitch. On the other hand, the concept of the optimum viewing circle (sub-section 2.2.2) was utilized to determine how many spectators are provided with a finer view. In both cases, the tree structure of the filtered eye points of the spectators constituted the main input to evaluate the maximum distance of the spectators from the activity. In this case, a Grasshopper script was produced to evaluate both aspects.

Therefore, the tree structure of the eye points and the touchline constituted the main inputs to evaluate the proximity to the touchline. Firstly, the focus points for each spectator were individuated. Secondly, the eye points were projected on the ground level. Then, the distance between the two points was calculated. The output is a tree structure containing all the values for each spectator. Hence, the visualization of the results was realized with a color gradient in relation to the overall stadium. Indeed, this solution allows the designer to have an insight in the proximity of the spectators, which is an aspect related to the atmosphere created in the stadium during the venues. In this case however, the maximum and minimum values were taken from the results' list as boundaries for the color gradient visualization, but a designer can evaluate the proximity based on his own set of limits.

Concerning the optimal viewing distance, the optimum viewing circle was produced in Grasshopper by creating four arches from the corners of the touchline. The radius utilized is of 190 m, which is the maximum distance for which the spectators can clearly follow a football activity. Therefore, the eye points falling within the boundaries of the optimal viewing circle were extrapolated and visualized in green, while the ones falling outside it are visualized in red. Hence, the percentage of spectators inside the optimum viewing circle was calculated and provided as output.

Concerning the topic of renovation, the percentage of spectators falling within the maximum distance should be at least of 95%. Whenever this condition is not matched, this aspect should be taken into account during the optimization process to tally the set limit. However, it should be mentioned that a designer can evaluate the proximity based on his own set of limitations.

Lastly, the results of all the spectators were grouped in panels to read the data, as well as the maximum and minimum values, while the visualization can be switched on and off within Grasshopper.

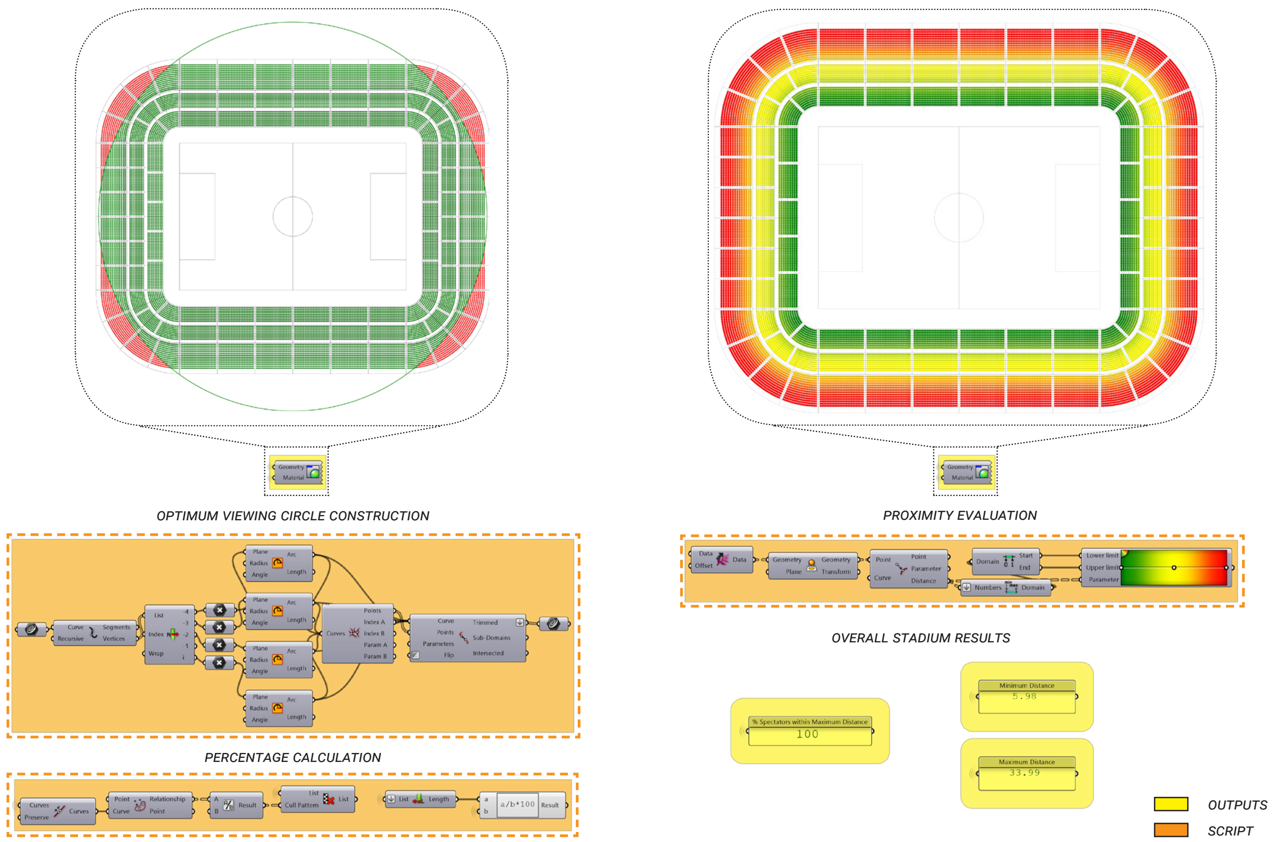


Figure 56. Visualization method and script utilized to perform the evaluation of the maximum distance of the spectators (Source: Self-made)

6.2.5 Capacity

As previously stated in sub-section 4.1.3, the capacity does not represent a performance indicator for the viewing quality, but it is however a crucial aspect to be evaluated. Indeed, it represents the number of tickets that can be sold for the venues, therefore providing an insight on the income of the stadium. After the form generation, the assessment of the capacity of the stadium did not require any particular script in order to assess the performance. Indeed, it was necessary to evaluate the length of the tree structures of the eye points to obtain the capacity of the stadium. However, an additional information was extrapolated to provide a wider insight on the number of seats present in the stands. Indeed, the capacity of each tier of stands is assessed. In fact, this information allows the designer to know the amount of seats in each tier, which is a factor that influences the price for the tickets of the stadium (Adams, 2003). To do so, the tree structure of the eye points is reorganized into three branches representing the three tiers of stands. Afterwards, the number of elements contained in each branch is extrapolated to obtain the number of spectators of the three tiers.

Lastly, the overall capacity and the number of seats in each tier were grouped in panels to read the data, while the visualization can be switched on and off within Grasshopper to observe the overview of the stadium's seats.

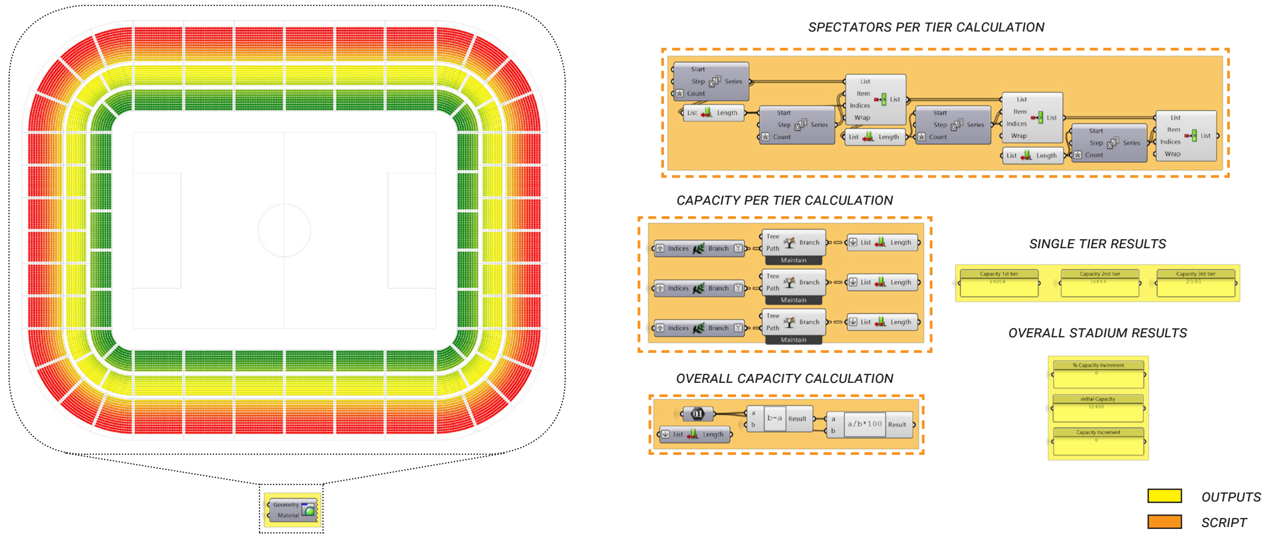


Figure 57. Visualization method and script utilized to perform the evaluation of capacity of the stadium (Source: Self-made)

6.2.6 Decision-Making Support

The performance assessment of the viewing quality permits to understand the behaviour of the grandstand geometry from an analytical point of view. However, graphic visualization methods can enhance the interpretation of the results and help the designer into making decisions. On the one hand, the objective is to simplify the comprehension of the output of the performance assessment and to provide a more detailed insight. On the other hand, the goal is to facilitate the decision-making process for the renovation of the stadium. Concerning the proposed computational method, two decision-making support systems were implemented, which are the 2D sections of the grandstands and the points of view of the spectators.

- **2D Sections.** The 2D sections of the grandstands were produced utilizing the tree structure of the grandstand geometry and the tree structure of the total eye curves of the spectators. Initially, the tree structures were fed to a "divide curve" component to extrapolate the number of 2D sections to be produced. As an output, two tree structures of points were obtained: the first one containing the eye points of the spectators for the sections, while the second one containing the vertex of the grandstand geometry for the sections. Hence, this last tree structure was fed to a "polyline" component to draw the 2D section along the stadium bowl. Afterwards, the focus points were produced by projecting the eye points of the spectators on the touchline. Therefore, as a final output, three tree structures were produced: the first one containing the 2D section of the grandstands, the second one containing the eye points of the spectators and the third one containing the focus points. Lastly, the tree structures were oriented on the xy plane and the sightlines were drawn by connecting the eye points to the focus points.

  Lastly, a slider input was utilized to select and explore one 2D section per time. In general, this solution allows the designer to observe the plan view of the stadium and to select the portion to evaluate further. Moreover, the drawn sightlines allows for a visual interpretation of the C-value.

- **Points of View.** The points of view of the spectators were realized "Horster camera control for Grasshopper". Indeed, this Grasshopper plug-in provides a "set camera" component to automatically set the camera of of Rhinoceros to a certain location by providing a point, a direction and a focus point. In this case, the eye points of the spectators were utilized to create a tree structure of vectors representing the sightline of the spectators. Hence, the eye points of the spectators, the sightlines and the focus points were fed to the "set camera" component and a slider input was utilized to provide the possibility to select one of the points of view.

  In general, this solution allows the designer to investigate the actual point of view of the spectator for a more detailed analysis of the viewing quality of the stadium.

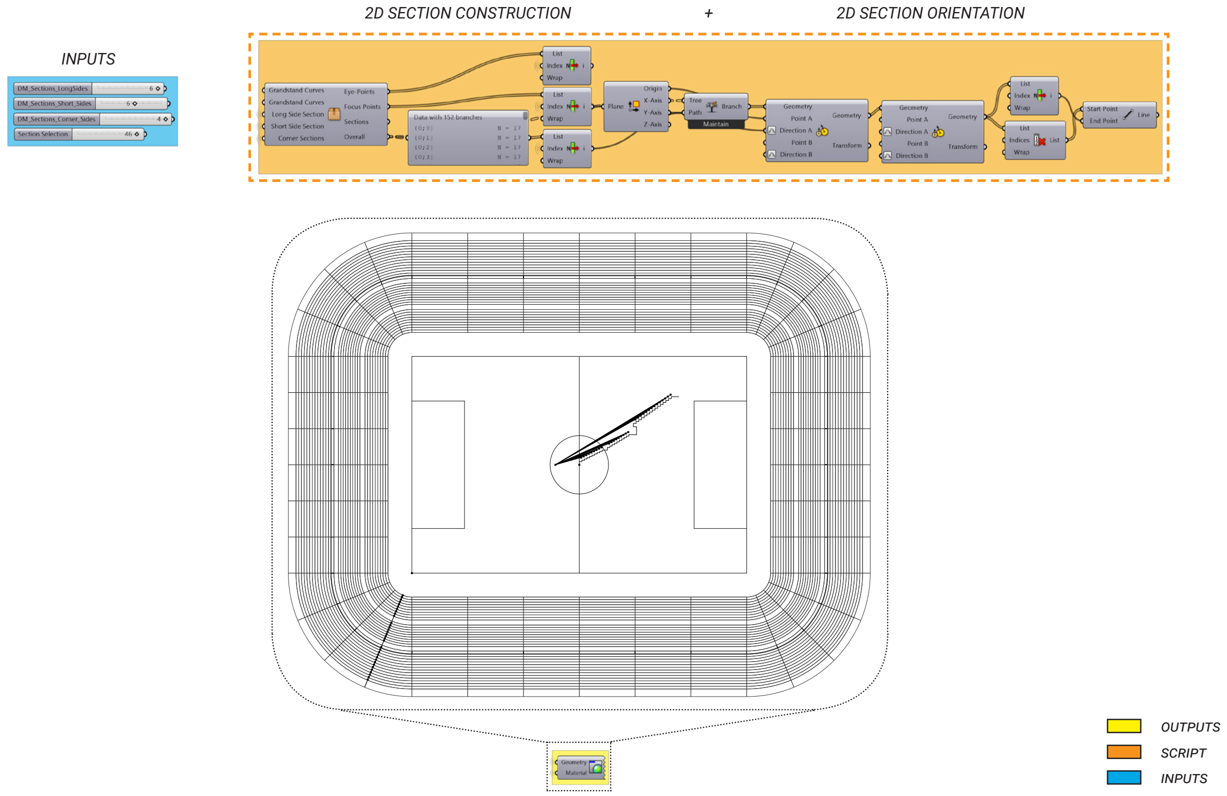


Figure 57. Visualization method and script utilized to produce the 2D sections (Source: Self-made)

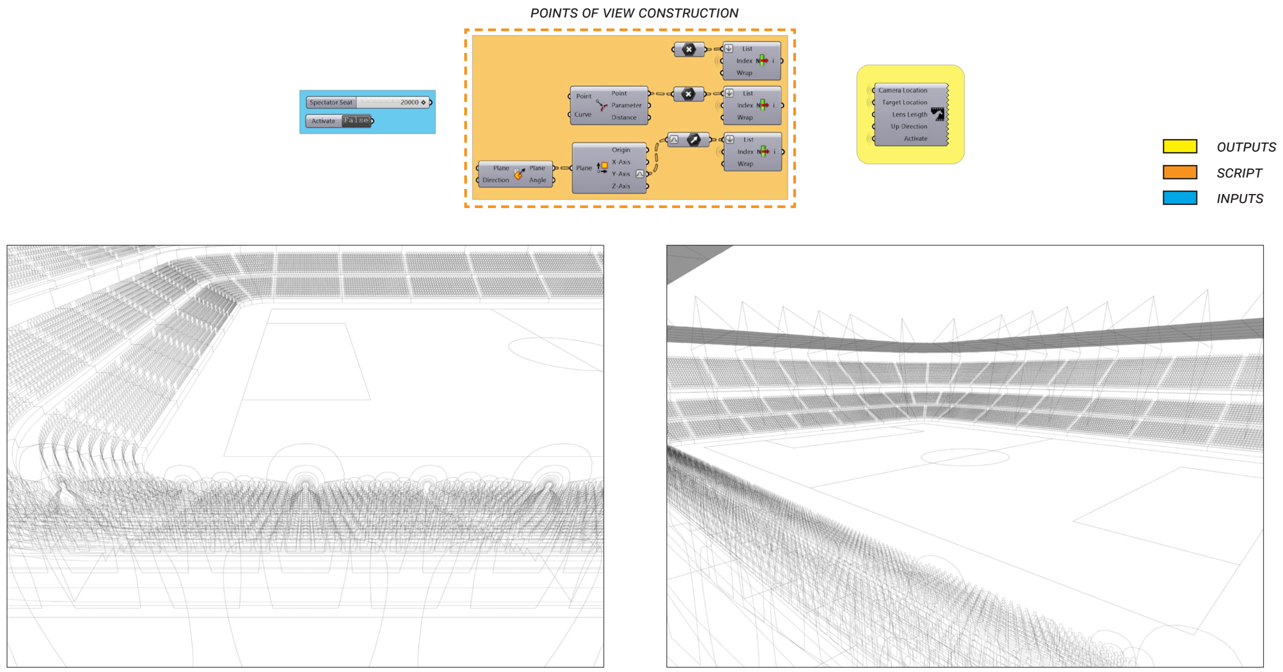


Figure 58. Visualization method and script utilized to produce the points of view of the spectators (Source: Self-made)

6.3 Structural Performance

The main objective of the roof structure is to transfer the dead weight and the external loads to the ground and to provide cover for the spectators seating in the stands. As previously stated in section 2.4, the roof structure of a stadium influence greatly the overall cost of a stadium. Hence, it is necessary to reduce the amount of material utilized to construct it in order to contain the expenses of the design. Considering these aspects, the structural performance assessment is carried out in order to evaluate the roof to ensure stability and to evaluate the features as the mass and the number of elements and joints needed to build it. In this chapter, an explanation of how the performance assessment of the structure was implemented in the computational method is provided.

Firstly, the structural systems described in sub-section 4.1.2 were simplified and evaluated within DIANA FEA to have an insight on their behaviour. Indeed, this evaluation allowed to understand where the maximum stresses and the maximum deflection are located within the structural elements. Secondly, the performance assessment was implemented within the computational method through Karamba 3D. The initial set-up concerning the support sets, the loads and the joints was realized. Then, the stresses, the deflections and features as the mass and the number of elements and joints were extrapolated. Lastly, the results were listed within panels and a visualization method with Karamba was produced to visualize the results.

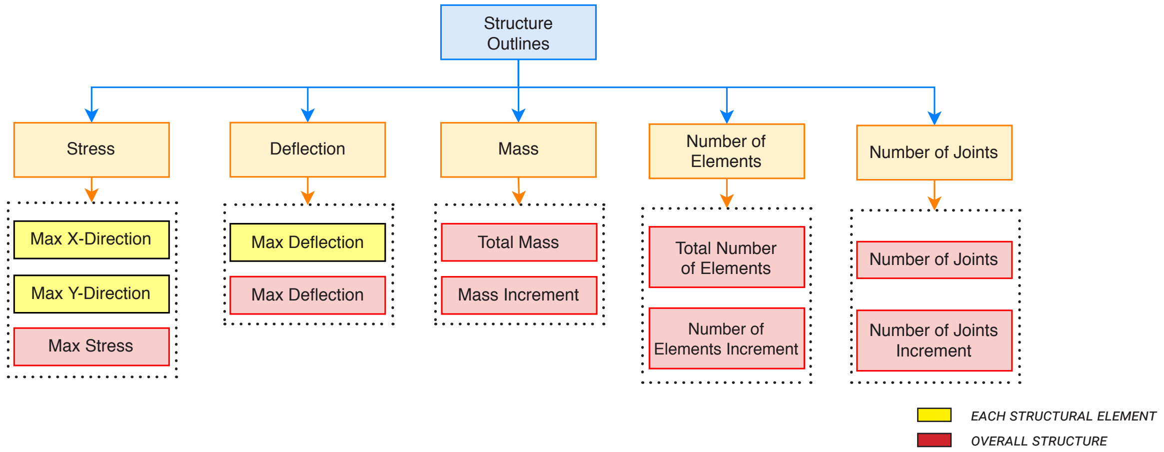


Figure 59. Flowchart of the evaluation for the structural performance of the roof (Source: Self-made)

6.3.1 Behaviour of the Structural Systems

The three structural systems implemented in the computational method have been introduced in sub-section 4.1.2. In order to have an insight on the behaviour of the principal elements of the roof structures, an initial evaluation was performed in DIANA FEA. It is notable that the evaluation was carried out exclusively to understand where the maximum deflections and the maximum stresses are located within the structural elements of the three structural systems with the different support sets individuated. Hence, the purpose is to individuate critical points for stability.

Considering the complexity of the structure, the DIANA FEA model was simplified. Indeed, the evaluation was carried out exclusively on the primary elements of the structure, therefore neglecting the action of the bracings. In relation to the loads, the dead weight was considered for all the structural elements, while the snow load and the wind load were considered to be acting exclusively on the cantilever elements. In this case, the wind load and the snow load were considered to act on the cross section of the elements. Hence, the load value is multiplied by the width of the cantilever elements. Lastly, the global deflection of the Y-axis was evaluated, as well as the bending moment acting on the Z-axis of the elements, which causes the maximum stresses within the elements since all the loads are acting on the y-axis. The simplified model is presented in figure 60.

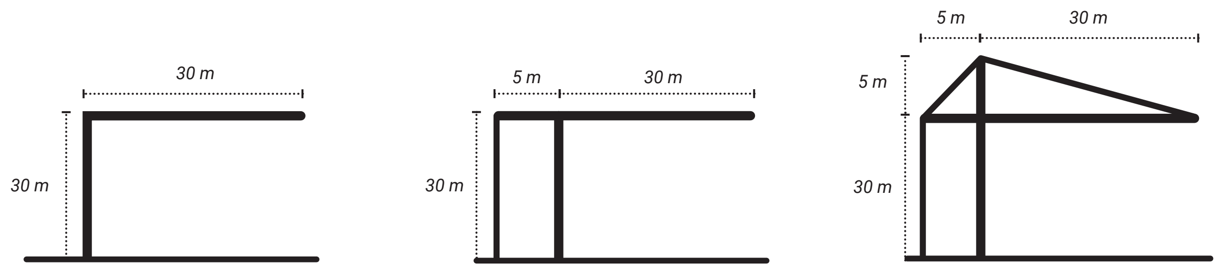


Figure 60. Structural Schemes: Simple Cantilever (Left), Tie-Back Cantilver (Middle) and Restrained Cantilever (Right) (Source: Self-made)

Concerning the cross sections, all the structural elements were simplified by considering the same cross section, which is a UK CHSC 1016x3.0 circular hollow beams. The properties of the beam are listed in figure 61.

Cross Section	Outer Diameter (m)	Thickness (m)	Inner Diameter (m)	Ix (m^4)	Iy (m^4)
CHSC1016x30.0	1,016	0,03	0,929	0,01130352	0,01130352

Figure 61. Properties of the cross section utilized in DIANA FEA (Source: Self-made)

The loads considered in the evaluation are the same implemented within Karamba 3D. Hence, the dead weight of the structural elements, the snow load as 1,5 kN/m^2 and the wind load for the uplift effect acting downwards as 0,8 kN/m^2, which is assumed as the worst case scenario for the structure. In this case, as a simplification of the model, the roof surface is not considered, as well as the bracing. Hence, the snow load and the wind load were applied exclusively on the cantilever parts of the structural systems. Therefore, the values had to be calculated as kN/m to create the distributed load acting on the cantilever elements. Thus, the values utilized were inserted as:

Snow Load = 1,5 kN/m^2 x Diameter = 1,5 kN/m^2 x 1,016 m = 1,524 kN/m
Wind Load = 0,8 kN/m^2 x Diameter = 0,8 kN/m^2 x 1,016 m = 0,812 kN/m

The loads were then divided into four different load combinations. The load combinations are shown in figure 62, while the application of the loads on the structural elements is presented in figure 63.

Load Combinations	Dead Weight (kN/m)	Snow Load (kN/m)	Wind Load (kN/m)
LC1	x		
LC2		x	
LC3			x
LC4	x	x	x

Figure 62. Load Combinations created in DIANA FEA (Source: Self-made)

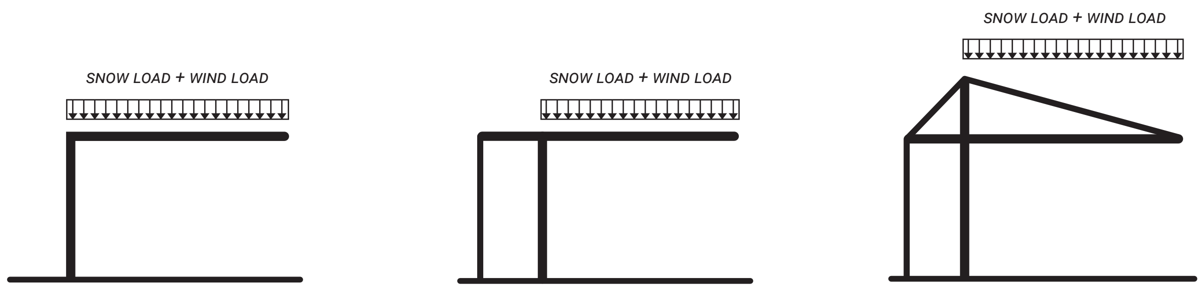


Figure 63. Scheme of the loads applied on the structural systems in DIANA FEA (Source: Self-made)

Concerning the material, it was selected based on the boundaries of the computational method. Hence, steel S235 was applied to all the structural elements to perform the evaluation within DIANA FEA. The properties of the material are presented in figure 64.

Structural Elements	Density (kg/m^3)	Unit Weight (kN/m^3)	Young's Modulus (Mpa)	Yield Strength (Mpa)
STEEL S235	7850	78,5	210000	235

Figure 64. Material Properties set in DIANA FEA (Source: Self-made)

Lastly, the support sets (see sub-section 4.1.2) were implemented within DIANA FEA and the evaluation was run. For each structural system and for each support set, the global deflection and the bending moment acting on the y-axis were evaluated. Initial hypothesis were established. In these regards, on the one hand the maximum deflection for all the structural systems was expected to be located in the cantilever element, more precisely at the free-end point of the beam. Concerning the three structural systems, the deflection was expected to be higher for the simple cantilever, while the value was expected to be reduced with the tie-back and to be even lower with the restrained cantilever On the other hand, the maximum bending moment was expected to be located at the connection between the cantilever beam and the pillar. Concerning the three structural systems, the maximum bending moment was expected to be located within the cantilever and the pillar for the simple cantilever system, while the tie-back and the restrained cantilever were expected to show the maximum bending moment exclusively acting on the cantilever beams.

A. Evaluation of Results

A structural linear static analysis was performed in DIANA FEA to evaluate the global deflection of the structure on the y-axis and to evaluate bending moment diagram on the z-axis. The objective was to obtain an insight on the behaviour of the structural systems under the considered load conditions. In this case, the results were visualized and understood only in relation to the load combination 4.

- **Simple Cantilever**

As expected, in the single cantilever system, the maximum bending moment was located at the corner joint between the cantilever beam and the pillar for all the three types of support sets. In this case, the highest value is referred to both the pillar and the cantilever element. Hence, it was noted to evaluate this critical location during the structural assessment within Karamba 3D for the computational method.

Concerning the global deflection, the maximum value was located at the end point of the cantilever beams, while the pillar had a deflection closer to 0 m. Hence, it was noted to evaluate this critical location during the structural assessment within Karamba 3D for the computational method.

In general, the support set 0 causes the maximum bending moment to be constant on the pillar, while the support set 1 and 2 reduces it greatly due to the presence of the hinge support of the grandstand. As well, the maximum deflection of the structure is greatly reduced with the support set 1 compared to the support set 0. Moreover, the support set 2 provides an additional reduction of the deflection value.

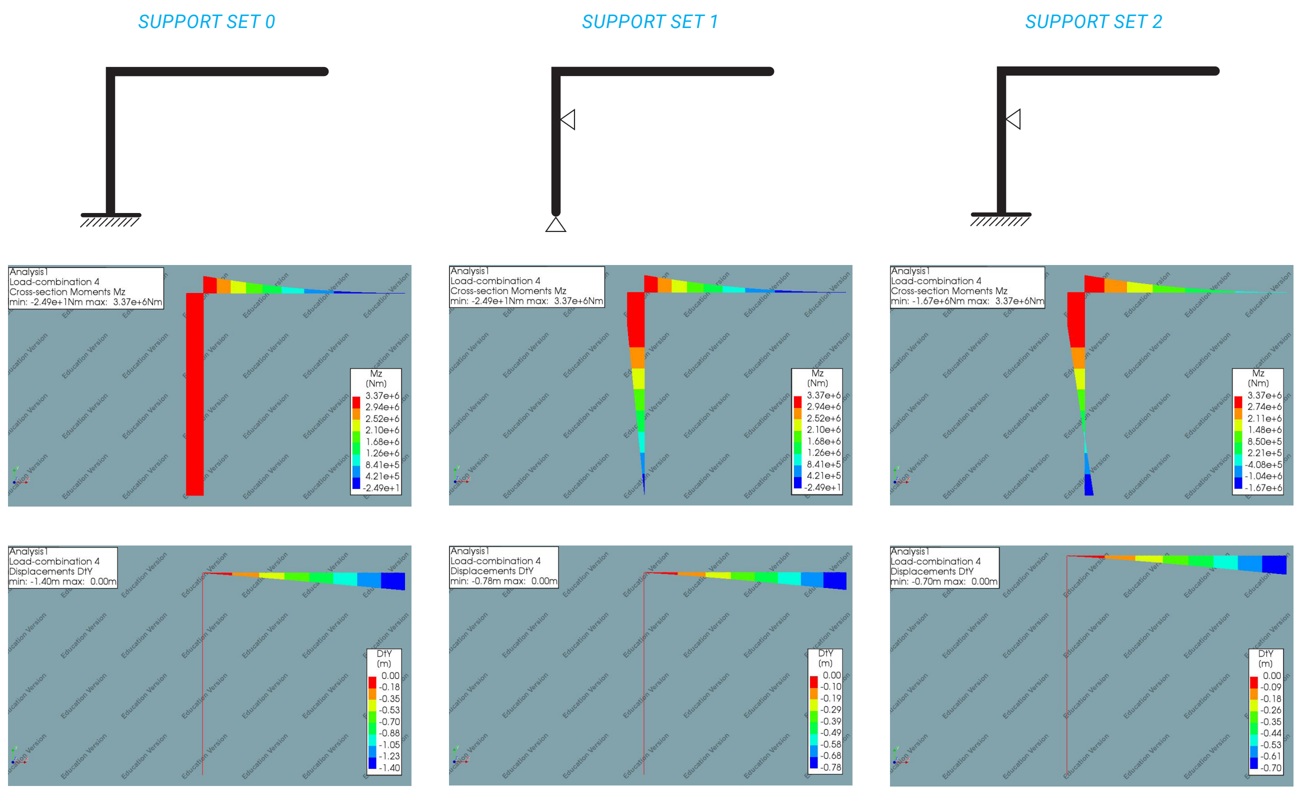


Figure 65. Structural system behaviour in DIANA FEA: Simple cantilver (Source: Self-made)

- **Tie-Back Cantilever**

As expected, also in the tie-back cantilever system the maximum bending moment was located at the corner joint between the cantilever beam and the pillar for all the three types of support sets. In this case, the highest value is referred only to the cantilever element. Indeed, the extension of the cantilever beam at the rear and the presence of the restraining element creates less bending moment within the pillar.

Concerning the global deflection, the maximum value was located at the end point of the cantilever beams, while the pillar had a deflection closer to 0 m. Hence, it was noted to evaluate this critical location during the structural assessment within Karamba 3D for the computational method.

In general, the support set 0 causes the maximum bending moment to be constant on the pillar, while the support set 1 and 2 reduces it greatly due to the presence of the hinge support of the grandstand. Concerning the global deflection of the structure, the support sets 1 and 2 provide a slight benefit to the deflection of the structure, which results to be reduced.

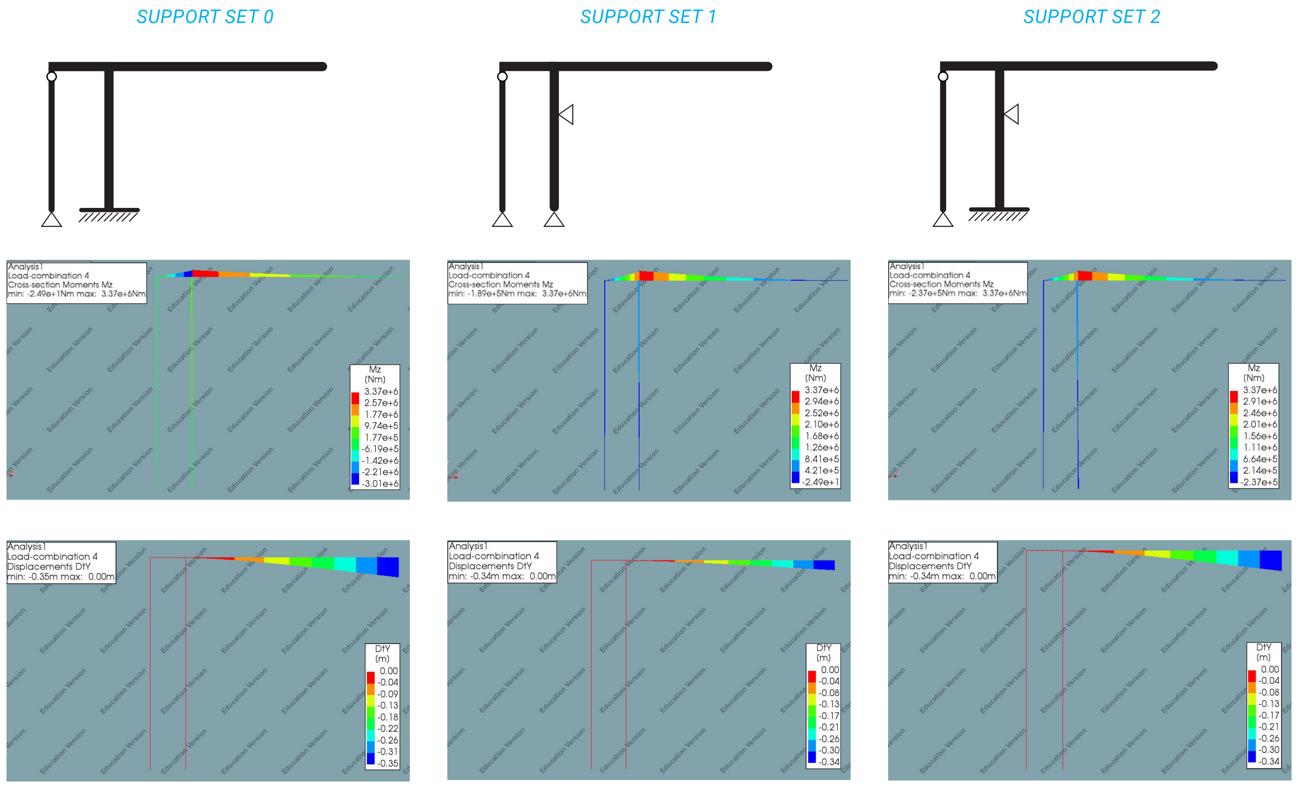


Figure 66. Structural system behaviour in DIANA FEA: Tie-Back cantilver (Source: Self-made)

- **Restrained Cantilever**

As expected, also in the tie-back cantilever system the maximum bending moment was located at the corner joint between the cantilever beam and the pillar for all the three types of support sets. In this case, the highest value is refered only to the cantilever element. Indeed, the extension of the cantilever beam at the rear and the presence of the restraining elements creates less bending moment within the pillar.

Concerning the global deflection, the maximum value was located at the end point of the cantilever beam, while the pillar had a deflection closer to 0 m. Hence, it was noted to evaluate this critical location during the structural assessment within Karamba 3D for the computational method. In addition, the global deflection diagram shows that the maximum value is located also within the third restraining element.

In general, the support set 0 causes the maximum bending moment to be constant on the pillar, while the support set 1 and 2 reduces it greatly due to the presence of the hinge support of the grandstand. Concerning the global deflection of the structure, the support sets 1 and 2 seems to provide a slight benefit to the deflection of the structure, which results to be reduced.

Overall, the critical points of the three structural elements results to be the corner joint between the pillars and the cantilever beams where the maximum bending moment is located. Moreover, the end point of the cantilever beams has to be considered as well as a critical point since the maximum deflection of the is located in that position.

Concerning the support sets, the support set 1 and 2 help in reducing the bending moments and the deflections of the structures. More in depth, the first support set eliminates the bending moment within the base of the pillar. Concerning the structural systems, the restrained cantilever reduces greatly the deflection of the structure and the bending moment compared to the tie-back and the simple cantilever, with the last one being the most engaged structural systems in relation to the bending moment diagram and the maximum deflection of the structure.

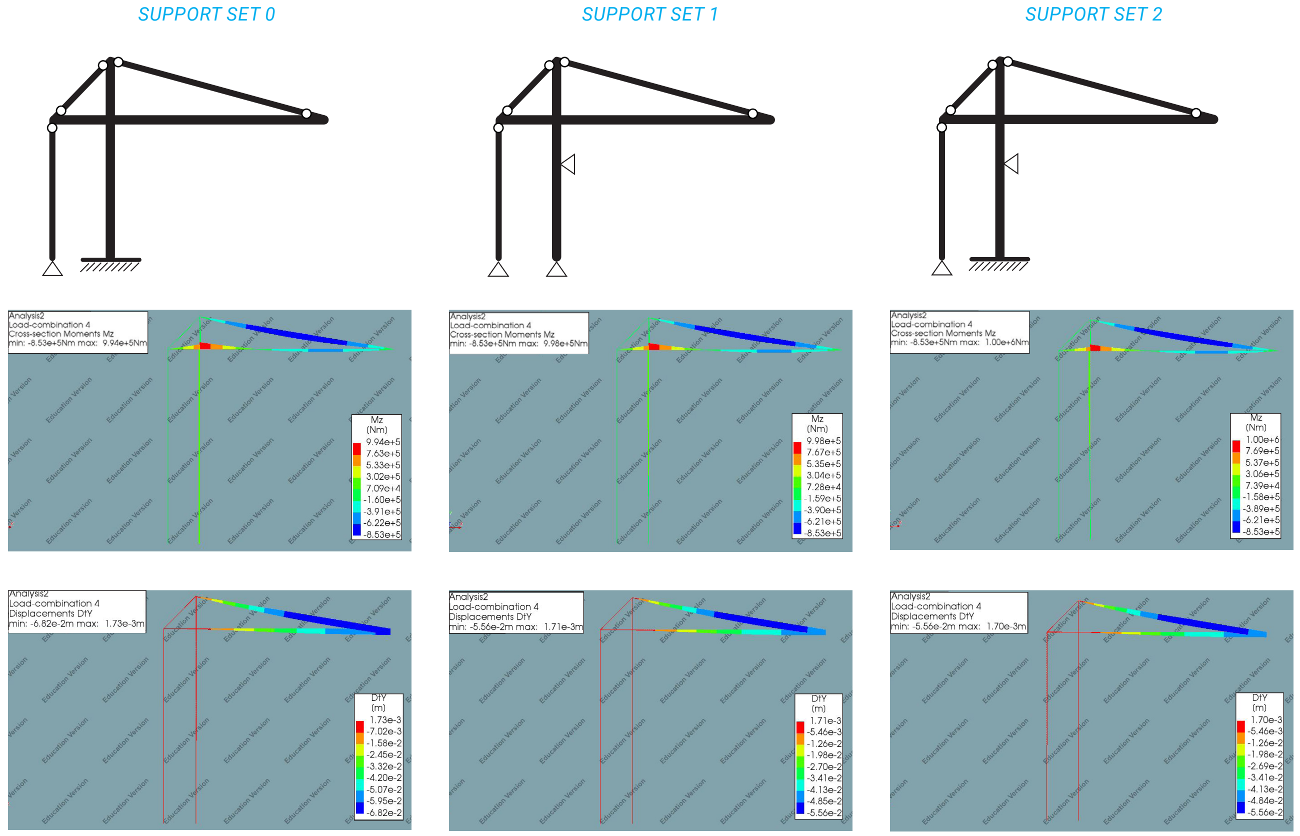


Figure 67. Structural system behaviour in DIANA FEA: Restrained cantilver (Source: Self-made)

6.3.2 Karamba 3D Set-up

The outline of the structural systems implemented in the computational method described in sub-section 5.5.1 constituted the main input for the structural evaluation within Karamba 3D. However, an initial set-up of the structure was necessary to implement the support sets, the loads, the materials and the joints between the elements. Concerning the implementation of the cross sections, the process followed was described in sub-section 5.5.2., while an overview of the groups of structural elements and the variety of cross sections elements is presented in figure 68 and figure 69.

STRUCTURAL ELEMENTS

Structural Elements	Simple Cantilever	Tie-back Cantilever	Restrained Cantilever	Released Rotation Y-axis at Start-Point	Released Rotation Y-axis at End-Point
Pillar	x	x	x		
Cantilever	x	x	x		
Bracing	x	x	x	x	x
1- Restrain		x	x		x
2- Restrain			x	x	x
3- Restrain			x	x	x

Figure 68. Overview of the groups of structural elements implemented in Karamba 3D (Source: Self-made)

ELEMENT TYPOLOGY AND CROSS-SECTION

Structural Elements	Beam Option	Truss Option	Circular Hollow Profile (UK CHSC)	I - Profile (EU HEA)
Pillar	x	x	x	x
Cantilever		x	x	x
Bracing	x		x	x
1- Restrain	x		x	x
2- Restrain	x		x	x
3- Restrain	x		x	x

Figure 69. Overview of the element typologies and cross sections implemented in Karamba 3D (Source: Self-made)

A. Support Sets

As previously mentioned, three support sets were implemented within the computational method. Karamba 3D provides a “support” component to establish the support conditions and apply them to a set of points and in reference to a set of plane for each point. Hence, three tree structures of points were needed to create the support sets of the three structural systems. The sets of points utilized are the ground points at the base of the pillars, the grandstands points to create the connection between the stands and the roof structure and lastly the tie-back points at the base of the first restraining element.

In this case, the tree structure of the ground points and the grandstand points were converted to planes and fed to the support components to determine the support condition for each set. It is notable that, in order to avoid the creation of two supports in the same position, which can alter the results of the performance assessment, the tree structure were flattened and filtered through a “cull points” component. Moreover, the indexes output of the component is utilized to cull the planes related to the rejected points. Afterwards, the created supports were grouped and entwined in relation to the structural system to which they had to be applied. Then, a slider input is utilized to provide the possibility to choose which support set should be utilized. Hence, only one of the support set is allowed to procede along the data stream. Subsequently, the supports of the first restraining elements were created following the same workflow and were entwined further. Lastly, based on the chosen structural system to utilize, only one of the completed support set is allowed to continue with the data stream.

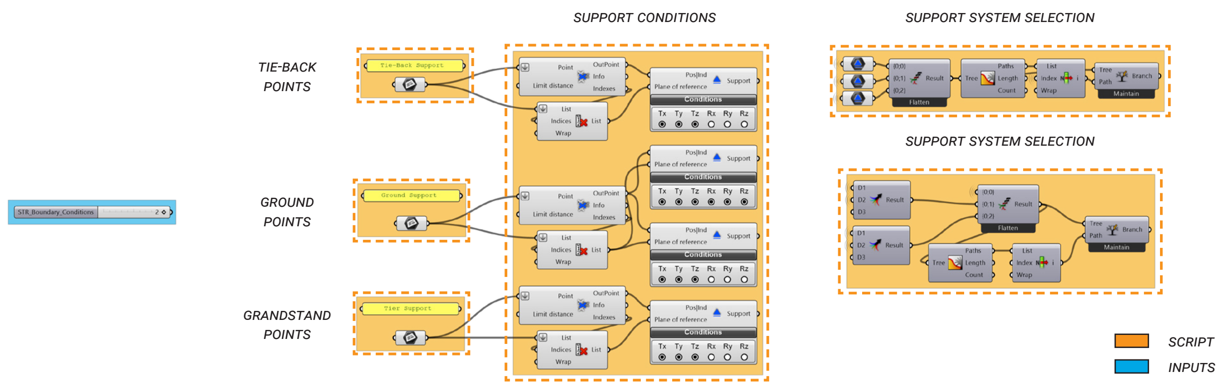
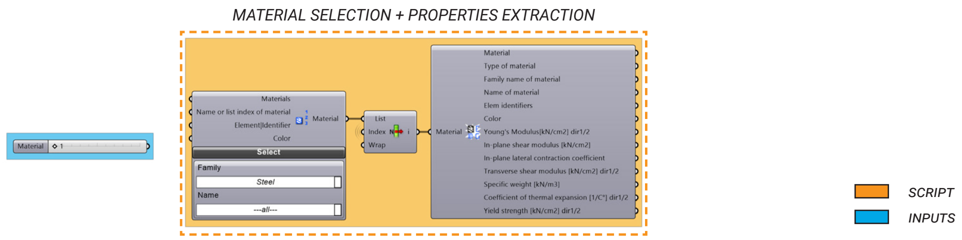


Figure 70. Script utilized to implement the support sets in Karamba 3D (Source: Self-made)

B. Material

As previously mentioned, three materials were implemented within the computational method. Karamba 3D provides a wide range of materials within a “material” component to establish the material properties of the elements of the structure. In this case, the material was directly connected to the 3D model to evaluate since all the structural elements were considered to be realized with the same typology of steel.

Hence, the selected materials (Steel S235, S275 and S355) were selected through a “list item” component and a slider input and was fed to the 3D model of the structure for the evaluation. In addition, the selected material was disassembled to extract its properties. Indeed, the density and the unit weight were utilized to calculate the dead weight of the roof structure and the overall mass of the roof.



Structural Elements	Density (kg/m^3)	Unit Weight (kN/m^3)	Young's Modulus (Mpa)	Yield Strength (Mpa)
STEEL S235	7850	78,5	210000	235
STEEL S275	7850	78,5	210000	275
STEEL S355	7850	78,5	210000	355

Figure 71. Script utilized to implement the materials in Karamba 3D (Source: Self-made)

C. Joints

As previously mentioned, the three structural systems require to release the rotation on the y-axis of the elements. In particular, the bracings, the second and the third restraining elements have a hinge connection to the pillars and the cantilevers. As well, the same degree of freedom was released for the first restraining elements. However, in this case, the rotation on the y-axis was released at the connection with the cantilevers only since an external support was set at their base.

Therefore, a “joint-beam” connection was utilized to release the degrees of freedom for the stuctural elements. Afterwards, the created joints were entwined and connected to a list item component. Therefore, the joint were connected to the 3D model to evaluate based on the selected structural system.

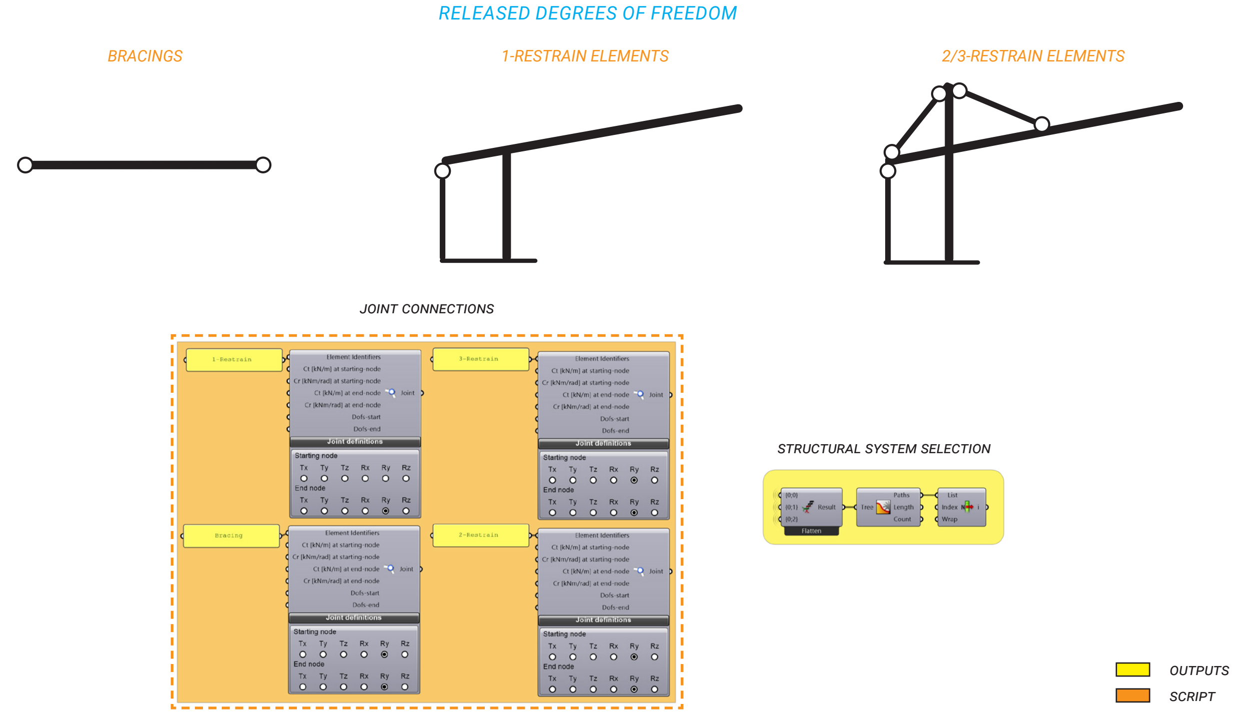


Figure 72. Scheme of Joints and Script utilized to implement them in Karamba 3D (Source: Self-made)

D. Loads

As previously mentioned, the loads considered for the performance assessment are the dead weight of the structure, the wind load as 1,5 kN/m^2 and the wind load for the uplift effect as 0,8 kN/m^2. Karamba 3D provides a “load” component to set the loads and to apply them on a selected set of structural elements. In this case, a mesh load was utilized to implement the snow load and the wind load. However, all three loads were applied on the elements as uniform line loads.

Concerning the dead weight, Karamba 3D is able to automatically calculate the weight of the structure by the application of the gravity acceleration to the elements. However, since the trusses were simplified to be implemented, it was necessary to calculate manually the dead weight of the structural elements in order to evaluate correctly the performance of the structure. In this instance, the weight of the trusses was implemented by considering the cross sections of the chords and by neglecting the presence of the diagonals. Hence, the materials and the cross section were firstly implemented. Secondly, the unit weight of the materials was extrapolated, as well as the area of the cross sections applied to the structural elements. Thus, the unit weight was multiplied by the area of the cross section to obtain the dead weight as kN/m. Then, the value obtained was fed to a negative Z vector and the load was applied to the correct structural element.

Concerning the snow load and the wind load, it was necessary to produce a mesh of the roof surface on which the loads had to be applied. Hence, a mesh was created by using the Grasshopper’s add-on “Pufferfish” (ekimroyrp, 2020). Indeed, this plug-in provides a “parameter loft mesh” component to create meshes and to refine them utilizing a set of curves and sliders as inputs. Thus, the outlines of the cantilever elements were utilized to create the mesh of the roof, which was later refined with a slider input set to 0,01 cm in both U and V direction. Indeed, the refinement of the mesh was a crucial step to set the mesh loads of both the wind and the snow. In fact, the “mesh-load” component of Karamba 3D applies a load vector at the center of every subdivision square of the mesh and automatically calculates the influence area of every structural element. Then, the uniform line load is calculated and applied to the elements. Lastly, the wind load was applied perpendicularly to the mesh, while the snow load was globally projected on it in the Z-direction.

It is notable that the wind loads and the snow loads were applied exclusively to the cantilevers and the bracing elements, therefore neglecting their action on the other structural elements. Indeed, it was decided to focus on the action of the roof surface, which is considered the most crucial portion of the overall structure. Lastly, the three loads were divided into four load cases combinations. Load combination 0 considers only the dead weight, while load combination 1 considers the snow load and load combination 2 examines the wind load. Lastly, the action of all the loads were grouped in load combination 3 to evaluate their effect combined.

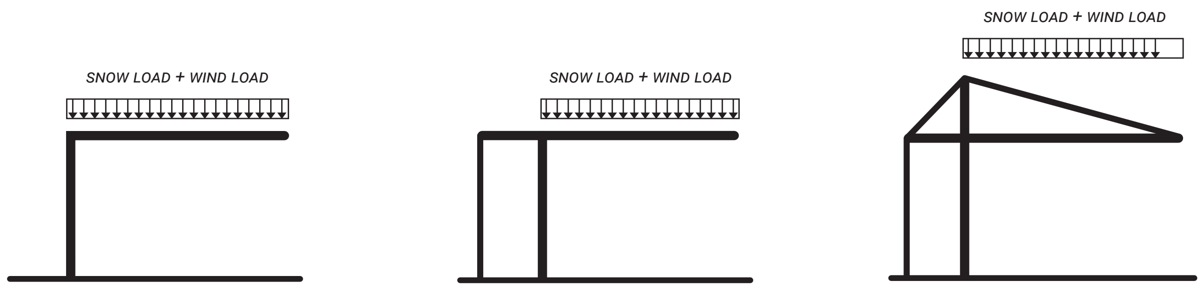


Figure 73. Scheme of the loads applied on the structural systems in Karamba 3D (Source: Self-made)

Load Combinations	Dead Weight (kN/m)	Snow Load (kN/m^2)	Wind Load (kN/m^2)
LC0	x		
LC1		x	
LC2			x
LC3	x	x	x

Figure 74. Load Combinations created in DIANA FEA (Source: Self-made)

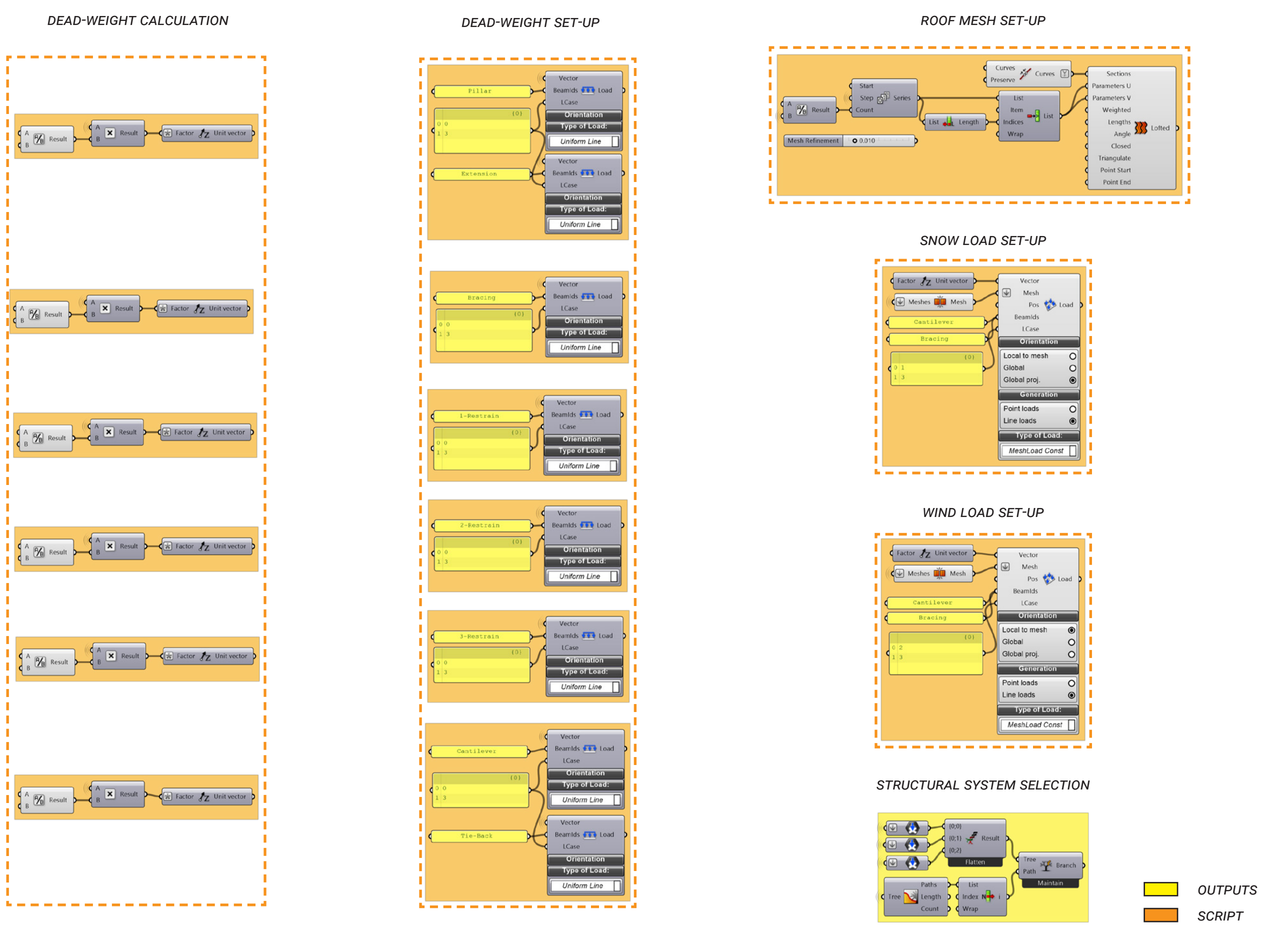


Figure 74. Script utilized to implement the loads in Karamba 3D (Source: Self-made)

E. 3D Model

Once the set-up was terminated, the elements, the loads, the joints, the supports and the materials were fed to the "assemble model" component of Karamba 3D to produce the 3D model of the roof structure. A slider input was implemented to easily switch between the structural systems and automatically modify the 3D model. Then, the model can be visualized with the "model view" component, which allows to observe the features of the model. Indeed, aspects as the load distribution and the cross sections applied to the structural elements can provide a useful user interface to understand the appearance of the roof structure.

Afterwards, the assembled model was fed to the "analyze" component of Karamba 3D for the evaluation. It is notable that Karamba 3D requires all the lists of information to be flattened in order to perform the analysis. The calculated model was then utilized to extrapolate the deflections and the stresses within the structural elements. Lastly, the "model view" and the "beam view" components were utilized to visualize the results. Indeed, the global displacement of the structure and the bending moments can be represented on the 3D model and highlighted with different color gradients to locate the most stressed portions of the structure.

Figure 75. Script utilized to assemble and analyze the 3D model of the roof structure in Karamba 3D (Source: Self-made)

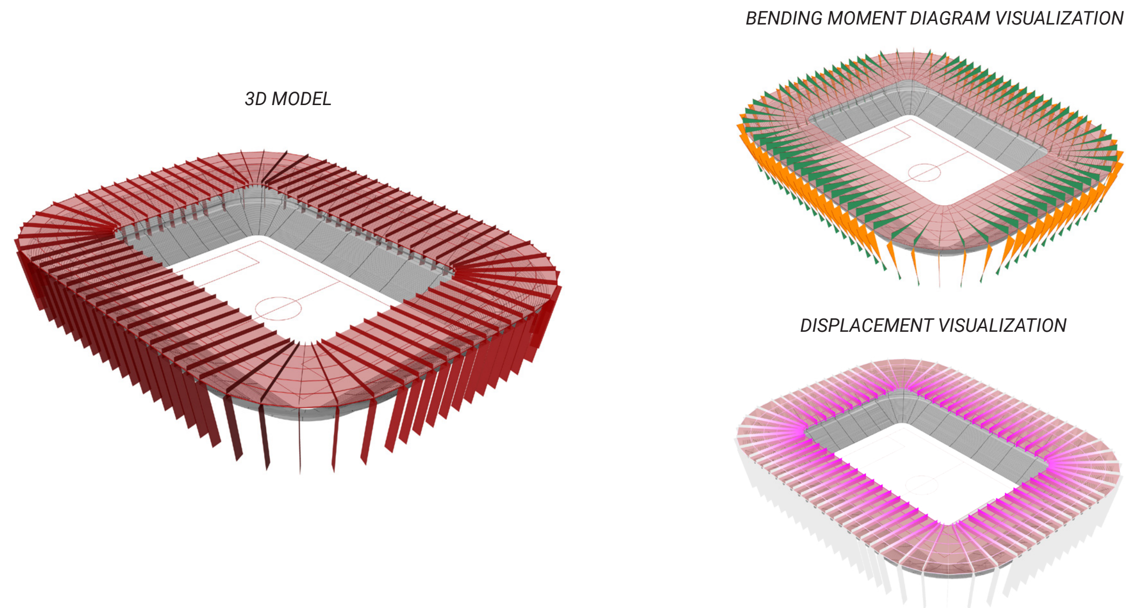


Figure 76. Examples of the visualization of the 3D model of the roof structure through Karamba 3D and Rhinoceros (Source: Self-made)

6.3.3 Displacement

The displacement was evaluated to ensure the stability of the structure. For all the elements, the deflection was calculated and confronted with a limit value. Considering the structural systems implemented, the limit values were set with a rule of thumbs of L/150 for cantilever elements and L/300 for the elements simply supported at both ends (Raven W. J., 2008). Considering the structural systems implemented, the limit value assigned to each group of structural elements is presented in figure 77.

Structural Elements	SIMPLE CANTILEVER	TIE-BACK CANTILEVER	RESTRAINED CANTILEVER	L/150 Limit	L/300 Limit
Pillar	x	x	x		x
Cantilever	x	x	x	x	
Bracing	x	x	x		x
1- Restrain		x	x		x
2- Restrain			x		x
3- Restrain			x		x

Figure 77. Limit Values for the displacement for each group of structural element. (Source: Self-made)

Concerning the workflow, the "element displacement" component of Karamba 3D was utilized to calculate the values. This components allows to evaluate the deflection of the structural elements along its length. In this case, the load combination considered for the evaluation of the displacement was the load combination 3, which results to be the most critical situation that the structure has to withstand. Moreover, the deflection was checked for the global z-direction for all the structural elements since no horizontal force is applied to the structure.

Taking into consideration the evaluation run in DIANA FEA and described in sub section 6.3.2, particular attention has to be kept on the deflection of the end points of the cantilever elements, which is the location of the maximum displacement for all the three structural systems. Concerning the other bracings, the deflection was checked at the center point where the maximum displacement is located. Regarding the pillars and the restraining elements, the deflection may not be located at their center since, based on the inclination of the elements, the maximum displacement can vary its position. Hence, the displacement was evaluated every 0,5 m along the length and the maximum value was extrapolated and confronted with the set limit value. Lastly, since the "element displacement" of Karamba 3D provides the deflection in relation to the global coordinates of the system, further calculation were needed to determine the displacement of the bracings. Hence, only the central bracings were evaluated for every section of the stadium, which are the most stressed bracing elements within the structure. Thus, the maximum deflection at the end point was subtracted from the maximum value at the center of the beam to obtain the maximum displacement within the element.

The maximum displacements of all the structural elements were calculated and listed in panels. Afterwards, the highest value for each group was extrapolated to locate it within the model. In order to achieve this solution, the maximum displacement was confronted within the list of the respective group and the index of the element was extrapolated. Afterwards, it was fed to a "list item" component to highlight the correspondent structural element.

To check the stability of the structure, the span of the structural elements was calculated and utilized to determine the maximum deflection allowed for each component of the structure. Hence, the absolute values for the calculated displacements were determined and subtracted from the correspondent limit value. This solution was necessary to create the objective constraint for the optimization in ModeFrontier. Therefore, the final output was a list for each structural elements containing the difference between the limit values and the correspondent displacement. More in depth, these values describes how close the displacement of an element is to its limit value. Thus, the values in the lists must be all positive to consider the structure to be stable. On the contrary, a negative value indicates that an element of the structure is failing to match its limit value for the displacement. Lastly, these lists were grouped to obtain the total values for each structural system and the minimum value was extrapolated to constitute the objective constraint for the optimization.

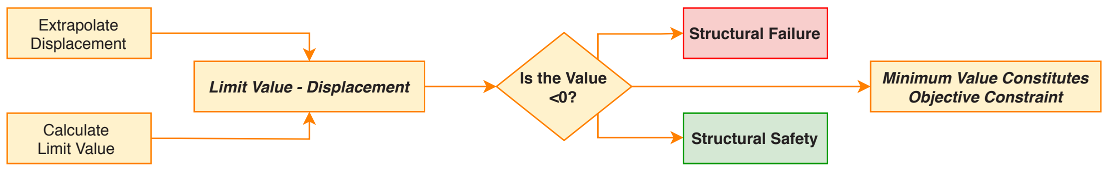


Figure 78. Scheme of the workflow followed to check the displacement of the structural elements within Karamba 3D. (Source: Self-made)

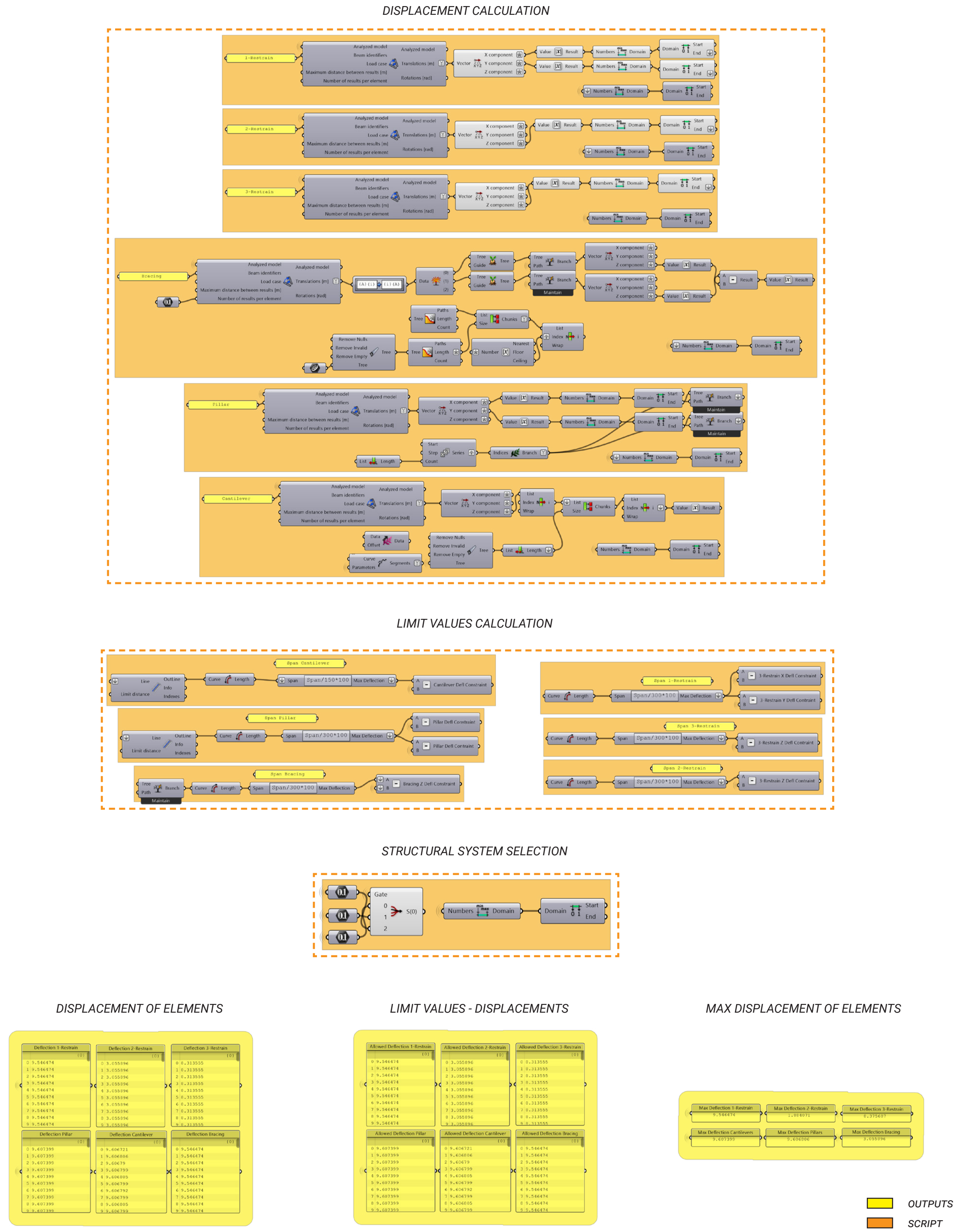


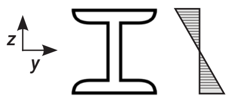
Figure 79. Script utilized to evaluate the displacement of the structure within Karamba 3D. (Source: Self-made)

6.3.4 Bending Stress

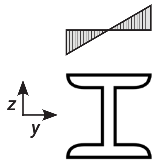
The bending stress within the structural elements was evaluated to ensure the stability of the structure. For all the elements, the stress was calculated and confronted with the yield strength value of the selected material. In this computational method, the materials implemented are steel S235, S275 and S355. Hence, their mechanical properties are presented in figure 80.

Structural Elements	Density (kg/m^3)	Unit Weight (kN/m^3)	Young's Modulus (Mpa)	Yield Strength (Mpa)
STEEL S235	7850	78,5	210000	235
STEEL S275	7850	78,5	210000	275
STEEL S355	7850	78,5	210000	355

Figure 80. Limit values for the stresses corresponding to the yield strength of the selected materials. (Source: Self-made)



$$\sigma_x = \frac{M_y * z}{I_y} = \frac{M_y}{S_y}$$



$$\sigma_x = \frac{M_z * y}{I_z} = \frac{M_z}{S_z}$$

Figure 81. Formulas to calculate the stresses due to the bending moments in y-direction and z-direction. (Source: Self-made)

The bending stresses were calculated for the bending moments acting on the beams in both the local y-direction and z-direction. However, it should be noticed that, since all the load cases were set to act in the global z-direction, the bending stresses due to the bending moments of the local z-axis of the structural elements will not be critical. Indeed, the bending moments of the local y-direction are much higher and the produced stresses are likely to reach the critical values.

In order to calculate the bending stresses of the structural elements, the section modulus for both the y-axis and the z-axis had to be calculated. Hence, the second moment of area for both axes was extrapolated by disassembling the cross sections within Karamba 3D and divided by the distance from the neutral axis of the beam. Concerning the trusses, the distance from the neutral axes in y-direction was considered as half of the base of the original cross section utilized. Afterwards, the bending moments were extrapolated through the "section forces" component in Karamba 3D, which allows to evaluate the bending moments along the length of an element in relation to its local axes.

Taking into consideration the evaluation run in DIANA FEA and described in sub section 6.3.2, particular attention had to be kept on the corner joint between the pillars and the cantilevers, which is the location of the maximum bending moment for all the three structural systems. Hence, the bending moment was evaluated in these two positions for the pillars and the cantilevers. Concerning the bracings, the bending moment was evaluated at half of their length. Indeed, the boundary conditions of the structural elements produces the maximum bending moment in that location. Furthermore, the bending moments of the 1-Restrain element was evaluated at its connection with the cantilevers, while for the 2-restrain and the 3-restrain the value was extrapolated at every 0,5 meters of their length. Indeed, even though their boundary conditions would produce the maximum bending moments at half of their length, the inclination alters the position of the maximum value. Hence, this solution was implemented in order to parametrically extrapolate the value. Lastly, the bending moments were automatically extrapolated at the starting and ending nodes of the elements for both axes.

Once the bending stresses were calculated, the highest value for each group was extrapolated to locate it within the model. In order to achieve this solution, the maximum bending stress was confronted within the list of the respective group and the index of the element was extrapolated. Then, it was fed to a "list item" component to highlight the correspondent structural element.

To check the stability of the structure, the absolute values for the calculated bending tresses were determined and subtracted from the yield strength of the material. This solution was necessary to create the obejctive constraint for the optimization in ModeFrontier. Therefore, the final output was a list for each structural elements containing the difference between the limit value and the correspondent bending stresses. More in depth, these values describes how close the bending stresses of an element is to the yield strength of the material. Thus, the values in the lists must be all positive to consider the structure to be stable. On the contrary, a negative value indicates that an element of the structure is exceeding the yield strength of the material, hence failing. Lastly, these lists were grouped to obtain the total values for each structural system and the minimum value was extrapolated to constitute the objective constraint for the optimization.

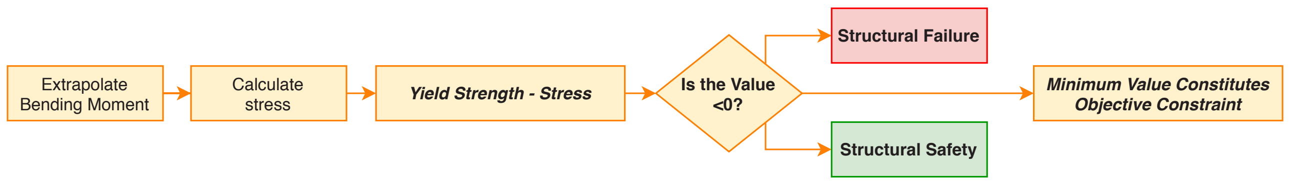


Figure 82. Scheme of the workflow followed to check the stresses of the structural elements within Karamba 3D. (Source: Self-made)

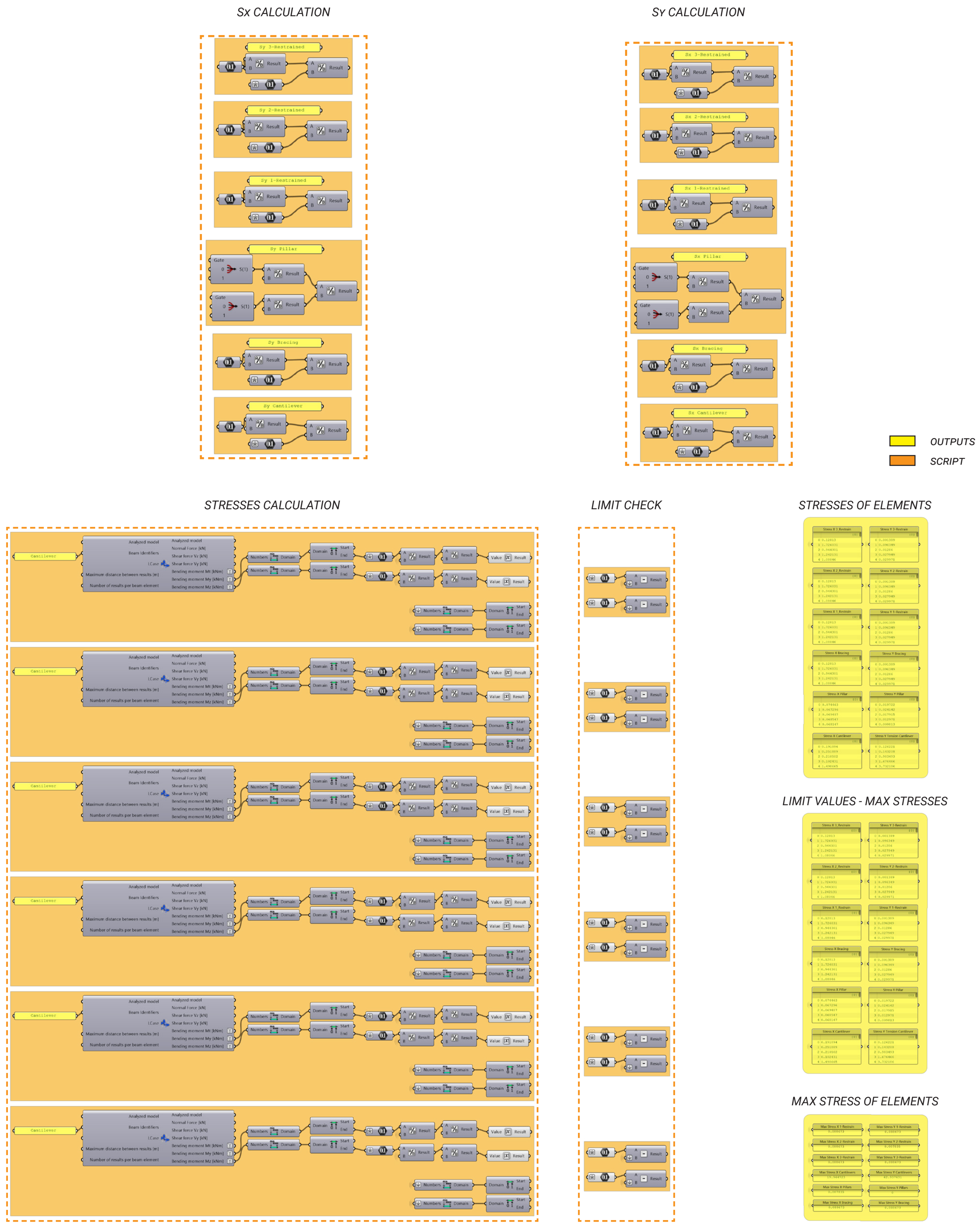


Figure 83. Script utilized to evaluate the stresses of the structure within Karamba 3D. (Source: Self-made)

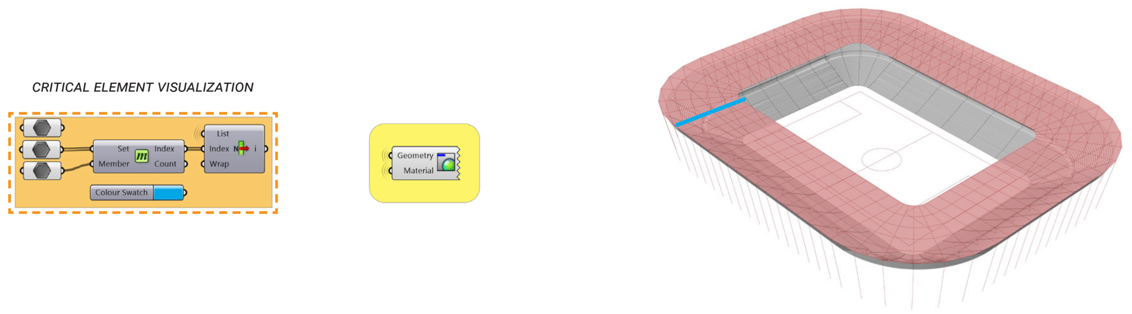


Figure 84. Script utilized to visualize the critical elements of the structure within Karamba 3D. (Source: Self-made)

6.3.5 Performance Indicators

As mentioned in sub-section 4.1.2, the displacement and the stresses were evaluated to ensure the stability of the roof structure. In addition, few performance indicators were individuated to evaluate the performance of the structure:

A. Mass

The mass value provides an insight on the cost of the material to construct the roof structure. Indeed, since the roof structure influences greatly the overall cost of a stadium (Nixdorf, 2009), it constitutes a useful indicator to evaluate the structural performance. Indeed a lighter structure reduces the cost of the design and it provides also useful benefits towards the displacements and the stresses within it. In Karamba 3D, the volume of the structural elements were calculated and multiplied by the density of the material to obtain the mass values. Hence, the masses of the structural elements were grouped based on their correspondent structural system and the values were summed up to obtain the total mass of the three structural systems.

Lastly, in order to evaluate the design alternatives in the optimization, the mass of the initial roof structure will be internalised within a "number" component. Hence, the value will confronted with the mass of the design alternatives to evaluate the increment or the decrement of the mass of the structure. As well, the total mass of the design alternatives will be provided.

B. Number of Elements and Joints.

An evaluation of the number of elements and joints present in the roof structure provides an insight on the labour work necessary to construct the roof structure. This is based on the assumption that a renovation process should be performed as quickly as possible to avoid a delay in the venues scheduled for a stadium. In Karamba 3D, the number of elements and joints were extrapolated thorugh the "disassemble model" component, which provides these values. Therefore, the values were listed in panels for the visualization.

Lastly, in order to evaluate the design alternatives in the optimization, the number of elements and joints of the initial roof structure will be internalised within a "number" component. Hence, the value will be confronted with the number of elements and joints of the design alternatives to evaluate the increment or the decrement of the values. As well, the total amount of elements and joints present in the design alternatives will be provided.

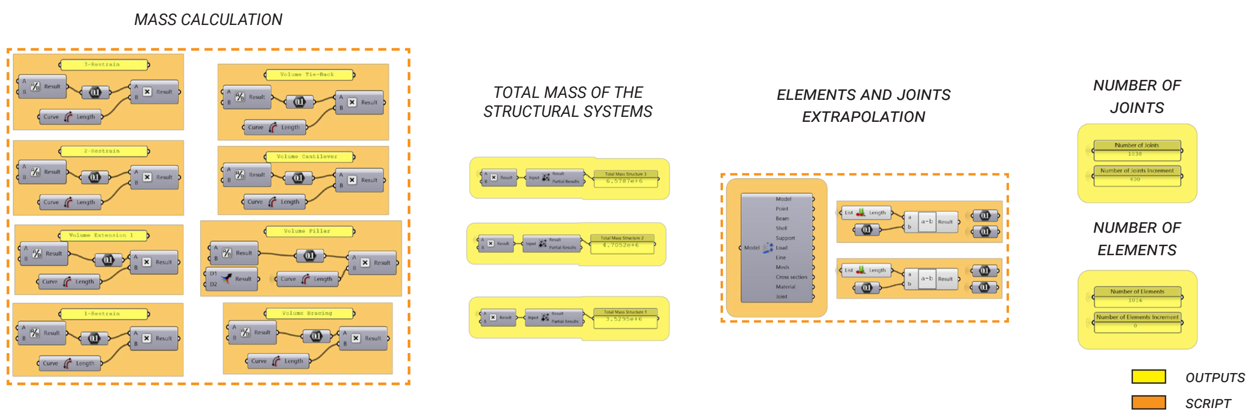


Figure 85. Script utilized to calculate the mass of the structure and the number of elements and joints within Karamba 3D. (Source: Self-made)

6.4 Overview of Performances

As previously described in sub-section 4.1.4, the performance assessment allows to evaluate the stadium with measurable criteria to determine the concept and the approach for the renovation. Indeed, once the performance assessment is terminated, the general overview produced can be utilized by the designer to determine which parts are worth to be kept and which portions should be redeveloped. Hence, a state-of-the-art of the two performances is evaluated to define an approach, which can be the refurbishment of the bad performing parts or the expansion of the stadium whether its portions perform well. Therefore, the main objective will be to produce design alternatives that do not worsen the initial performances.

Hence, the pitch is considered to remain inalterated, as well as the layout. Furthermore, the grandstands are considered as well performing whether more than 80% of the seats provides a minimum C-value of 9 cm and no seats have a C-value lower than 6 cm. In addition, the capacity will not have to be affected by the renovation. Likewise, 95% of the stadium will have to respect the limit of 190 m of the optimum viewing circle, while, in case of refurbishment, the maximum distance from the touchline should not increase more than 10 m.

Concerning the roof, the number and the position of the supports should not be modified to avoid a complete alteration of the structure from the initial situation. Hence, in case of renovation, these parameters will be kept constant. However, the designer should be left free to decide based on the results of the performance assessment whether redifine completely the roof structure or to consider these aspects as constraints for the optimization. Moreover, since the roof has the main function of covering the spectators from the wheater conditions, the produced design alternatives will have to shelter at least the same area of the grandstands of the initial situation. Lastly, in order to avoid any obstruction to the spectator's view towards the pitch and the opposite section of the stadium, the roof structure will be constrained above the last spectator's horizontal sightline.

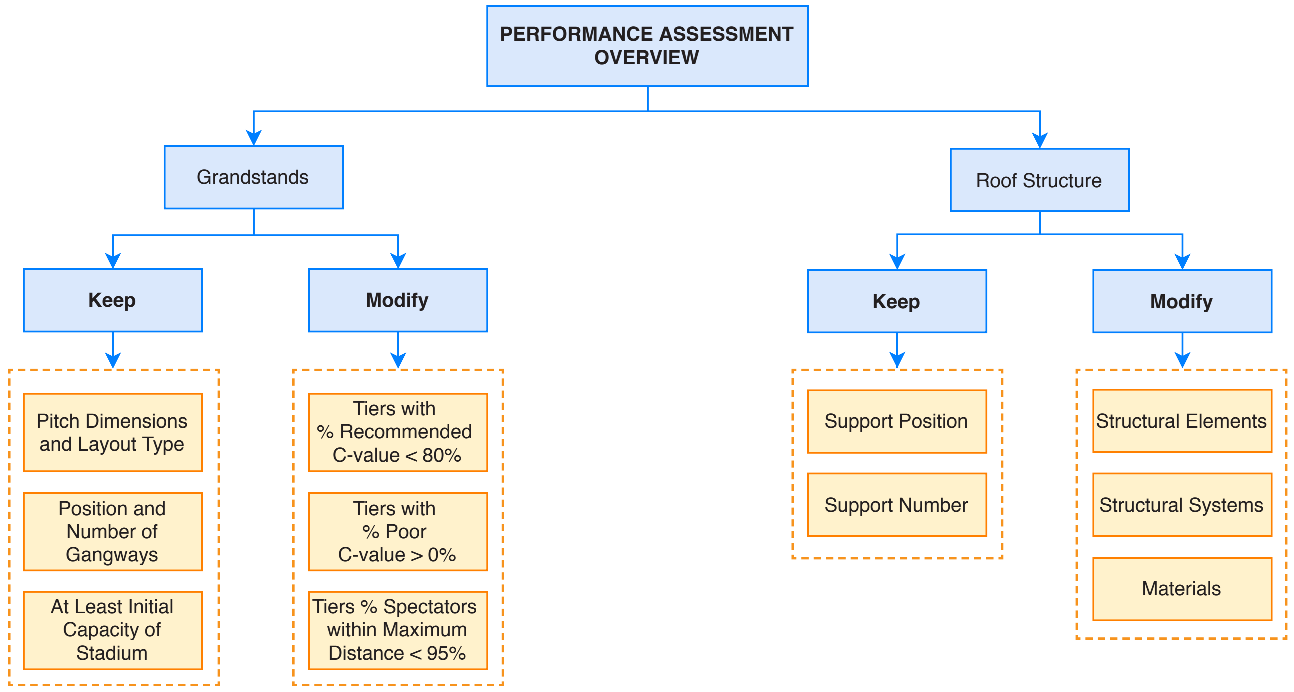


Figure 86. Scheme of the workflow followed for the optimization and the design exploration. (Source: Self-made)

07 | OPTIMIZATION AND DESIGN EXPLORATION

OPTIMIZATION AND DESIGN EXPLORATION

The third phase that constitutes a computational method is the optimization process. As previously stated in section 3.3, the computational optimization can be defined as the generation through optimization tools of multiple design variants within the solution space via the definition of continuous or discrete parameters to achieve a set objective (Bradner et al., 2014).

Four main steps were individuated for the optimization process. Firstly, based on the results of the performance assessment, the components of the stadiums are divided into the portions that have to be kept and those that need a renovation. Hence, an approach for the optimization is selected. On the one hand, the stadium can be renovated by refurbishing its components. On the other hand, the stadium can be expanded. Secondly, In order to perform the optimization, the inputs that can be modified, the objectives of the optimization and the constraints have to be defined to set-up the optimization. Thirdly, the optimization is performed to produce the design alternatives. Lastly, the produces designs are explored to individuate most promising ones.

Concerning the computational tools, ModeFRONTIER was selected to perform the optimization and the design exploration of the alternatives. Indeed, it provides multiple metaheuristics algorithms for MOO and MDO, as well as multiple analysis tools to evaluate the produced data and to facilitate the trade-off of the produced design alternatives. Moreover, the optimization process requires a minimal set-up before starting, which allows to select inputs, outputs, objectives and constraints and to easily control the range of values for the exploration.

7.1 Definition of the Approaches

Concerning the objective of this thesis, two main approaches for the optimization were individuated. On the one hand, design alternatives for the renovation of the grandstands and the roof structure will be produced whether the viewing quality is poor. On the other hand, design alternatives to expand the stadium will be produced by modifying the grandstands and the roof structure whether no parts of the stadium necessitates renovation. The designer can freely follow one of the approaches based on the results of the performance assessment of the initial situation of the stadium. Hence, it is notable the expansion of the stadium can be performed also when the viewing quality is poor. However, this portions of the stadium must be optimized to match the set requirements.

Independently from the followed approach, few requirements have been individuated to determine which portions of the stadium can be kept. Firstly, the pitch and the layout were considered to be kept. Indeed, a modification of these elements will lead to the design of a new stadium. Secondly, the viewing quality determines whether a grandstand needs renovation. In particular, the C-value and the maximum distance are utilized as indicators. Therefore, the percentage of c-values higher than the recommended value of 9 cm for each tier must be higher than 80%. Moreover, the percentage of c-values lower than 6 cm for each tier must be equal to 0. Indeed, 80% was considered a reasonable percentage to provide the majority of the spectators with a finer view of the action, while a C-value lower than 6 cm indicates an obstructed view. Hence, whether the two conditions are matched, the analysed portion of the stadium is considered as well performing, thus not needing renovation. Thirdly, the percentage of the spectators within the limit viewing distance of 190 m must be higher than 95%. Indeed, 95% was assumed as a reasonable percentage to provide the majority of the spectators with a finer view of the action. It is notable that the criteria selected are useful to identify the portions of the stadium that are worth to be kept. However, a designer can freely select its own set of limits values based on a specific stadium and in relation to the project they have to evaluate. Lastly, the number of gangways present within the stands is considered to be maintained as in the initial situation.

Figure 87. Overview of the two approaches for the renovation and their objectives. (Source: Self-made)

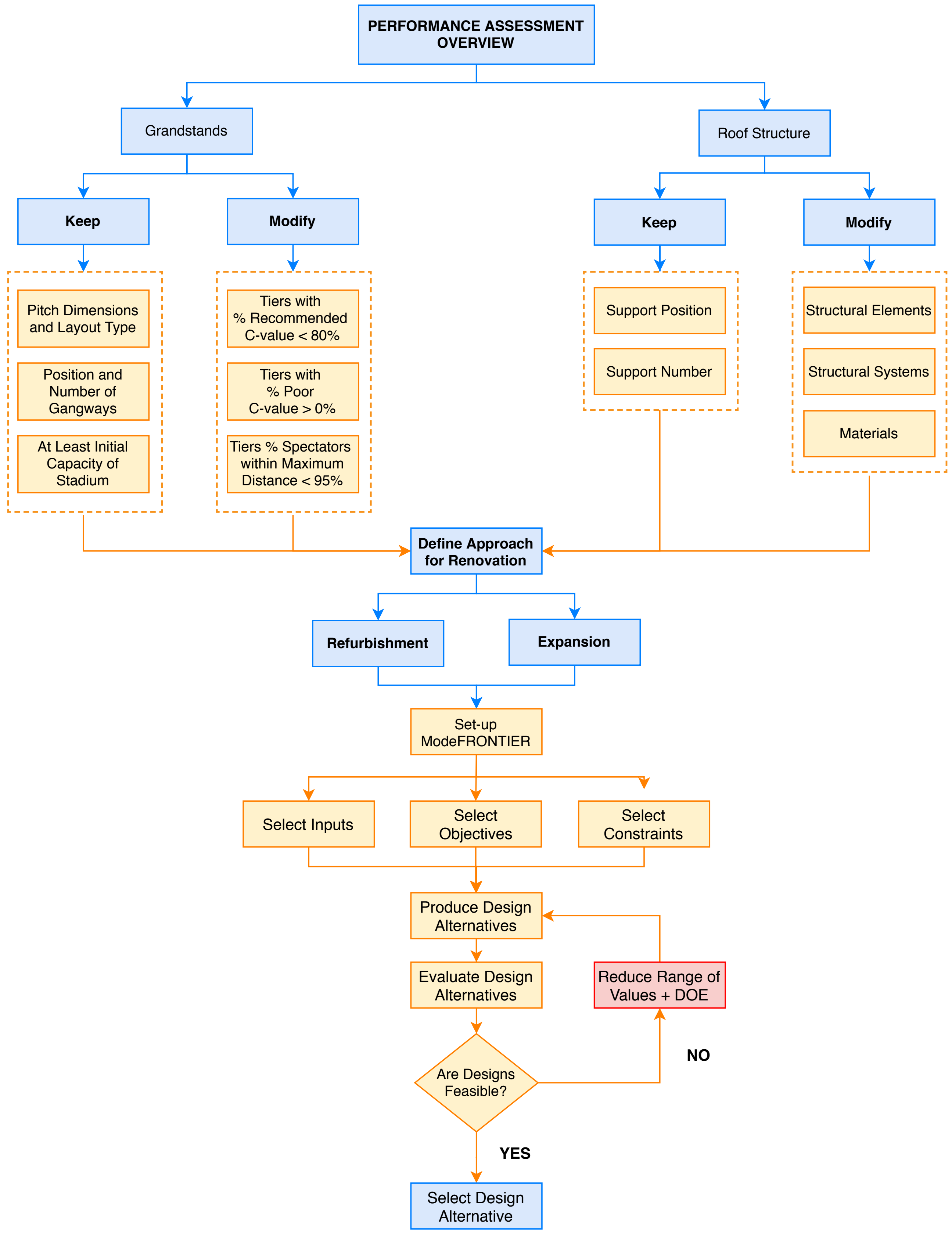


Figure 88. Scheme of the workflow followed for the optimization and the design exploration. (Source: Self-made)

Concerning the roof, the number and the position of the supports should not be modified to avoid a complete alteration of the structure from the initial situation. Hence, in case of renovation, these parameters will be kept constant. Moreover, since the roof has the main function of covering the spectators from the wheater conditions, the produced design alternatives will have to shelter at least the same area of the grandstands of the initial situation. Lastly, in order to avoid any obstruction to the spectator's view towards the pitch and the opposite section of the stadium, the roof structure will be constrained above the last spectator's horizontal sightline.

In conclusion, the two approaches have been explained in detail. However, it is important to notice that these information can serve as useful guidelines to individuate portions of the stadiums to be kept and support the designer into making decisions related to the concept for a renovation design. Hence, a designer can freely choose its own set of limit values or to modify further features of the stadium based on the project they have to develop.

7.2 Set-up

Once the apporach is defined and the portions of the stadium that need a refurbishment are individuated, the set-up of ModeFRONTIER can be inizialized. ModeFRONTIER (Esteco, 2020), is an optimization software that allows to solve optimization problems through the application of an optimization algorithm. Indeed, the software utilizes the algorithm to simulate the design alternatives to maximize or minimize one or multiple objectives. Moreover, it allows to set design constraints to both the outputs of the simulation and the objective functions that have to be respected to produce feasible solutions.

In general, the set-up consists in the selection of an optimization algorithm to perform the optimization, the implementation of the inputs, the objectives and the constraints and the model on which the simulation is run. Hence, in this case the "Grasshopper-node" is utilized since Grasshopper constitutes the parametric environment in which the model was realised. Then, the Grasshopper file is uploaded in the node and an introspection is performed. Indeed, this process allows to import the inputs and the outputs of the Grasshopper model to ModeFRONTIER. Thus, the designer can select the inputs and the outputs of the model that must be imported in the software. Then, ModeFRONTIER automatically creates and connects the inputs and outputs nodes to the "Grasshopper-node". Afterwards, objective nodes and constraint nodes are implemented. These nodes can be fed with the outputs to determine the objective(s) to be maximized or minimized and to determine the design constraints that the optimization tool have to respect. Lastly, the Grasshopper-node is connected to an end-node to terminate the process.

Multiple varieties of algorithms available in ModeFRONTIER, such as for example metaheuristic algorithms. As mentioned in sub-section 4.1.7, this typology of algorithms was individuated as suitable to solve the optimization problem. In particular, considering the multiple constraints of the design problems considered in this computational method, NSGA-II genetic algorithm was selected to solve the optimization problem. Indeed, this algorithm allows to explore the design space to find feasible solutions and performs better in presence of multiple design constraints that have to be matched. In the scheduling start-node, the algorithm can be self-initialized to produce a set number of design alternatives. In alternative, the algorithm can be manually set-up. However, this solution requires an in-depth knowledge of the optimization process and the software. Hence, in this computational method the algorithm was self-initialized, but a designer can freely set it up manually to produce the design alternatives.

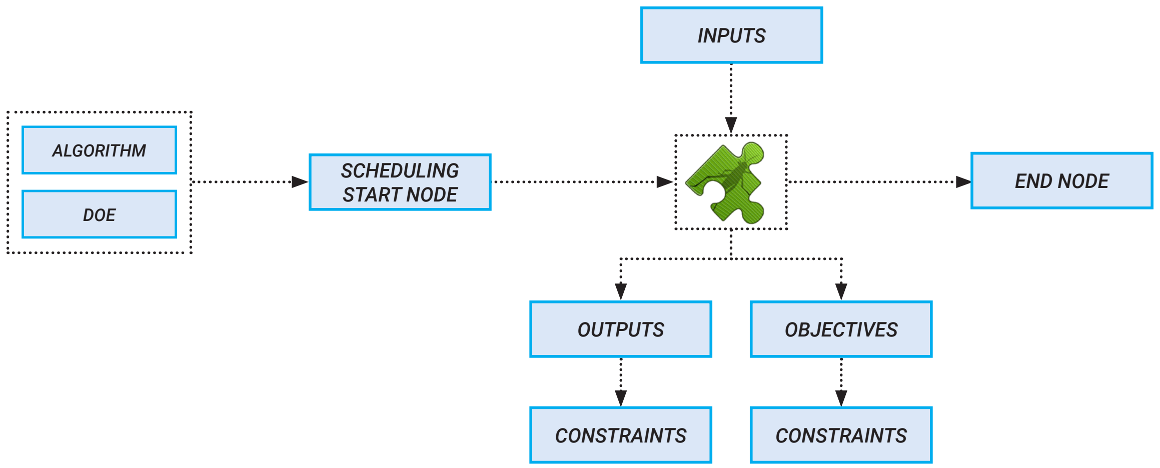


Figure 89. Scheme of the set-up of ModeFRONTIER for the optimization. (Source: Self-made)

7.3 Input Parameters

The input parameters of the parametric model are evaluated through the introspection of the grasshopper-node in order to import them in ModeFRONTIER. As previously mentioned, the designer can freely select which input have to be imported in the software. In general, two solutions were available. On the one hand, all the input parameters can be imported in ModeFRONTIER. Then, the inputs of the components to be refurbished can be set as variables to be modified by the optimization algorithm, while the inputs of the portions of the stadium to be kept can be set as constant. Hence, ModeFRONTIER is not able to alter them. On the other hand, only the inputs of the components that need to be refurbished can be imported and set as variables to be modified. Hence, ModeFRONTIER is not able to alter the inputs of the portions of the stadium to be kept. This last option was considered for the proposed computational method. Indeed, this solution allows the designer to have a better control of the data and reduces the possibility of making mistakes in the set-up. Indeed, this process is carried out in Grasshopper and the designer can visualize the 3D model of the stadium, while in ModeFRONTIER only the names of the inputs are present.

Once the inputs are imported in ModeFRONTIER, a designer can select the range of values of the inputs and their steps. This aspect is crucial since it affects greatly the computational time needed to simulate each design alternative and the dimensions of the design space. Indeed, a wide range of values in relation with the number of the inputs increases the number of solutions that can be produced. For this reason, it is important to determine the range of values for the first run of optimization. Then, the designer can evaluate the design alternatives to vary the range of values to reduce the computational time and to drive the algorithm towards the area of the design space with feasible solutions. An overview of the principal input parameters for the components of the stadium is provided in figure 90 and figure 91.

PLAYING AREA

COMPONENT	DESCRIPTION
Pitch	Dimensions of the pitch *(Based on the stadium to be implemented)*
Track	Presence of the track. *(Based on the stadium to be implemented. "1" produces a standard athletic track, while "0" does not produce an athletic track)*
OffsetTrack	Distance between the athletic track and the pitch. *(The distance is set based on the stadium to be implemented)*

GRANDSTANDS CONFIGURATION

COMPONENT	DESCRIPTION
Tier1 *(One for each section)*	Presence of the 1st tier of stands *(Based on the stadium to be implemented.)*
Tier2 *(One for each section)*	Presence of the 2nd tier of stands *(Based on the stadium to be implemented.)*
Tier3 *(One for each section)*	Presence of the 3rd tier of stands *(Based on the stadium to be implemented.)*
T1_StandType *(One for each section)*	Stand Typology to apply to the 1st tier of stands *(Based on the stadium to be implemented. Linear (1), double linear (2))*
T2_StandType *(One for each section)*	Stand Typology to apply to the 2nd tier of stands *(Based on the stadium to be implemented. Linear (1), double linear (2))*
T3_StandType *(One for each section)*	Stand Typology to apply to the 3rd tier of stands *(Based on the stadium to be implemented. Linear (1), double linear (2))*

LAYOUT TYPOLOGIES

COMPONENT	DESCRIPTION
Layout	Layout Typology based on the stadium to be implemented. *(Open Rectangle (0), Rounded Rectangle (1), Circular (2), Semi-circular (3), Super-Ellipse (4), Basket Arch (5), Oval (6))*
FRD_X *(Layout_0_1_5)*	Distance of the first row of seats on the X-direction *(Based on the stadium to be implemented. Recommended Min value = 7.5 m)*
FRD_Y *(Layout_0_1_5)*	Distance of the first row of seats on the Y-direction *(Based on the stadium to be implemented. Recommended Min value = 6.0 m)*
FRD *(Layout_2_3_4_6)*	Distance of the first row of seats on the Y-direction *(Based on the stadium to be implemented. Recommended Min value = 7.5 m)*
Gap_X *(Layout_0)*	Length of the stands on the X-direction *(Based on the stadium to be implemented)*
Gap_Y *(Layout_0)*	Length of the stands on the Y-direction *(Based on the stadium to be implemented)*
Radius *(Layout_1)*	Radius of the corners of the layout *(Based on the stadium to be implemented)*
Radius *(Layout_2)*	Radius of the circular layout *(Based on the stadium to be implemented)*
Divergence_CP *(Layout_4_5)*	Divergence of the corner points of the layout *(Based on the stadium to be implemented)*
Arc_Radius *(Layout_4_6)*	Curvature of the curve parallel to the pitch *(Based on the stadium to be implemented)*

STAND TYPOLOGIES

COMPONENT	DESCRIPTION
Initial Riser ***(One for each stand type)***	Height of the first riser of the stand *(Based on the stadium to be implemented. Recommended Min value = 0.2 m)*
Tread Depth ***(One for each stand type)***	Depth of the rows of the stand *(Based on the stadium to be implemented. Recommended Min value = 0.6 m, Recommended Max value = 1.0 m)*
NRows ***(One for each stand type)***	Number of seating rows of the stand *(Based on the stadium to be implemented)*
RiserHeight ***(One for each stand type)***	Height of the risers of the stand *(Based on the stadium to be implemented. Recommended Min value = 0.2 m, Recommended Max value = 0.6 m)*
LastRowDepth ***(One for each stand type)***	Depth of the last row of the stands *(Based on the stadium to be implemented. Recommended Min value = 0.6 m, Recommended Max value = 2.4 m)*
TierHeight ***(One for each stand type)***	Height of the starting point of the 2nd/3rd tier *(Based on the stadium to be implemented)*
CantileverDist ***(One for each stand type)***	Length of the cantilever of the 2nd/3rd tier *(Based on the stadium to be implemented)*
VC *(One for each tier and section)*	Number of Gangways for the vertical circulation *(Based on the stadium to be implemented)*
VC_Width *(One for each tier and section)*	Width of the Gangways for the vertical circulation *(Based on the stadium to be implemented. Recommended Min value = 1.2 m)*
Seat_Width *(One for each tier and section)*	Width of the Seats *(Based on the stadium to be implemented. Recommended Min value = 0.5 m)*
Seat_Distance *(One for each tier and section)*	Distance between the Seats *(Based on the stadium to be implemented)*

INPUTS CONSIDERED TO BE ALTERED IN MODEFRONTIER

Figure 90. Overview of the inputs of the parametric model. (Part 1) (Source: Self-made)

ROOF STRUCTURE OUTLINE

COMPONENT	DESCRIPTION
Structural System	Structural System of the Roof *(Based on the stadium to be implemented. Simple Cantilever (1), Tie-Back Cantilever (2), Restrained Cantilever (3))*
N_Support *(One for each section of the stadium)*	Number of ground supports, grandstand supports and restraining supports *(Based on the stadium to be implemented)*
G_SupPos *(One for each section of the stadium)*	Position of the ground supports *(Based on the stadium to be implemented)*
Start Cantilever	Height of the starting point of the cantilever *(Based on the stadium to be implemented)*
Cantilever End 2D	Position of the end point of the cantilevers on the XY plane *(Based on the stadium to be implemented)*
Clear Height above Spectators	Height of the end point of the cantilevers *(Based on the stadium to be implemented)*
ExtensionPillar	Length of the extension of the Pillar for structural system 2 and 3 *(Based on the stadium to be implemented)*
End Position (3-Restrain)	Position of the connection between 3-Restrain and the cantilevers *(Based on the stadium to be implemented)*

STRUCTURAL ELEMENTS

COMPONENT	DESCRIPTION
Materials	Materials of the structural elements *(Based on the stadium to be implemented. Implemented Materials: S235, S275, S355)*
Boundary Conditions	Boundary condition of the structural system *(Based on the stadium to be implemented)*
CS_Type *(one for each group of STR elements)*	Cross Section Type of the structural elements *(Based on the stadium to be implemented. EU HEA (0), UK CHSC Circular hollow (1))*
Beam/Truss	Beam or Truss selection for the Pillars *(Based on the stadium to be implemented. Beam (0), Truss (1))*
I_CS *(one for each group of STR elements)*	EU HEA cross section to assign *(Based on the stadium to be implemented)*
O_CS *(one for each group of STR elements)*	UK CHSC Circular hollow cross section to assign *(Based on the stadium to be implemented)*

INPUTS CONSIDERED TO BE ALTERED IN MODEFRONTIER

Figure 91. Overview of the inputs of the parametric model. (Part 2) (Source: Self-made)

7.4 Objectives

The outputs of the parametric model are evaluated thorugh the introspection of the grasshopper-node in order to import them in ModeFRONTIER. As previously mentioned, the designer can freely select which output have to be imported in the software based on the approach, the concept of the design alternatives and therefore the objectives of the optimization.

Initially, a set-up of the outputs within Grasshopper has to be performed in order to import the information within ModeFRONTIER. Hence, a "number" component for each of the outputs related to the performance assessment (see section 6.2 and 6.3) were created and fed with the correspondent data. Then, the outputs were named and grouped. It is important to name the group of outputs as "mf_out". Indeed, ModeFRONTIER is able to recognize the name of the group and extrapolate the values within the "number" component as outputs of the optimization process. However, further set-up was needed to extrapolate the outputs. Indeed, ModeFRONTIER is not able to read lists of values, but only the first item within the lists. Hence, two options were available. On the one hand, the most crucial value of a list can be extrapolated as an output. On the other hand, the a "number" component can be inserted for all the values within a list. In this case, the first option was selected, especially for the outputs of the structural performance, while the second option was utilized for few outputs of the viewing quality performance. Lastly, the designer can select which outputs have to be imported within ModeFRONTIER based on the design concept and the information they need for the optimization process. However, it is possible to import all the outputs of the performance assessment for the evaluation.

Once the outputs are imported in ModeFRONTIER, the designer can choose which output to set as an objective for the optimization process. Concerning the approaches of this computational method, few outputs are implemented and suggested to be assigned as objectives. On the one hand, the objectives of a renovation approach can be to maximize the percentage of C-values higher than 9 cm of the overall stadium to improve the viewing quality and to eliminate the view obstruction provided by the other spectators. Moreover, the maximum viewing distance can be minimized to enhance the atmosphere of the stadium. On the other hand, for an expansion approach, an objective to maximize the capacity of the stadium can be added to increase the number of spectators of the venues, hence suggesting an increment of the income of the stadium. Furthermore, for both approaches, the roof structure will be modified. Therefore, for the roof structure the objectives related to the minimization of the mass, the number of elements and the number of joints are implemented and suggested as objectives for the optimization. Indeed, a reduction of these values represents a decrement of the cost of the materials and a decrement of the labor time needed to construct the structure.

Lastly, it is notable that the objectives are implemented to confront the performances of the design alternatives to the ones of the initial situation as values or percentages. Indeed, this solution can facilitate the trade-off of the alternatives and to understand whether a feasible design improves the initial situation. An overview of the principal outputs and the objectives is provided in figure 93.

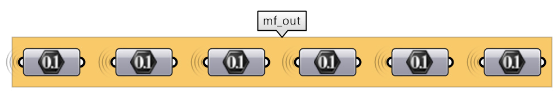


Figure 92. Example of the set-up of the outputs in Grasshopper for the importation within ModeFRONTIER. (Source: Self-made)

OUTPUT	DESCRIPTION	OBJECTIVE
Capacity	Value of the Capacity of the Overall Stadium	
Capacity Increment	Difference between NEW Capacity and INITIAL capacity	
% Capacity Increment	**Percentage of increment/decrement of Stadium Capacity**	**MAXIMIZE**
Capacity Tier1	Value of the Capacity of the 1st Tier of the Stadium	
Capacity Tier2	Value of the Capacity of the 2nd Tier of the Stadium	
Capacity Tier3	Value of the Capacity of the 3rd Tier of the Stadium	
% Poor C-value	Percentage of C-values < 6 cm of the Overall Stadium	
% Acceptable C-Value	Percentage of C-values 6 cm < X < 9 cm of the Overall Stadium	
% Recommended C-Value	Percentage of C-values 9 cm < X < 12 cm of the Overall Stadium	
% > Recommended C-Value	**Percentage of C-values > 9 cm of the Overall Stadium**	**MAXIMIZE**
% Excellent C-Value	Percentage of C-values > 12 cm of the Overall Stadium	
% > Poor C-value Tier1	Percentage of C-values > 6 cm of the 1st Tier	
% > Poor C-value Tier2	Percentage of C-values > 6 cm of the 2nd Tier	
% > Poor C-value Tier3	Percentage of C-values > 6 cm of the 3rd Tier	
% > Recommended C-Value Tier1	Percentage of C-values > 9 cm of the 1st Tier	
% > Recommended C-Value Tier2	Percentage of C-values > 9 cm of the 2nd Tier	
% > Recommended C-Value Tier3	Percentage of C-values > 9 cm of the 3rd Tier	
Maximum Vertical Viewing Angle	Maximum vertical viewing angle of the overall Stadium	
% Spectators within Max Distance	Percentage of Spectators provided with the minimum viewing distance	
Maximum Distance	**Maximum distance of the spectators to the pitch of the overall stadium**	**MINIMIZE**
% Field of View < 120°	Percentage of spectators provided with a field of view > 120° of the Overall Stadium	
Inclination Tier 1	Inclination of the stands of the 1st Tier	
Inclination Tier 2	Inclination of the stands of the 2nd Tier	
Inclination Tier 3	Inclination of the stands of the 3rd Tier	
STR_Stress	Maximum Allowed Stress Value of the Overall Roof Structure	
STR_Deflection	Maximum Allowed Displacement Value of the Overall Roof Structure	
STR_Njoints	Number of Joints of the Roof Structure	
STR_NJoints_Increment	**Difference Between the NEW and the INITIAL Number of Joints of the Roof Structure**	**MINIMIZE**
STR_Nelements	Number of Elements of the Roof Structure	
STR_NElements_Increment	**Difference Between the NEW and the INITIAL Number of Elements of the Roof Structure**	**MINIMIZE**
STR_Mass	Mass of the Overall Roof Structure	
STR_Mass_Increment	**Difference Between the NEW and the INITIAL Mass of the Roof Structure**	**MINIMIZE**
Cantilever_Truss_Height	Height of the Truss of the Cantilevers	
Pillar_Truss_Height	Height of the Truss of the Pillars	
STR_Cantilever_Deflection	Maximum Displacement Value of the Cantilevers	
STR_Cantilever_YStress	Maximum Stress Value of the Cantilevers	
STR_Cantilever_ZStress	Maximum Stress Value of the Cantilevers	
STR_Pillars_Deflection	Maximum Displacement Value of the Pillars	
STR_Pillars_YStress	Maximum Stress Value of the Pillars	
STR_Pillars_ZStress	Maximum Stress Value of the Pillars	
STR_Bracings_Deflection	Maximum Displacement Value of the Bracings	
STR_Bracings_YStress	Maximum Stress Value of the Bracings	
STR_Bracings_ZStress	Maximum Stress Value of the Bracings	
STR_1-Restrain_Deflection	Maximum Displacement Value of the 1-Restrain	
STR_1-Restrain_YStress	Maximum Stress Value of the 1-Restrain	
STR_1-Restrain_ZStress	Maximum Stress Value of the 1-Restrain	
STR_2-Restrain_Deflection	Maximum Displacement Value of the 2-Restrain	
STR_2-Restrain_YStress	Maximum Stress Value of the 2-Restrain	
STR_2-Restrain_ZStress	Maximum Stress Value of the 2-Restrain	
STR_3-Restrain_Deflection	Maximum Displacement Value of the 3-Restrain	
STR_3-Restrain_YStress	Maximum Stress Value of the 3-Restrain	
STR_3-Restrain_ZStress	Maximum Stress Value of the 3-Restrain	
STR_Roof_Inclination	Minimum Inclination of the Roof Structure	

OBJECTIVES CONSIDERED TO BE IMPLEMENTED

Figure 93. Overview of the outputs and the objectives individuated for the optimization within ModeFRONTIER. (Source: Self-made)

7.5 Constraints

The outputs of the parametric model are evaluated through the introspection of the grasshopper-node in order to import them in ModeFRONTIER. As previously mentioned, the designer can freely select which output have to be imported in the software based on the approach, the concept of the design alternatives and therefore the constraints of the optimization.

As mentioned in section 7.4, the designer can select which outputs have to be imported within ModeFRONTIER based on the design concept and the information they need for the optimization process. However, it is possible to import all the outputs of the performance assessment for the evaluation.

Once the outputs are imported in ModeFRONTIER, the designer can choose which output to set as a constraint for the optimization process. Two typologies of constraints were considered in this computational method. On the one hand, the constraints are related to the existing stadium, hence to the portions that can be kept as unaltered. On the other hand, the constraints are related to the objectives of the design alternatives. Thus, the limitations created to the new designs to be considered as feasible. In this instance, a further distinction is necessary. The design constraints can be implemented as constraint-nodes within ModeFRONTIER or by limiting the range of values of the related inputs.

Concerning the objective of this thesis, the constraints related to the existing stadium were handled by avoiding to import in ModeFRONTIER the inputs related to the portions of the stadium to be kept. Then, the constraints related to the objectives of the design alternatives where managed by implementing constraint-nodes within ModeFRONTIER. As an exception, the range of values of the position of the end-points of the cantilever elements (input name "Clear Height Above Spectators") was restricted by setting the minimum value to 2.5 m. Indeed, as mentioned in sub-section 5.5.1, these points are positioned at the eye-height of the spectators of the last row of seats of the stadium and its position can be varied on the Z-axis. Hence, setting a minimum value to 2.5 m ensure that the roof structure will not provide a view obstruction to the spectators. Likewise, the position of the end-points of the cantilever elements (name input "Cantilever End 2D") was restricted by setting the minimum value to 0 m. Indeed, as mentioned in sub-section 5.5.1, these points are positioned exactly above the starting point of the first row of the stands. Hence, setting a minimum value to 0 m ensure that the roof structure will provide cover to all the spectators.

Concerning the "constraint-node" of ModeFRONTIER, the outputs selected to be constrained are connected to the nodes and a limit value is set. In this instance, the design alternatives will be produced in respect of the set constraints to be considered feasible. The outputs can be set to be higher, lower or equal to a set limit value. In relation to the objective of this thesis, the limits value are set and suggested to obtain efficient designs. However, a designer can freely determine their own set of limit values based on the design concept and the efficiency of the design alternatives they want to produce. Hence, the percentage of poor c-values (> 6 cm) is set to 100% to avoid the obstruction of the view of the spectators, while the percentage of c-values higher than the recommended value (>9 cm) is set to 80% to consider a successful renovation of the grandstands. These two constraints are set for the overall stadium and for the three tiers of stands. In addition, the inclination of the stands is constraint to 35° to ensure the security of the spectators seating in the stands. Concerning the roof structure, the principal constraints are the stresses and the displacements. Indeed, the maximum values are set to be higher than 0 Mpa and 0 cm respectively. Indeed, considering the process followed to extrapolate the values for the optimization (see section 6.3), whether the values are higher than 0, the stability of the structure is ensured. Then, the inclination of the roof is set to be higher than 1,5° to ensure the the runoff of the water.

In addition, few additional constraints are added. The maximum viewing angle is set to be lower than 60° to ensure comfort to the spectators following the activity, while the maximum distance is set to be lower than the initial distance plus a certain distance set by the designer. In this case, a maximum of 10 m is added to provide flexibility to the optimization algorithm. Indeed, a smaller value will reduce greatly the design space for the optimization. In this case, a designer is suggested to determine its own value based on the existing stadium to renovate. Moreover, the percentage of the spectators within the maximum viewing distance is set to be higher than 95% to provide the majority of the spectators with a finer view of the action. Lastly, in order to have an insight on the aesthetic quality of the roof structure, the pillar and the truss height are limited to a certain height set by the designer. It is notable that this last set of constraints can be utilized based on the existing stadium to renovate. Hence, their implementation for the optimization is determined by a designer based on the case study to implement.

Lastly, An overview of the principal outputs and the constraints with the suggested limit values is provided in figure 95.

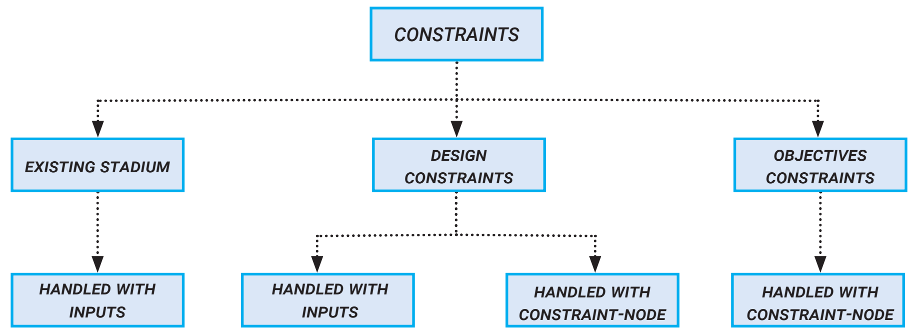


Figure 93. Scheme of managment of design constraint in the computational method (Source: Self-made)

OUTPUT	DESCRIPTION	CONSTRAINT	NOTE
Capacity	Value of the Capacity of the Overall Stadium		
Capacity Increment	Difference between NEW Capacity and INITIAL capacity		
% Capacity Increment	Percentage of increment/decrement of Stadium Capacity	HIGHER THAN 0%	
Capacity Tier1	Value of the Capacity of the 1st Tier of the Stadium		
Capacity Tier2	Value of the Capacity of the 2nd Tier of the Stadium		
Capacity Tier3	Value of the Capacity of the 3rd Tier of the Stadium		
% Poor C-value	Percentage of C-values > 6 cm of the Overall Stadium	EQUAL TO 100%	
% Acceptable C-Value	Percentage of C-values 6 cm < X < 9 cm of the Overall Stadium		
% Recommended C-Value	Percentage of C-values 9 cm < X < 12 cm of the Overall Stadium		
% > Recommended C-Value	Percentage of C-values > 9 cm of the Overall Stadium	HIGHER THAN 80%	Designer can select its own limit
% Excellent C-Value	Percentage of C-values > 12 cm of the Overall Stadium		
% > Poor C-value Tier1	Percentage of C-values > 6 cm of the 1st Tier	EQUAL TO 100%	
% > Poor C-value Tier2	Percentage of C-values > 6 cm of the 2nd Tier	EQUAL TO 100%	
% > Poor C-value Tier3	Percentage of C-values > 6 cm of the 3rd Tier	EQUAL TO 100%	
% > Recommended C-Value Tier1	Percentage of C-values > 9 cm of the 1st Tier	HIGHER THAN 80%	Designer can select its own limit
% > Recommended C-Value Tier2	Percentage of C-values > 9 cm of the 2nd Tier	HIGHER THAN 80%	Designer can select its own limit
% > Recommended C-Value Tier3	Percentage of C-values > 9 cm of the 3rd Tier	HIGHER THAN 80%	Designer can select its own limit
Maximum Vertical Viewing Angle	Maximum vertical viewing angle of the overall Stadium	LOWER THAN 60°	
% Spectators within Max Distance	Percentage of Spectators provided with the minimum viewing distance	HIGHER THAN 95%	Designer can select its own limit
Maximum Distance	Maximum distance of the spectators to the pitch of the overall stadium	LOWER THAN (X + 10 m)	Designer can select its own limit
% Field of View < 120°	Percentage of spectators provided with a field of view > 120° of the Overall Stadium		
Inclination Tier 1	Inclination of the stands of the 1st Tier	LOWER THAN 35°	
Inclination Tier 2	Inclination of the stands of the 2nd Tier	LOWER THAN 35°	
Inclination Tier 3	Inclination of the stands of the 3rd Tier	LOWER THAN 35°	
STR_Stress	Maximum Allowed Stress Value of the Overall Roof Structure	HIGHER THAN 0 Mpa	
STR_Deflection	Maximum Allowed Displacement Value of the Overall Roof Structure	HIGHER THAN 0 cm	
STR_Njoints	Number of Joints of the Roof Structure		
STR_NJoints_Increment	Difference Between the NEW and the INITIAL Number of Joints of the Roof Structure		
STR_Nelements	Number of Elements of the Roof Structure		
STR_NElements_Increment	Difference Between the NEW and the INITIAL Number of Elements of the Roof Structure		
STR_Mass	Mass of the Overall Roof Structure		
STR_Mass_Increment	Difference Between the NEW and the INITIAL Mass of the Roof Structure		
Cantilever_Truss_Height	Height of the Truss of the Cantilevers	LOWER THAN X cm	Designer can select its own limit
Pillar_Truss_Height	Height of the Truss of the Pillars	LOWER THAN X cm	Designer can select its own limit
STR_Cantilever_Deflection	Maximum Displacement Value of the Cantilevers		
STR_Cantilever_YStress	Maximum Stress Value of the Cantilevers		
STR_Cantilever_ZStress	Maximum Stress Value of the Cantilevers		
STR_Pillars_Deflection	Maximum Displacement Value of the Pillars		
STR_Pillars_YStress	Maximum Stress Value of the Pillars		
STR_Pillars_ZStress	Maximum Stress Value of the Pillars		
STR_Bracings_Deflection	Maximum Displacement Value of the Bracings		
STR_Bracings_YStress	Maximum Stress Value of the Bracings		
STR_Bracings_ZStress	Maximum Stress Value of the Bracings		
STR_1-Restrain_Deflection	Maximum Displacement Value of the 1-Restrain		
STR_1-Restrain_YStress	Maximum Stress Value of the 1-Restrain		
STR_1-Restrain_ZStress	Maximum Stress Value of the 1-Restrain		
STR_2-Restrain_Deflection	Maximum Displacement Value of the 2-Restrain		
STR_2-Restrain_YStress	Maximum Stress Value of the 2-Restrain		
STR_2-Restrain_ZStress	Maximum Stress Value of the 2-Restrain		
STR_3-Restrain_Deflection	Maximum Displacement Value of the 3-Restrain		
STR_3-Restrain_YStress	Maximum Stress Value of the 3-Restrain		
STR_3-Restrain_ZStress	Maximum Stress Value of the 3-Restrain		
STR_Roof_Inclination	Minimum Inclination of the Roof Structure	HIGHER THAN 1.5°	Designer can select its own limit

CONSTRAINTS CONSIDERED TO BE IMPLEMENTED

Figure 94. Overview of the outputs and the constraints individuated for the optimization within ModeFRONTIER. (Source: Self-made)

7.6 Generation and Exploration of the Design Alternatives

Once the set-up of the file in ModeFRONTIER is terminated, the design alternatives can be produced. It is notable that, based on the number of inputs and their range of values, the number of objectives and constraints implemented, the dimensions of the design space vary, as well as the computational time needed to produce the design alternatives. Indeed, the more the variables implemented within ModeFRONTIER, the more the computational time increases and the design space is enlarged. Thus a workflow for the optimization is proposed to gradually reduce the computational time and the dimensions of the design space in order to obtain feasible design alternatives more quickly. As a start, few information of the user-interface of ModeFRONTIER have to be provided. Indeed, ModeFRONTIER automatically groups the results of the optimization process in feasible (green) and unfeasible (yellow) designs. Then, a session table is automatically produced to store the design alternatives and their data. Moreover, an ID is assigned to each design. This information is important since all the designs produced are stored in a directory and grouped in folders labeled with the ID number of the correspondent solution. Hence, the designer is provided with a Grasshopper script and a snapshot of the design produced. In this case, the camera settings have to be imported in ModeFRONTIER to control the focus of the snapshot of the solution.

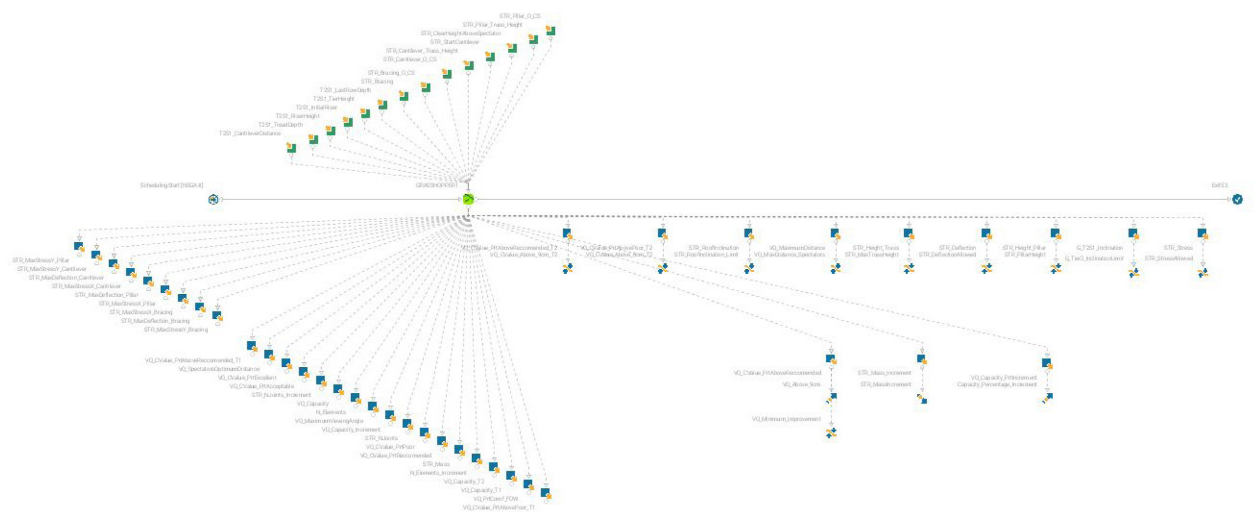


Figure 95. Example of set-up of the optimization in ModeFRONTIER. (Source: Self-made)

Concerning the process, firstly an initial optimization is run to produce few design alternatives, which constitutes a first batch of solutions to evaluate the design space, the range of values of the inputs and the implemented objectives. Indeed, the objectives that have a direct relation can be excluded from the optimization and the focus can be kept on one of them, since the design alternatives produced will be maximized or minimized anyway. As an example, the minimization of the increment of the structural mass drives the algorithm to search for design alternatives that reduce the amount of material needed, but also the number of elements and joints present within the structure whether the inputs of these components are inserted. Therefore, only the minimization of the increment of the structural mass is kept as an objective.

Secondly, after the first batch of solutions have been produced, ModeFRONTIER automatically groups them in feasible (green) and unfeasible (yellow) designs. Two options can be followed based on the presence or the absence of feasible designs. On the one hand, whether feasible designs are produced, a parallel coordinates chart is extrapolated within ModeFRONTIER to confront the inputs and their range of values in relation to the produced designs. Hence, this chart allows to understand which values of each input provides the creation of feasible solutions. Therefore, the range of values can be reduced to save computational time and restrict the design space to an area containing feasible solutions. On the other hand, whether only unfeasible solutions are produced, a broken constraint chart is created to individuate which limitation was not matched during the optimization and the number of solutions that exceeded the limit value. Therefore, the effects of the inputs on the constraints are examined with the sensitivity tool to individuate the factors that influence them the most. Hence, the constraint broken are evaluated in relation to the inputs with a bubble diagram 4D or a parallel coordinates chart. Indeed, these two options allow to reduce the range of values in order to drive the optimization algorithm to produce solutions that match the constraints. As an example, a bubble diagram 4D is created to evaluate the inclination of a tier and the percentage of c-values of the overall stadium in relation to the riser height and the tread depth of the correspondent stand.

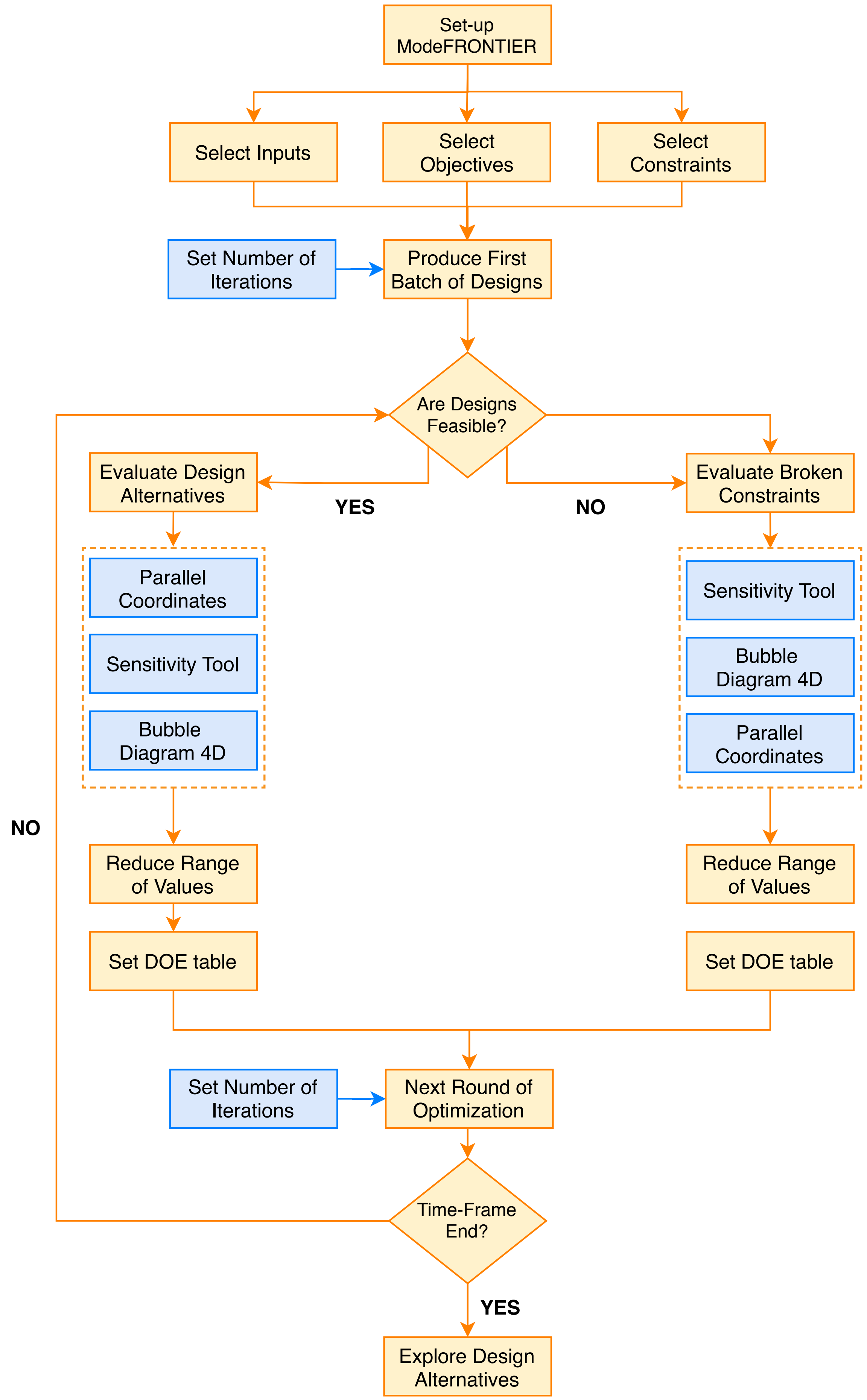


Figure 96. Workflow followed to produce the design alternatives in ModeFRONTIER. (Source: Self-made)

Figure 97. Examples of the charts utilized to evaluate the design alternatives during the optimization process. (Source: Self-made)

Thirdly, once the range of values have been reduced, few designs are selected to form a DOE table, which serves as a training table to address the computational algorithm to the area of the design space provided with feasible solutions. Indeed, this operation speeds up the optimization process. On the one hand, whether feasible solutions are present, they are selected to be part of the DOE table. In this case, dominant and non-dominant solutions have to be utilized. Indeed, a variety of feasible inputs and outputs enhance the selected algorithm NSGA-II to cross the inputs and produce better results. On the other hand, whether only unfeasible solutions are present, the ones that match the majority of the constraints are selected to be part of the DOE table.

Hence, a second round of optimization is run and the steps are repeated to refine everytime the obtained results. Based on the number of inputs and their range of values, the number of objectives and constraints implemented, the time needed to complete the optimization process varies. In this case, the time-frame available to perform the optimization constitutes a limitation that may end the process before a pareto-front or a global solution is obtained.

The described process was developed and tested with the validation case explained in chapter 8. In this case, both approaches for the renovation were followed. In both instances, the initial optimization was run to produce 200 design alternatives, which allowed to obtain a reasonable batch of solutions in approximately 4 hours. Hence, the DOEs of the subsequent iterations were composed of 20 designs each. Indeed, considering the set-up utilized, 20 designs were sufficient to train the optimization algorithm in producing a greater amount of feasible solutions Afterwards, the following optimizations were set to produce 500 design alternatives each. In this case, the number of iterations was limited since the computational time started to increase around that quantity. However, this can be due to the limitations of the machine used. Hence, a more powerful device may not experience the same problematic. Therefore, it must be stressed that the process described for the optimization provides useful guidelines to solve a problem related to the renovation of an existing stadium. However, based on the specific case study to optimize and the time-frame available, a designer is encouraged to utilize its own set of values in order enhance the efficiency of the design alternatives to produce.

Exploration of the Design Alternatives

Once the optimization process is terminated, the produced design alternatives have to be evaluated to individuate the set of optimal solutions. Indeed, considering the objectives of this computational method, the results of the optimization process consist in a series of dominant and non-dominant solutions. Concerning the objective of the proposed computational method, the non-dominant solutions are selected. Indeed, these designs fulfill all the objectives of the optimization, while the dominant solutions favor one objective more than the others. Therefore, the data of the design alternatives have to be managed within ModeFRONTIER to individuate these solutions. Firstly, the total feasible results are grouped in a session table to obtain the overview of all the design alternatives that match the set constraints.

Hence, two methods were explored to facilitate the trade-off of the solutions for the designer. As a first method, a self-organizing map (SOM) was created to sub-divide the solutions and individuate the ones that maximize or minimize the objectives of the optimization. Indeed, a SOM can be utilized to individuate groups of similar data, which are shown graphically with a color gradient and grouped in a SOM table. However, this solution was discarded in favour of a hierarchical clustering, which resulted to be more intuitive in order to trade-off the alternatives.

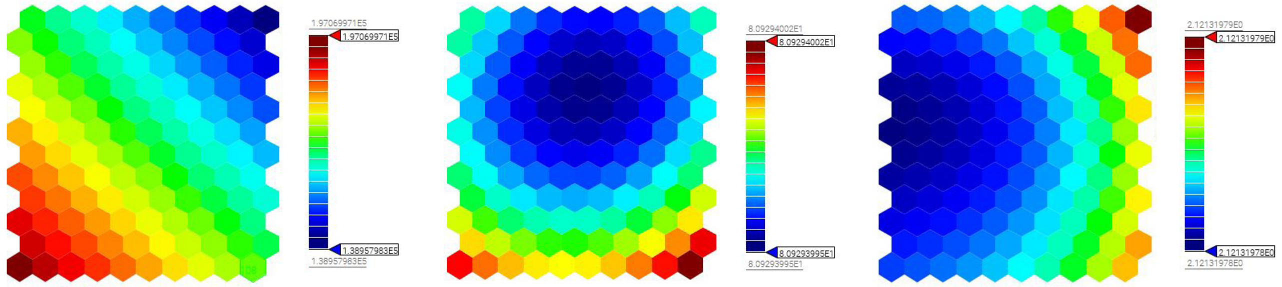


Figure 98. Examples of visualization of SOM in relation to different objective functions of the optimization process. (Source: Self-made)

The secondo method consists in the creation of a hierarchical clustering in ModeFRONTIER to group the design alternatives in clusters. In this case, a centroid-linkage algorithm is utilized to enchance the subdivision of the designs in more robust manner. Therefore, the designer can set the number of clusters to create based on the disposition of the designs in the solution space. The goal in to obtain a homogeneous number of designs in each cluster. Then, the clusters are plotted in a bubble diagram 4D to evaluate the relation between the groups of solutions and the objectives of the optimization. Hence, based on the objectives of the designer, a cluster can be selected. Therefore, this process allows to reduce the focus to a smaller group of design alternatives that fulfills the objectives of the optimization process.

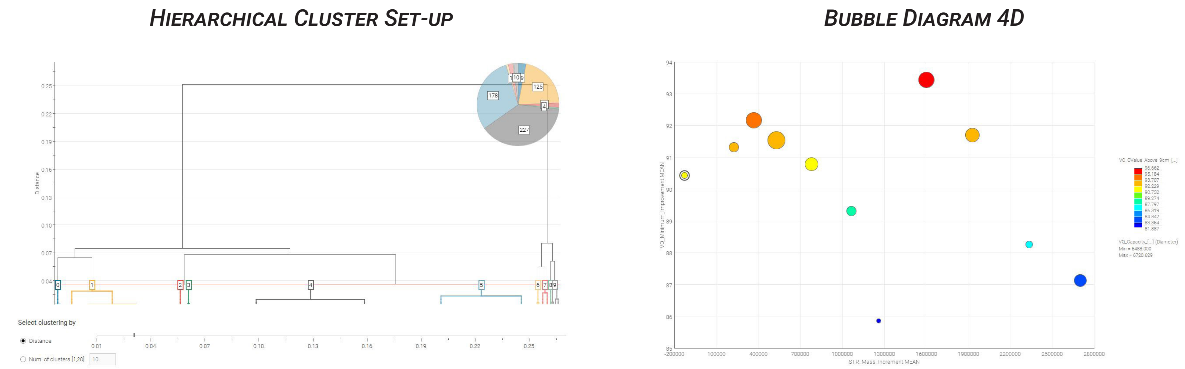


Figure 99. Examples of Cluster creation and evaluation within ModeFRONTIER. (Source: Self-made)

Afterwards, a categorization of the design solutions is performed. Indeed, the designer can categorize the design alternatives in relation to the objectives. Few categories are proposed based on the ones created to evaluate the results of the validation case (see chapter 8). However, a designer is encouraged to create its on set of categories based on the case study implemented and the objectives of the optimization. Moreover, the objectives can be prioritized. Concerning the objectives of this computational method, the hierarchy foresees the reduction of the mass of the roof as first, the viewing quality as second and the capacity as third. However, a designer is encouraged to utilize its on hierarchy based on the case study implemented and the objectives of the optimization. A color is assigned to each category and, based on the relation between the categories, few optimal design alternatives can be individuated.

Lastly, in order to trade-off the alternatives based on a aesthetic criteria, the design alternatives can be further categorized based on the inclination of the roof (inwards or outwards) or in relation to the clear height of the roof above the spectators. Moreover, the designer can individuate the ID code of the selected design alternatives and visualize the correspondent snapshot of the design from the directory created by ModeFRONTIER.

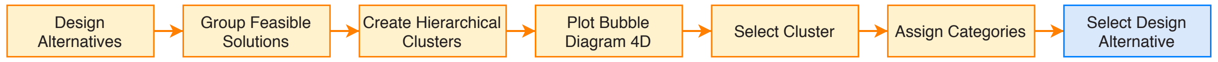


Figure 100. Workflow followed to trade-off the design alternatives in ModeFRONTIER. (Source: Self-made)

		ID	Algorithm	Phase	Clusters	Cluster1	Reduction Mass	Capacity higher than 20%	Viewing quality Higher than 90%
1		758	NSGA2		CLUSTER_0	CLUSTER_0	Reduced	18<20	90<95
2		815	NSGA2		CLUSTER_0	CLUSTER_0	Reduced	18<20	90<95
3	✓	830	NSGA2		CLUSTER_0	CLUSTER_0	Reduced	>20	>95
4	✓	848	NSGA2		CLUSTER_0	CLUSTER_0	Reduced	>20	>95
5		853	NSGA2		CLUSTER_0	CLUSTER_0	Reduced	18<20	85<90
6		858	NSGA2		CLUSTER_0	CLUSTER_0	Reduced	18<20	85<90
7		869	NSGA2		CLUSTER_0	CLUSTER_0	Reduced	18<20	90<95
8	✓	885	NSGA2		CLUSTER_0	CLUSTER_0	Reduced	>20	>95
9		894	NSGA2		CLUSTER_0	CLUSTER_0	Reduced	18<20	90<95
10		899	NSGA2		CLUSTER_0	CLUSTER_0	Reduced	18<20	85<90
11		909	NSGA2		CLUSTER_0	CLUSTER_0	Reduced	18<20	85<90
12		913	NSGA2		CLUSTER_0	CLUSTER_0	Reduced	18<20	85<90
13		926	NSGA2		CLUSTER_0	CLUSTER_0	Reduced	18<20	85<90
14		932	NSGA2		CLUSTER_0	CLUSTER_0	Reduced	18<20	90<95
15		935	NSGA2		CLUSTER_0	CLUSTER_0	Reduced	18<20	85<90
16		940	NSGA2		CLUSTER_0	CLUSTER_0	Reduced	18<20	85<90
17		942	NSGA2		CLUSTER_0	CLUSTER_0	Reduced	18<20	90<95
18		943	NSGA2		CLUSTER_0	CLUSTER_0	Reduced	18<20	90<95
19		945	NSGA2		CLUSTER_0	CLUSTER_0	Reduced	18<20	90<95
20		0	NSGA2		CLUSTER_1	CLUSTER_4	E5<E6	18<20	85<90
21		5	NSGA2		CLUSTER_1	CLUSTER_4	E5<E6	18<20	85<90
22		6	NSGA2		CLUSTER_1	CLUSTER_4	E5<E6	18<20	85<90
23		7	NSGA2		CLUSTER_1	CLUSTER_5	E5<E6	18<20	85<90
24		8	NSGA2		CLUSTER_1	CLUSTER_4	E5<E6	18<20	85<90
25		9	NSGA2		CLUSTER_1	CLUSTER_4	E5<E6	18<20	85<90
26		11	NSGA2		CLUSTER_1	CLUSTER_4	E5<E6	18<20	85<90
27		56	NSGA2		CLUSTER_1	CLUSTER_4	E5<E6	18<20	85<90

Figure 101. Examples of categorization and design selection in ModeFRONTIER. (Source: Self-made)

MASS CATEGORIES	RANGE	COLOR CODE
Reduced	< 0 Kg	
E4 < E5	1e4 Kg < x < 1e5 Kg	
E5 < E6	1e5 Kg < x < 1e6 Kg	
> E6	x > 1e6 Kg	

C-Value CATEGORIES	RANGE	COLOR CODE
80 < 85	80% < 85%	
85 < 90	85% < 90%	
90 < 95	90% < 95%	
> 95	x > 95 %	

% Capacity CATEGORIES	RANGE	COLOR CODE
< 20%	< 20%	
> 20 %	> 20 %	

Capacity CATEGORIES	RANGE	COLOR CODE
< 6500	< 6500	
> 6500	> 6500	

Roof Inclination CATEGORIES	RANGE	COLOR CODE
Inwards	-	
Outwards	-	

Clear height CATEGORIES	RANGE	COLOR CODE
0 m < 2 m	-	
2 m < 4 m	-	
4 m < 6 m	-	
> 6 m	-	

Figure 102. Categories utilized for the validation case in ModeFRONTIER. (Source: Self-made)

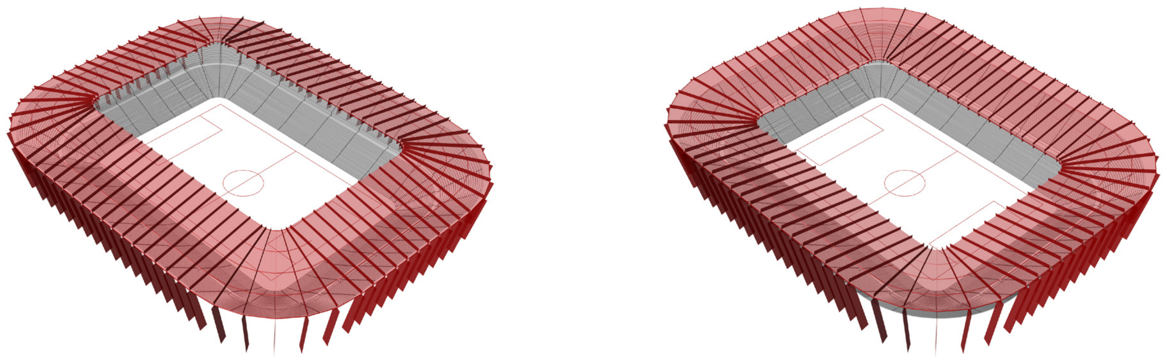


Figure 103. Example of Design Alternatives in the design space of the Validation Case. (Source: Self-made)

08 | SUMMARY AND VISION OF FUTURE DEVELOPMENT

8.1 Summary of the Computational Method

The phases of the computational method and the workflow followed to develop it have been explained in the previous chapters. In this section, a summary of the computational method is provided by introducing an overview of the phases of PCA and an overview of the typologies of the components implemented.

COMPUTATIONAL METHOD

A. Form Generation

Firstly, the playing area is set-up by determining the dimensions of the pitch and the presence of the athletic track. Secondly, the layout of the stadium is selected and shaped. Thirdly, the number of tiers and the stand typology to apply for each section of the stadium is set. Then, the stands are shaped by defining the geometry through the alteration of the input parameters, such as the tread depth and the riser height. Once the bowl is terminated, the number and the position of the gangways is inserted, as well as the dimensions of the seats and the gap between them to produce the eye points of the spectators. Lastly, the roof structure is defined by selecting the structural system, the position and the number of the supports and the cross sections of the structural elements.

B. Performance Assessment

Once the stadium is generated, the performance assessment of the viewing quality of the grandstands and the structural performance of the roof can be carried out. Hence, the performances are evaluated on the basis of the selected indicators and limit values.

Concerning the viewing quality, the c-value, the field of view, the vertical viewing angle and the maximum distance are evaluated and their results represented in panels. Moreover, the capacity of the stadium is calculated. In this case, the capacity and the c-value are evaluated in relation to the overall stadium and towards the individual tiers of stands. Lastly, the results are visualized with a color gradient to support the decision-making of the designer, which can relate the results to the displayed maps.

Concerning the structural performance, the maximum displacement and the maximum stresses for all the groups of structural elements is provided, as well as the values of the mass, the number of elements and joints present within the roof structure. Then, the results are visualized through Karamba 3D and the critical elements are displayed to support the decision-making of the designer, which can relate the results to the displayed maps.

C. Optimization and Design Exploration

Once the performances are analyzed, the portions of the stadium that need renovation can be individuated and the approach for the optimization can be determined. In this case, C-value and the maximum distance constitute the crucial indicators concerning the grandstands. Indeed, these features have a major implication on the viewing quality of the spectators. Therefore, they constitute a threshold to distinguish whether a stand requires to be renovated or to be kept unaltered.

Hence, the set-up for the optimization is performed in ModeFRONTIER by implementing the inputs, the objectives and the design constraints. Then, the optimization is started to obtain multiple design alternatives. The inputs imported in ModeFRONTIER are related exclusively to the portions of the stadium to be renovated, while the parts to be kept are maintained unaltered by excluding their inputs from the optimization.

Subsequently, a hierarchical cluster is created to group the results based on their proximity within the design space. Lastly, the designer can select a cluster based on the necessities of the renovation project to carry out and its design alternatives can be categorized. Therefore, the trade-off of the alternatives is completed and the designer is able to select a design solution to be further developed.

The steps of the developed computational method are represented as a scheme in figure 104, where the macro-phases of the workflow and the tools utilized are highlighted. It is notable, that the blue elements indicates the information or the actions that the designer have to determine outside the computational environment in order to provide the input data for the computational method.

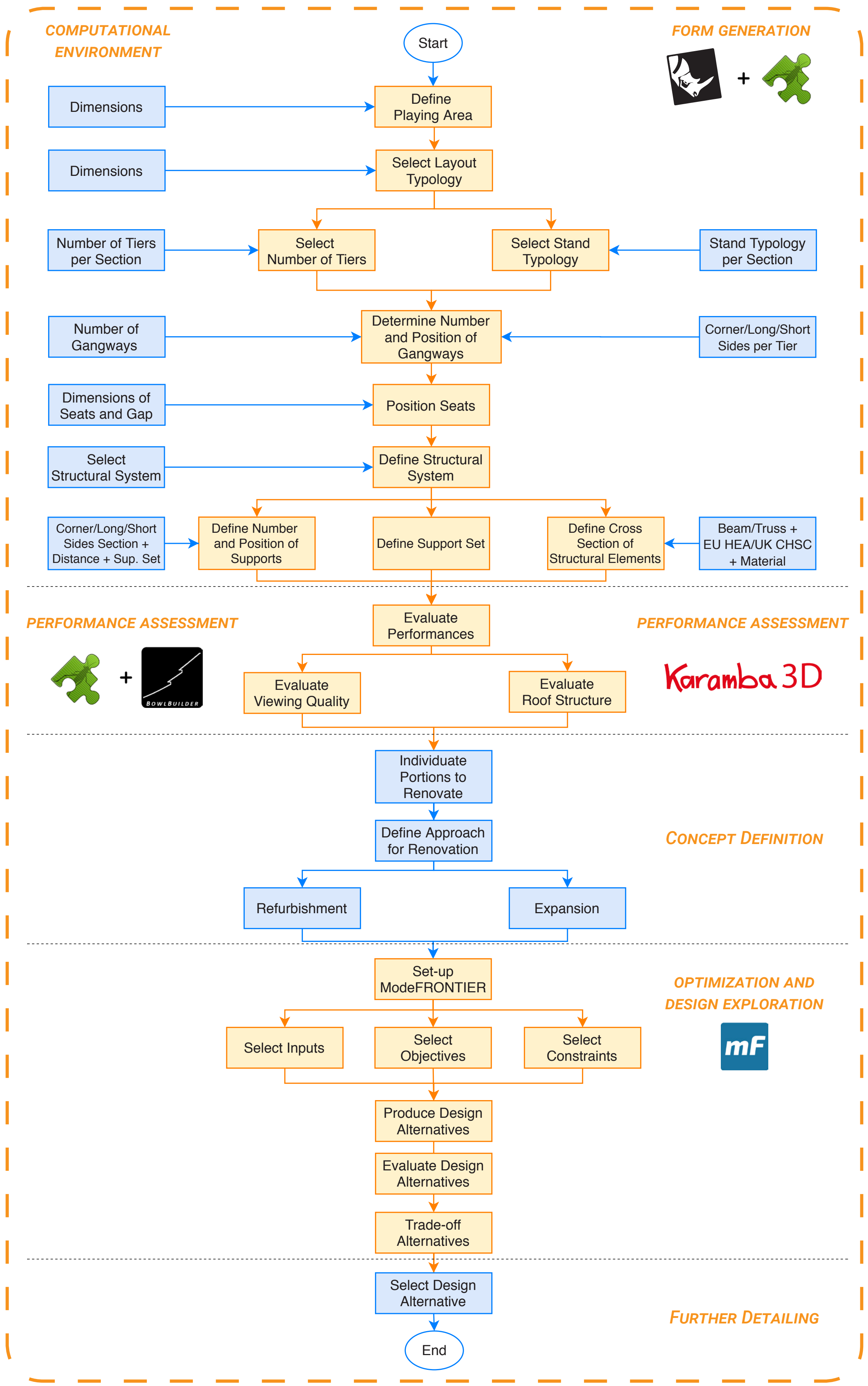


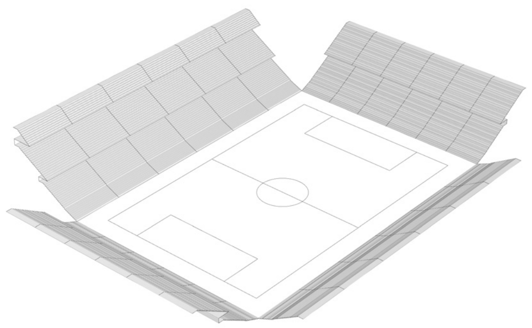
Figure 104. Overview of the steps of the developed computational method. (Source: Self-made)

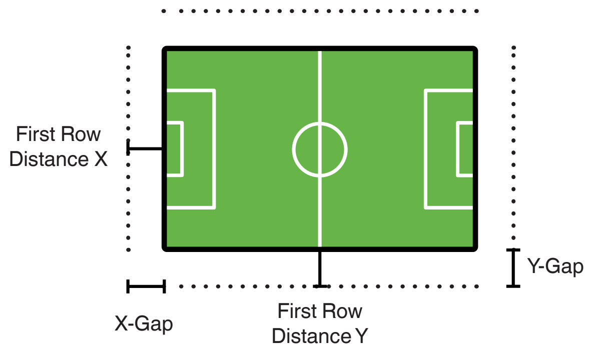
LAYOUT TYPOLOGIES

From the literature review, seven common layout typologies were implemented in the computational method. In this case, since the computational method was developed to be applicable on multiple stadiums rather than focusing on a specific one, this choice enlarges the design space. The influence of the layout typologies on the performances to be evaluated and the parameters included in the computational method are described.

A. Open Rectangle

The open rectangle layout typology has an influence on the capacity of the stadium. Indeed, since the corners are not built, the number of spectators that can be hosted by a stadium with this layout typology is greatly reduced compared to the other types implemented. Concerning the viewing quality, the open rectangle geometry allows to maintain the C-value constant for all the seats of a row, while the field of view results to be wide (> 120°) for the spectators seating in the central areas of the stands. In general, a layout curve closer to the pitch reduces the C-value and increases the field of view, hence affecting negatively the viewing quality. However, the proximity to the pitch allows to increase the atmosphere of the stadium since the spectators are closer to the activity hosted in the playing area. Lastly, in relation to the roof, the structure of every section of the stadium results to be independent from the others. An example of a stadium with an open rectangle layout is Anfield (UK), the home ground of Liverpool FC.





- **Advantages**

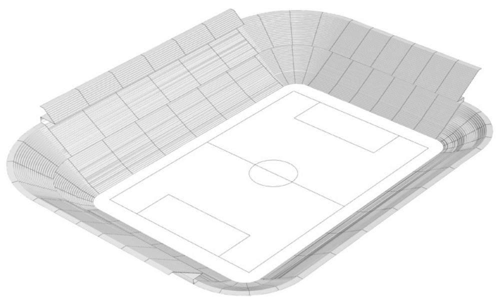
  Proximity to Pitch enhance atmosphere
  C-value is constant in the same row of seats

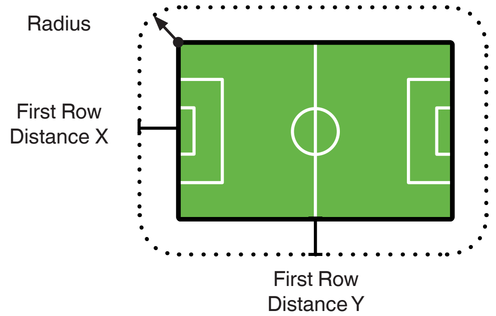
- **Disadvantages**

  Field of view > 120° in central area of the stands
  Empty Corners affect capacity

A. Open Rectangle

The rounded rectangle layout typology provides a reduction of the C-value in the corner areas of the stadium since the proximity to the pitch is reduced, while the field of view results to be wide (> 120°) for the spectators seating in the central areas of the stands. In general, a layout curve closer to the pitch reduces the C-value and increases the field of view, hence affecting negatively the viewing quality. However, the proximity to the pitch allows to increase the atmosphere of the stadium since the spectators are closer to the activity hosted in the playing area. An example of a stadium with a rounded rectangle layout is Old Trafford (UK), the home ground of Manchester United FC.





- **Advantages**

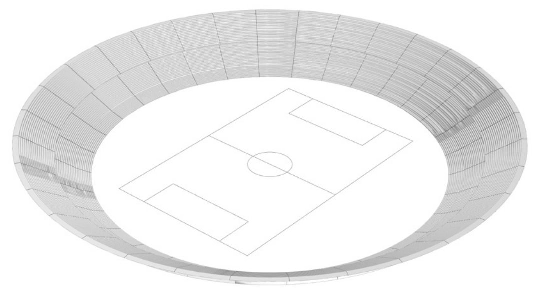
  Proximity to Pitch enhance atmosphere
  C-value is constant in the center area of stands

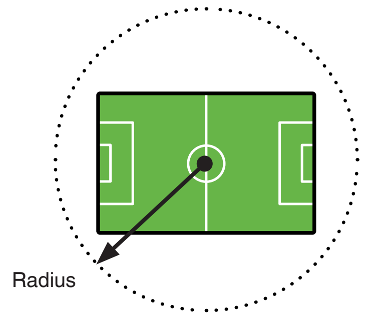
- **Disadvantages**

  Field of view > 120° in central area of the stands

C. Circular

The circular layout typology provides a variable C-value in the same row of seats. Indeed, the C-value decreases towards the corners of the pitch. However, it is facilitated to obtain higher values since the distance from the point of focus is increased compared to layout curves that are parallel to the pitch. In general, a better viewing quality can be achieved more easily. Although, the distance of the spectators from the pitch constitutes a downside of this layout typology, which affects negatively the atmosphere of the stadium. An example of a stadium with a circular layout is the Maracana stadium (Brazil), the home ground of Fluminense and Flamengo.





- **Advantages**

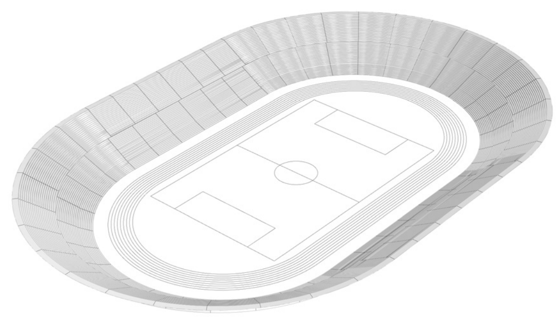
  Higher C-values can be achieved more easily
  Better viewing quality compared to other layouts

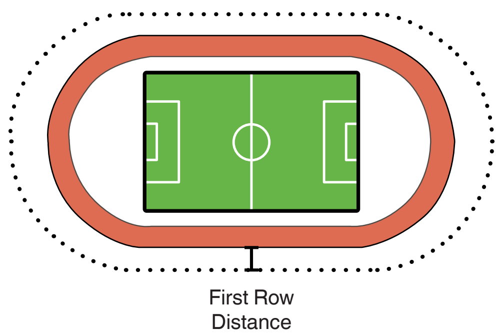
- **Disadvantages**

  Larger distance from pitch affects atmosphere

D. Semi-Circular

The semi-circular layout typology presents an athletic track around the pitch, which has an influence on both the viewing quality of the spectators and the atmosphere of the stadium. Indeed, it is facilitated to obtain a higher c-value since the distance from the point of focus is increased compared to layouts that do not present an athletic track. Although, the distance of the spectators from the pitch constitutes a downside of this layout typology, which affects negatively the atmosphere of the stadium. In addition, due to its shape, it is likely to obtain seats outside the optimum viewing circle, hence affecting negatively the viewing quality. An example of a stadium with a semi-circular layout is the Olympic Stadium of Rome (Italy), the home ground of AS Roma and S.S. Lazio.





- **Advantages**

  Larger distance from pitch increases C-value
  Larger dimensions increase capacity

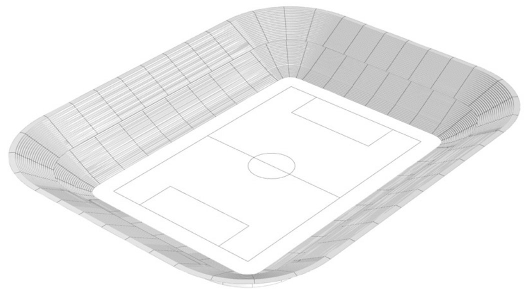
- **Disadvantages**

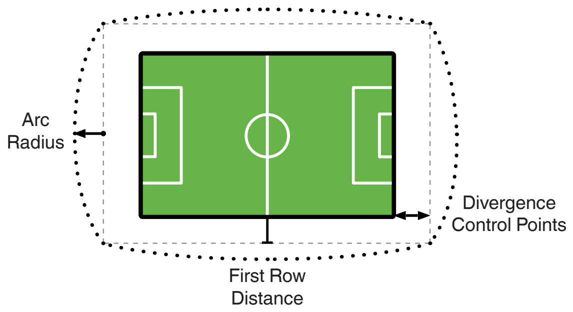
  Larger distance from pitch affects atmosphere
  Larger distance from pitch can affect viewing quality (Recommended viewing distance not matched)

E. Super Ellipse

The super ellipse layout typology provides a variable C-value in the same row of seats. Indeed, the C-value decreases towards the corners of the stadium. Considering the curvature of the layout curve along the touchline of the pitch, the C-value is higher in the centre area of the stands and decreases while moving towards the corners. Similarly to the open rectangle geometry, the field of view results to be wide (> 120°)

for the spectators seating in the central areas of the stands. In general, a layout curve closer to the pitch reduces the C-value and increases the field of view, hence affecting negatively the viewing quality. However, the proximity to the pitch allows to increase the atmosphere of the stadium since the spectators are closer to the activity hosted in the playing area. An example of a stadium with a super ellipse layout is the Aviva Stadium (Ireland), the home ground of the national team of Ireland.





- **Advantages**

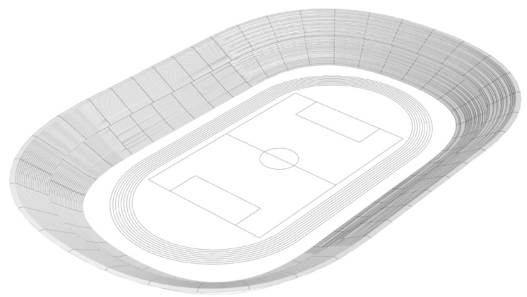
  Proximity to Pitch enhance atmosphere
  C-value higher in the center area of the stands

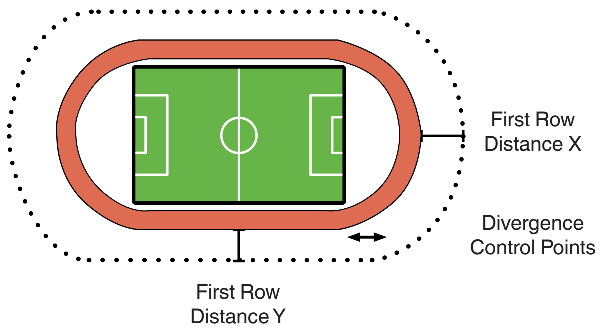
- **Disadvantages**

  Field of view > 120° in central area of the stands

F. Basket-Arch

The basket-arch layout typology presents an athletic track around the pitch, which has an influence on both the viewing quality of the spectators and the atmosphere of the stadium. Indeed, it is facilitated to obtain a higher c-value since the distance from the point of focus is increased compared to layouts that do not present an athletic track. Although, the distance of the spectators from the pitch constitutes a downside of this layout typology, which affects negatively the atmosphere of the stadium. In addition, due to its shape, it is likely to obtain seats outside the optimum viewing circle, hence affecting negatively the viewing quality. Compared to the semi-circular layout, the C-value results to be higher closer to the corners of the pitch, since the distance from the touchline is increased. An example of a stadium with a basket-arch layout is the Stade de France (France), the home ground of the national team of France.





- **Advantages**

  Larger distance from pitch increases C-value
  Larger dimensions increase capacity

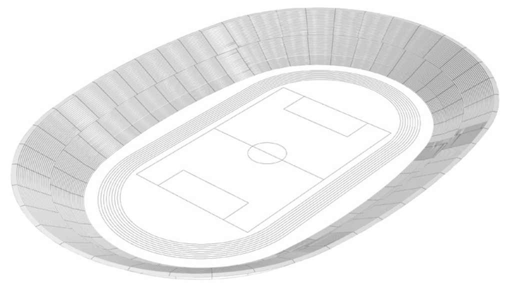
- **Disadvantages**

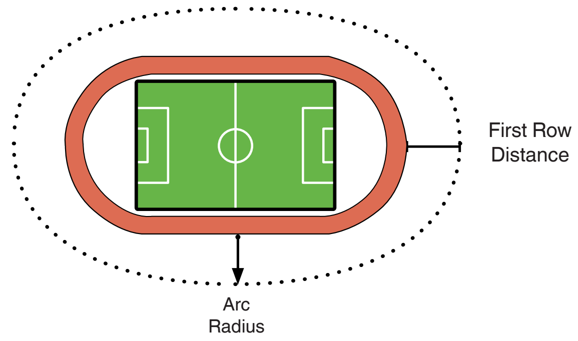
  Larger distance from pitch affects atmosphere
  Larger distance from pitch can affect viewing quality (Recommended viewing distance not matched)

G. Oval

The oval layout typology presents an athletic track around the pitch, which has an influence on both the viewing quality of the spectators and the atmosphere of the stadium. Indeed, it is facilitated to obtain a higher c-value since the distance from the point of focus is increased compared to layouts that do not present an athletic track. Although, the distance of the spectators from the pitch constitutes a downside of this layout typology, which affects negatively the atmosphere of the stadium. In addition, due to its shape, it is likely to obtain seats outside the optimum viewing circle, hence affecting negatively the viewing quality. Compared to the semi-circular layout, the C-value results to be higher in the center area of the stands, since

the distance from the touchline is increased. An example of a stadium with an oval layout is the Jamsil Olympic Stadium (South Korea).





- **Advantages**

  Larger distance from pitch increases C-value
  Larger dimensions increase capacity

- **Disadvantages**

  Larger distance from pitch affects atmosphere
  Larger distance from pitch can affect viewing quality (Recommended viewing distance not matched)

GRANDSTANDS

From the literature review, the stand typologies with a linear riser were implemented in the computational method. In this case, since the computational method was developed to be applicable on multiple stadiums rather than focusing on a specific one, this choice enlarges the design space. The main difference between the stands with a linear and a parabolic riser can be found in the C-value produced by the geometry. Indeed, with a linear riser, the C-value reduces at every row of seats, while maintaining constant the riser height. On the other hand, with a parabolic riser, the riser height increases at every row of seats, while maintaining constant the c-value between the spectators seating one behind the other.

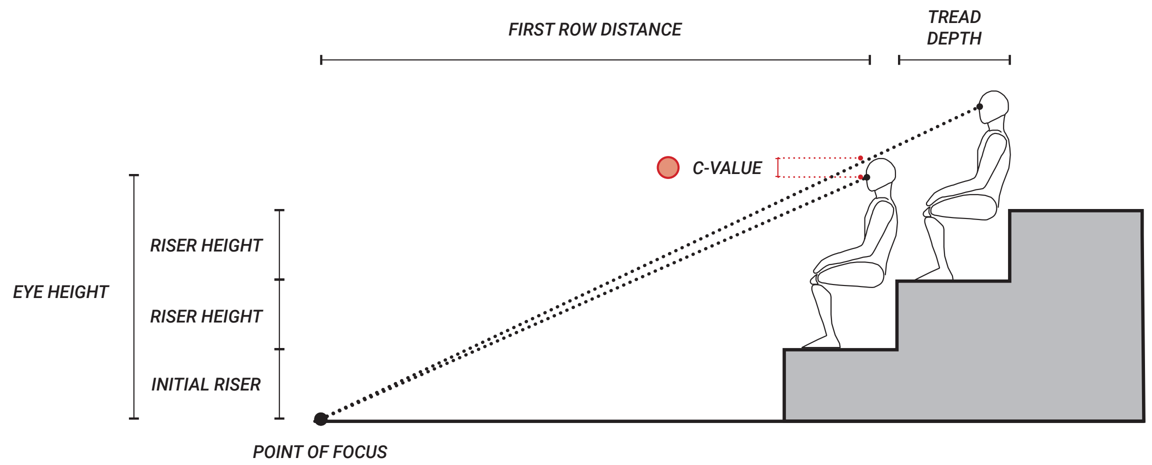


Figure 105. Scheme of construction of the stands within the computational method. (Source: Self-made)

A. Tread Depth and Riser Height

The tread depth is the horizontal distance between one spectator's eye-point and the eye-point of the spectator seating exactly behind him. Extensively, it represents the depth of the seating/standing step of the grandstand. This parameter determines the seating comfort of the spectators. Therefore, the higher the value is, the more comfortable the user will be.

The riser height is the height of every row of seats. A higher value increase the C-value and therefore the viewing quality of the spectators. However, the tread depth of the stands, in relation with the riser height, influences the inclination of the stands, which can therefore limit the C-value and the capacity of the stadium.

The inclination of the stands is calculated within the computational method as the angle between the ground plane and the diagonal line that connects all the steps of the stand. Therefore, the inclination of the stand is determined by the variation of the tread depth and the riser height. As displayed in figure 106, a decrement of the tread depth leads to a steeper stand, reducing also the comfort of the spectators, while and increment of the riser height provides an increment of the C-value, but the maximum inclination of 35° can be reached quickly. As can be seen, the second tier has a higher depth, but the sightlines of the spectators result to be obstructed. On the other hand, the first tier presents a lower depth. Hence, the comfort of the spectators is reduced, providing however a benefit to the C-value, which is increased avoiding therefore an obstruction of the spectators' view. Similarly, the starting position of the second tier influence the C-value. Indeed, the viewing quality is improved whether the cantilever distance and the tier height is reduced, as can be seen from figure 107.

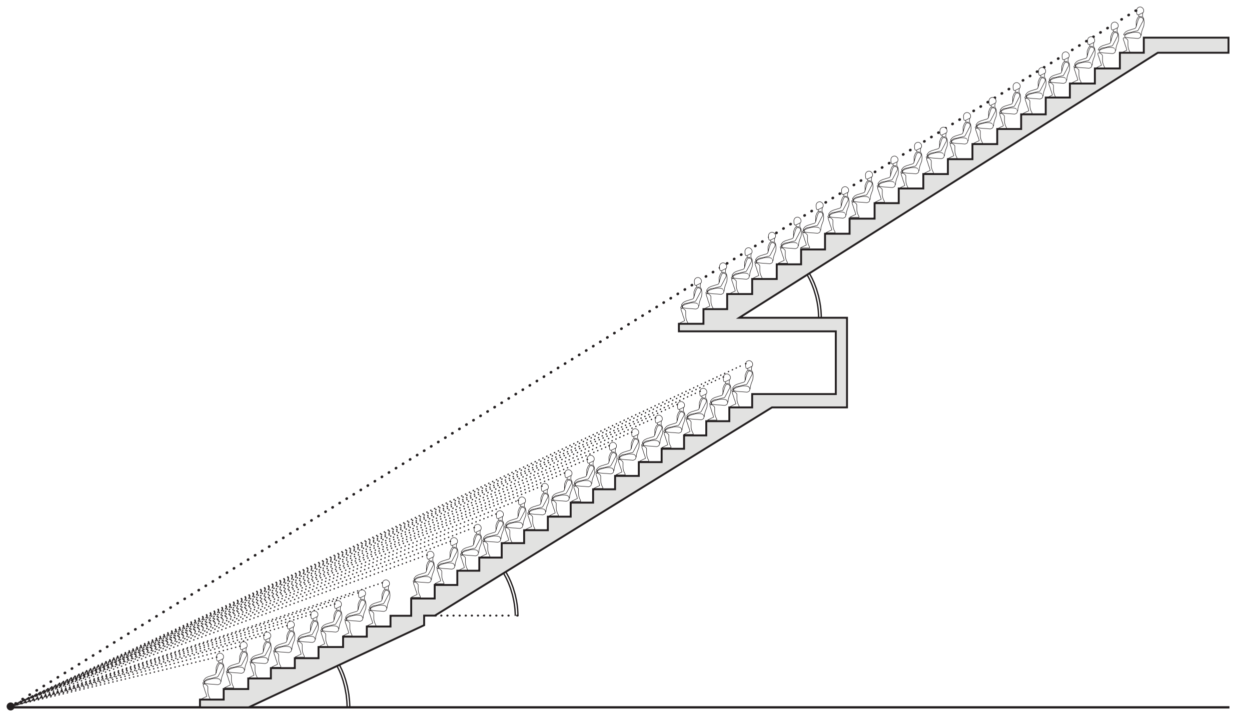


Figure 106. Example of Grandstand section with spectators' sightlines. (Source: Self-made)

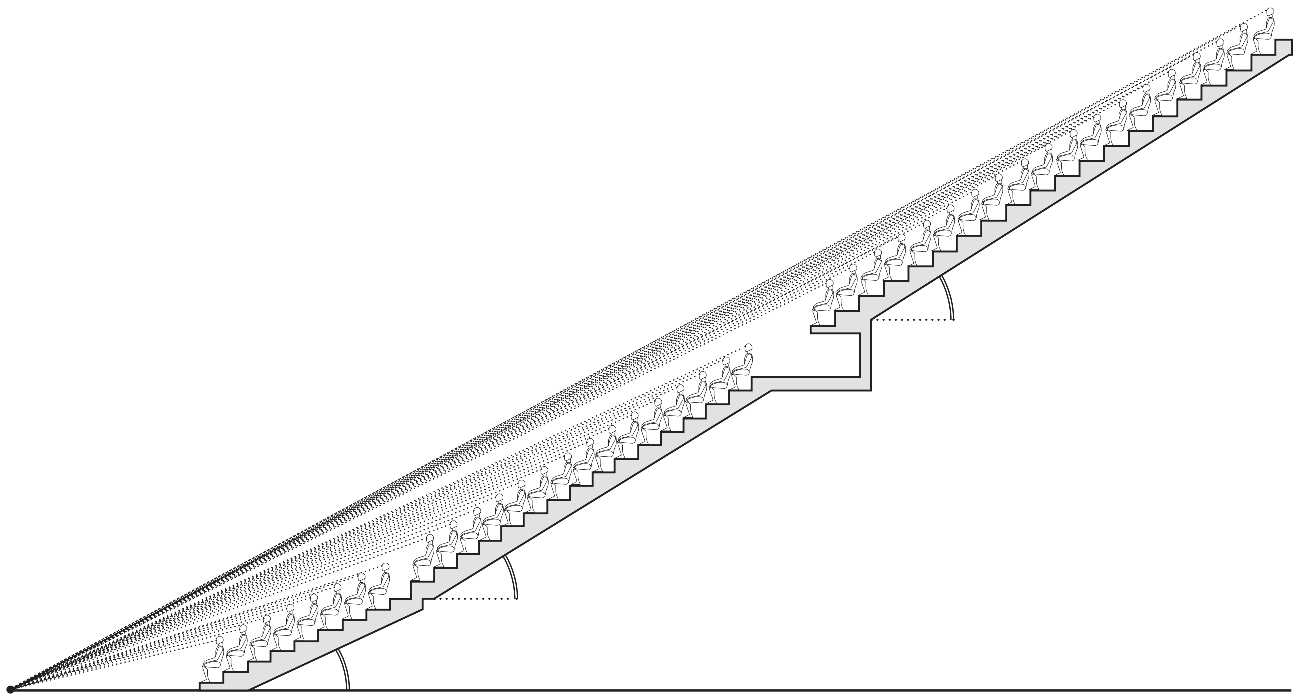


Figure 107. Example of Grandstand section with spectators' sightlines. (Source: Self-made)

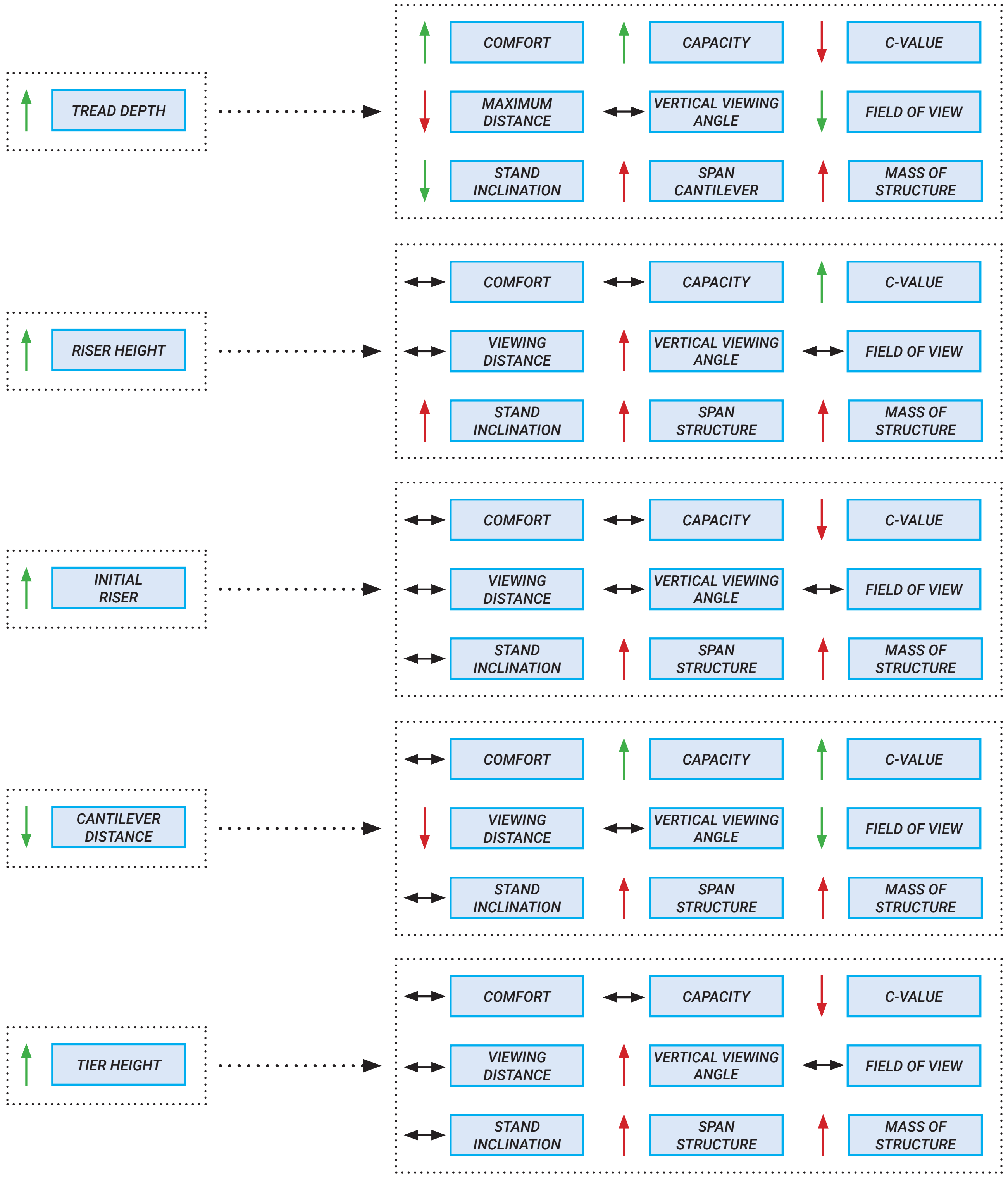


Figure 108. Relation between parameters and outputs of the performance assessment. (Source: Self-made)

ROOF STRUCTURE

From the literature review, three cantilever structural systems were implemented in the computational method. In this case, since the computational method was developed to be applicable on multiple stadiums rather than focusing on a specific one, this choice enlarges the design space. Firstly, the structural systems are implemented and few parameters can be utilized to determine its outline. Hence, the structural elements are grouped and a cross section can be applied for each group. This choice constitutes a limitation of the computational method, since the cross section is applied to the group of structural elements independently from the span they have to cover. Therefore, on the one hand structural elements within the same group (i.e. cantilever elements) may be over-dimensioned. On the other hand, the optimization of a single group of elements will lead to the alteration of all the structural elements of the group, even though it may not be necessary.

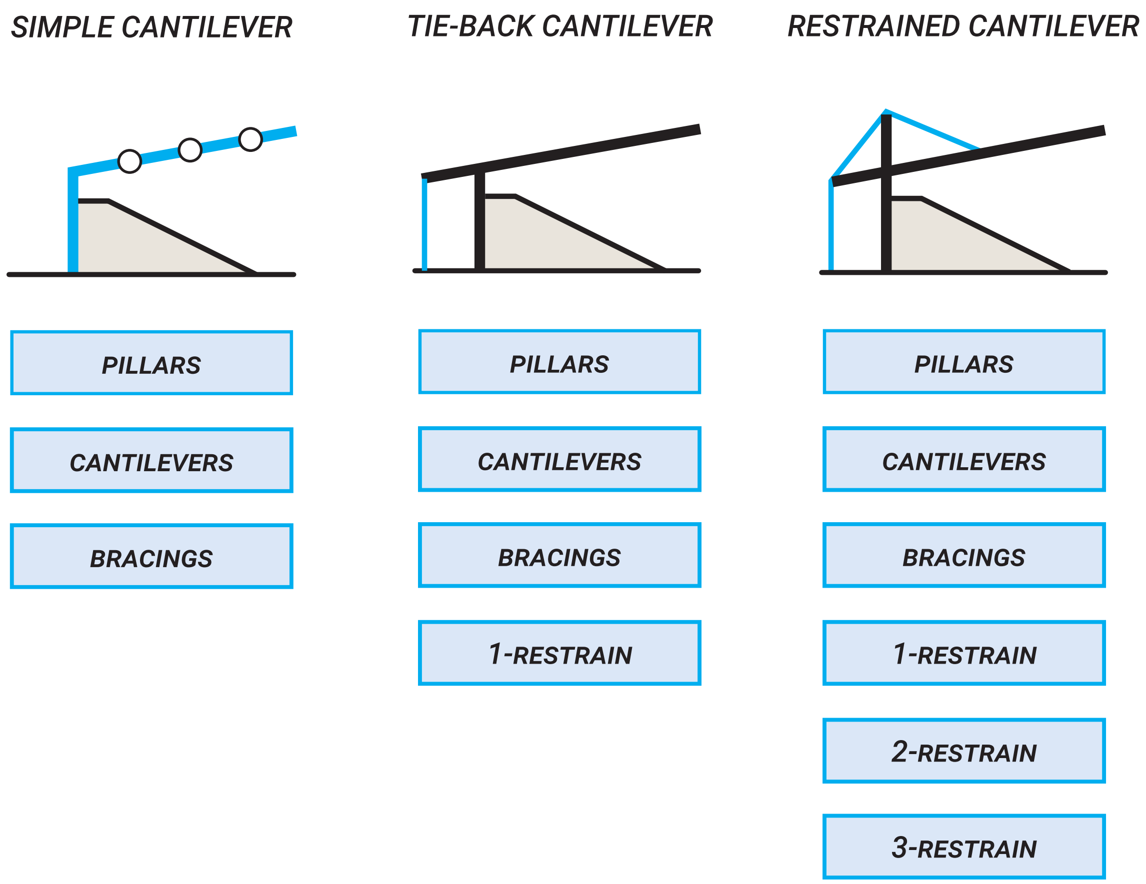


Figure 109. Structural elements divided per group and structural system. (Source: Self-made)

Concerning the structural systems, few considerations can be derived. As introduced in chapter 6, the simple cantilever system requires larger cross-sections to withstand the bending stresses and to deflect lower than the limit values compared to the tie-back and the restrained cantilever systems. Hence, to reduce the mass of the structure while complying with the design constraints, the tie-back or the restrained cantilever system can be utilized. Indeed, these systems reduce the deflection of the cantilever elements by restraining them.

In the case of a renovation, the structural system applied to the existing stadium should be kept unaltered to avoid major alteration from the initial situation. On the one hand, whether a simple cantilever is applied as the initial structural system, the application of a tie-back system or a restrained system would provide a benefit in relation to the deflection of the structure, while increasing the mass of the structure and the number of joints and elements in the process. On the other hand, these systems allow to reduce the number of supports and therefore the mass of the roof structure.

Overall, the structural systems implemented in the computational method can provide advantages and disadvantages to the roof structure and the overall efficiency of the design. However, a designer should determine which system should be applied based on the existing stadium on which the renovation have to be performed. In the case of the validation case that is introduced in the next chapter, the approach followed is to maintain unaltered the initial situation as much as possible. Hence, the simple cantilever initially applied is considered as the only structural system for the optimization.

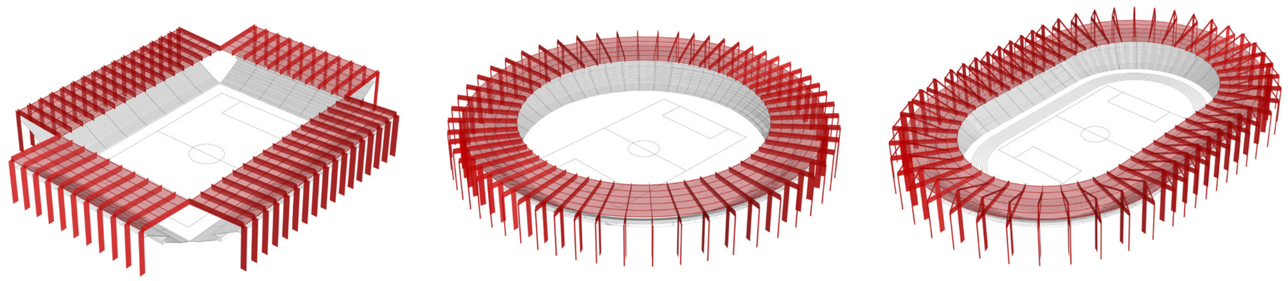


Figure 110. Examples of the structural systems applied to three different layout typologies. (Source: Self-made)

8.2 Vision of Future Development

The computational method developed in this thesis aims to provide designers and engineers with an overview of the viewing quality performance and of the structural performance of a stadium. Hence, the overview helps the designer in determining the portions of a stadium that needs to be renovated. Lastly, the computational method includes a workflow explore multiple design alternatives for the renovation of the stadium that optimize the initial performances, producing therefore efficient design solutions.

In order to support the designer along the design process, the user interface constitutes a crucial feature of the computational method. In fact, a visualization system allows to relate the produced data with a graphic display, therefore providing support to the designer. Indeed, the designer can be offered an immediate feedback on the performances to quickly understand the behavior of the components of the stadium. Therefore, in a second time, it is possible to distinguish the portions of the stadium to be renovated, hence selecting the inputs, the constraints and the objectives to be utilized during the optimization process.

Concerning the computational method described in the previous chapters, the user interface is constituted by the graphic interface of the computational tools utilized, which are Grasshopper and ModeFRONTIER.

FORM GENERATION

The form generation of the parametric model of the stadium is performed in the computational environment of Rhino and Grasshopper. In this phase, the designer can modify the implemented input parameters to determine the geometry of the stadium and the outline of the roof structure. Therefore, the parametric model of the existing stadium to be renovated or expanded can be obtained.

The typologies of the components and the input parameters that control them implemented in the computational method can be combined to generate different designs. Hence, the designer can generate different configuration to recreate the existing stadium that have to be analyzed and renovated.

In this case, the user interface allows the designer to modify the parameters within Grasshopper, while the preview of the generated stadium can be visualized in Rhinoceros. The parameters are divided in groups based on the geometry and the component that they control, while the elements to be displayed have to be manually visualized by switching on the preview of the objects within Grasshopper. Hence, the designer is provided with a real time feedback of the variation of the geometry whether the input parameters are modified.

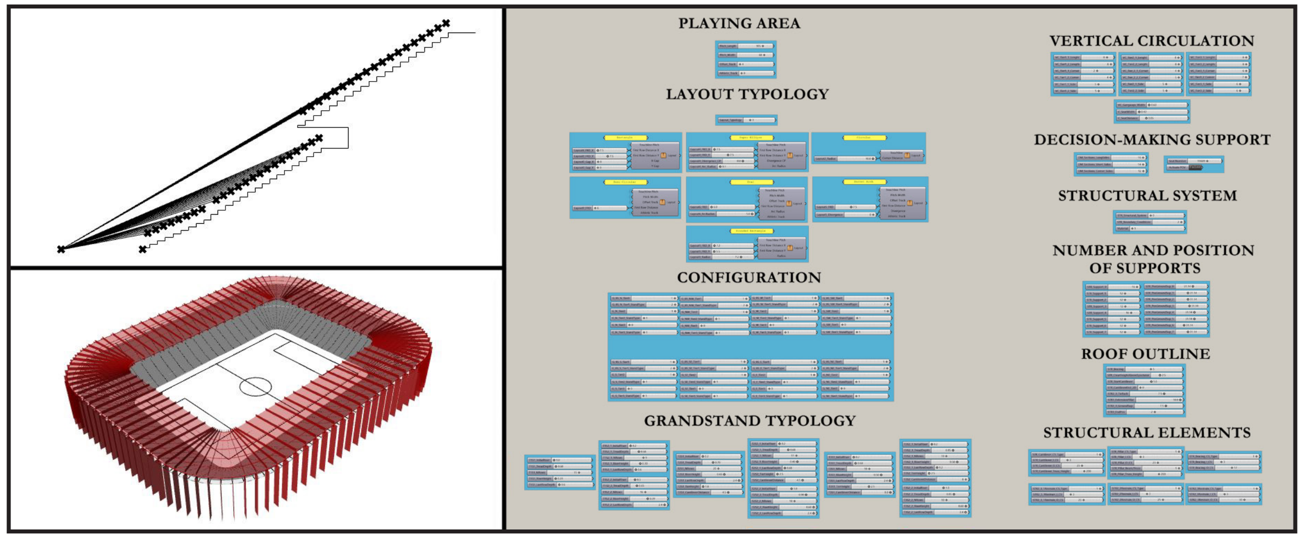


Figure 111. User interface of the computational method in the form generation phase. (Source: Self-made)

Considering the importance of the user interface, which facilitate the designer in the navigation within the computational tool and in the generation of the geometries, it can be improved by creating a custom graphic interface. Indeed, this development can improve the clearness of the method and it can facilitate further the designer in navigating the computational method.

As an example, Human UI (Andrew Heumann et al., 2016) is a plug-in of Grasshopper that can be utilized to create custom user interfaces. As a future development, the user interface of the computational method can be envisioned to be realized. As a vision, the designer can be allowed to select the portions of the stadium to be generated and information can be provided to support the decision-making process. An example of the envisioned user interface for the form generation phase is shown in figure 112 and figure 113.

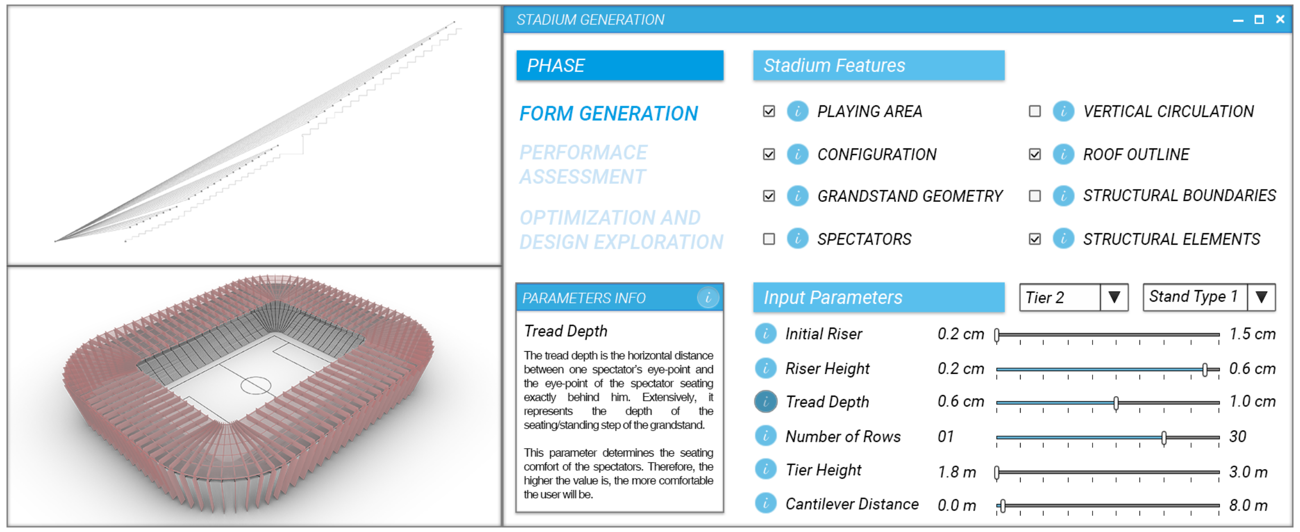


Figure 112. Example of the envisioned user-interface of the form generation. (Source: Self-made)

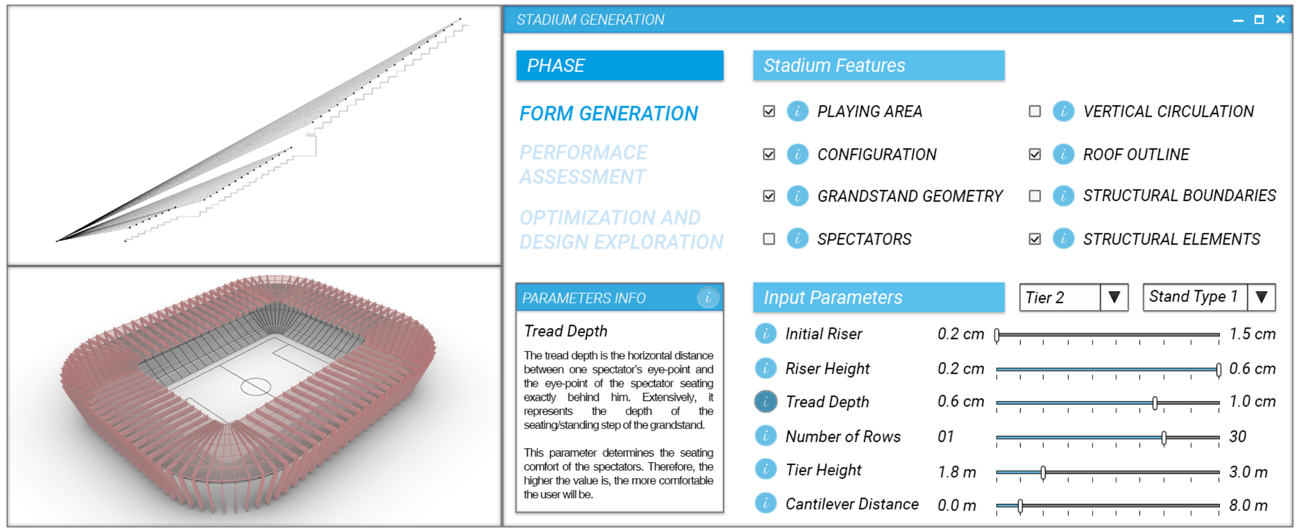


Figure 113. Example of the envisioned user-interface of the form generation. (Source: Self-made)

PERFORMANCE ASSESSMENT

In the performance assessment phase the evaluation of the behavior of components of the stadium is performed in the computational environment of Rhino and Grasshopper. In this phase, the designer can extrapolate the values related to the performance indicators. Hence, with the support of a graphic visualization method, the designer is informed of the most critical elements of the roof structure and they are facilitated in the individuation of the portions of the stadium to be renovated.

In this case, the user interface allows the designer to visualize the data within panels within Grasshopper, while the preview of the graphic map can be visualized in Rhinoceros. In this case, the diagrams can be visualized one at the time by switching on the previews within Grasshopper. In addition, 2D sections and the points of view of the spectators can be visualized to evaluate further the performances, allowing to visualize the sightlines of the spectators in relation to the geometries of the stadium.

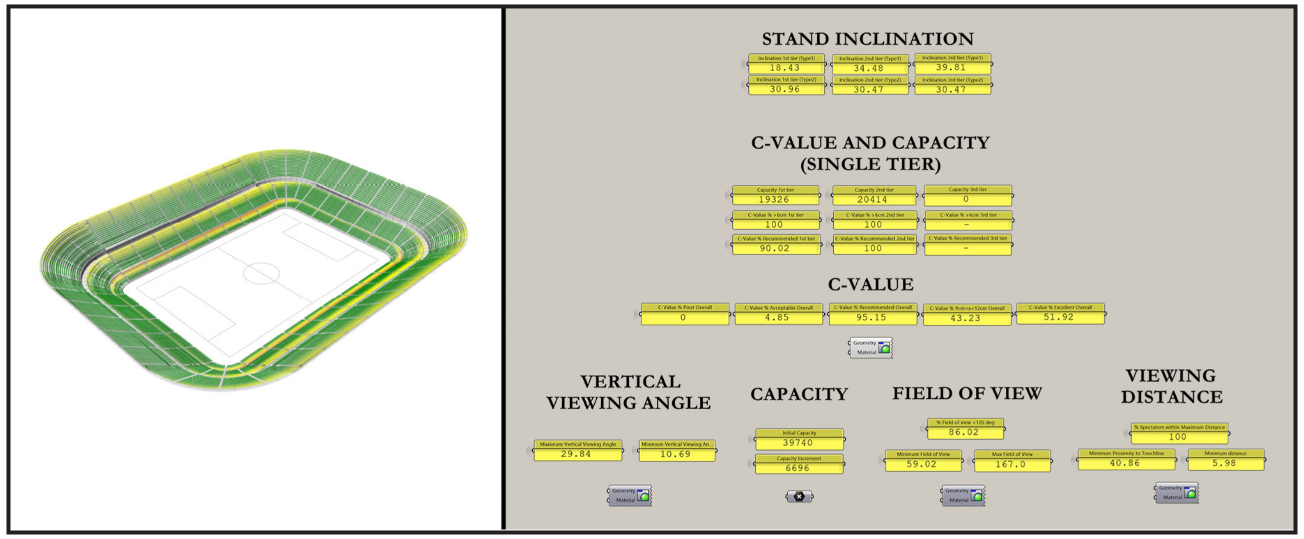


Figure 114. User interface of the computational method in the performance assessment phase. (Source: Self-made)

Considering the importance of the user interface, which facilitate the designer in the navigation within the computational tool and in the evaluation of the performances, it can be improved by creating a custom graphic interface. Indeed, this development can improve the clearness of the method and it can facilitate further the designer in the individuation of the portions of the stadium to be renovated.

As an example, Human UI (Andrew Heumann et al., 2016) is a plug-in of Grasshopper that can be utilized to create custom user interfaces. As a future development, the user interface of the computational method can be envisioned to be realized. As a vision, the designer can be to allowed visualize multiple diagrams at the time along with the results of the performance assessment. An example of the envisioned user interface for the performance assessment phase is shown in figure 115 and figure 116.

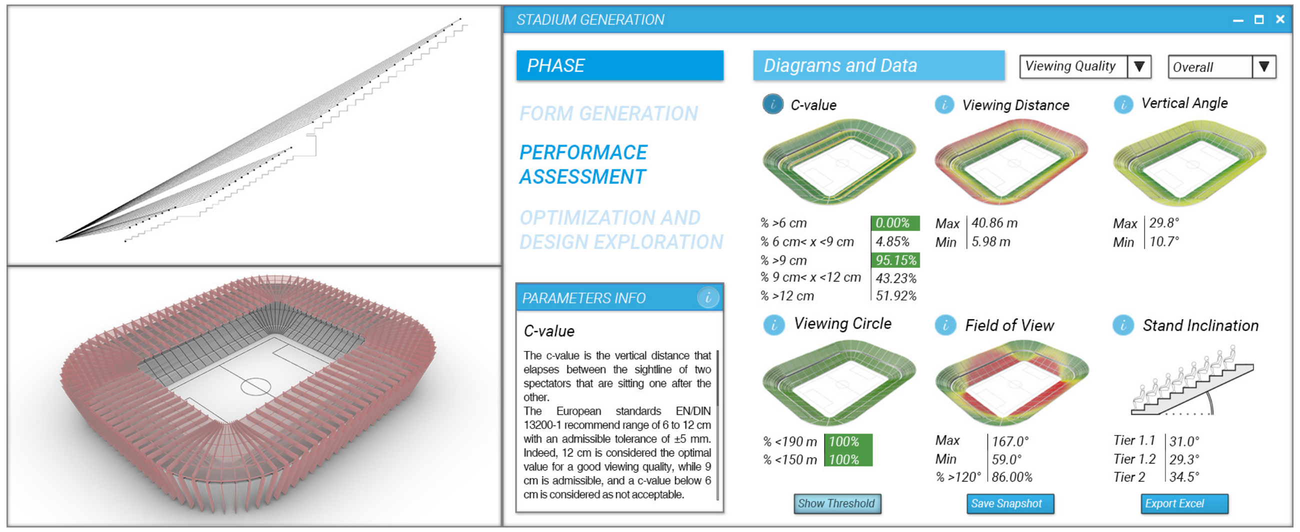


Figure 115. Example of the envisioned user-interface of the performance assessment. (Source: Self-made)

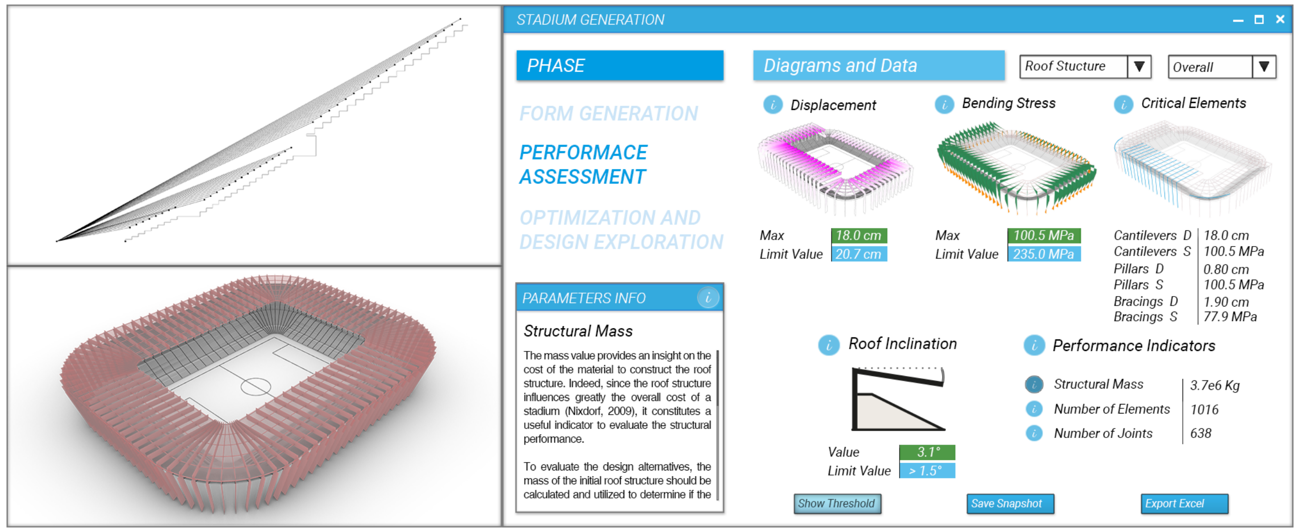


Figure 116. Example of the envisioned user-interface of the performance assessment. (Source: Self-made)

OPTIMIZATION AND DESIGN EXPLORATION

In the optimization and design exploration phase, the design alternatives are produced in the computational environment of ModeFRONTIER. In this phase, the designer can generate multiple design solutions by selecting the inputs, the constraints and the objectives of the optimization process. Hence, a trade-off of the alternatives can be carried out to individuate the optimal solutions of the objective functions.

In this case, the user interface is constituted by the interface of ModeFRONTIER. A designer can navigate the computational tool to set-up the optimization process and, in a second moment, to explore the multiple design alternatives produced and to trade-off the optimal solutions. During the set-up phase, the designer can determine the range of values of the input parameters, as well as the step of the variation within the range. Similarly, the objectives and the constraints can be set to be higher, lower or equal to a limit value. Once the optimization is launched, the designer in provided with an overview of the design alternatives produced. Hence, in the design space tab, multiple graphs and diagrams can be produced to explore the solution space to refine the optimization and trade-off the alternatives. The output of the performances of the design alternatives are listed in a worktable. However, the designer does not have a possibility to relate the values with a graphic support system that displays the stadium.

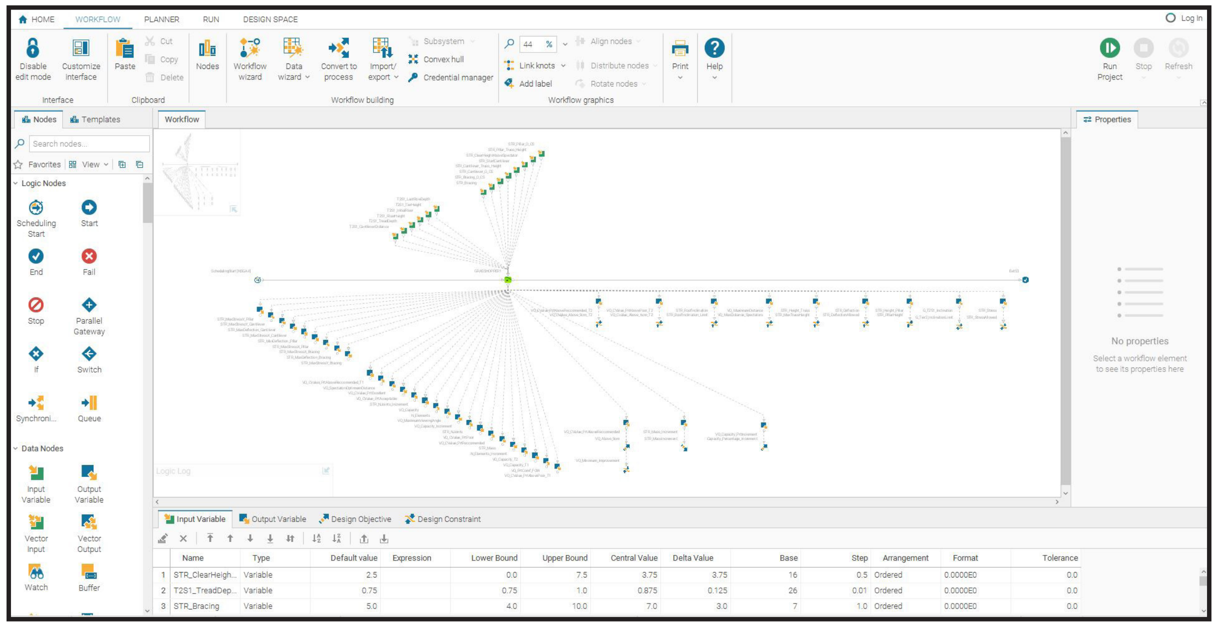


Figure 117. User interface of the computational method in the optimization phase (set-up). (Source: Self-made)

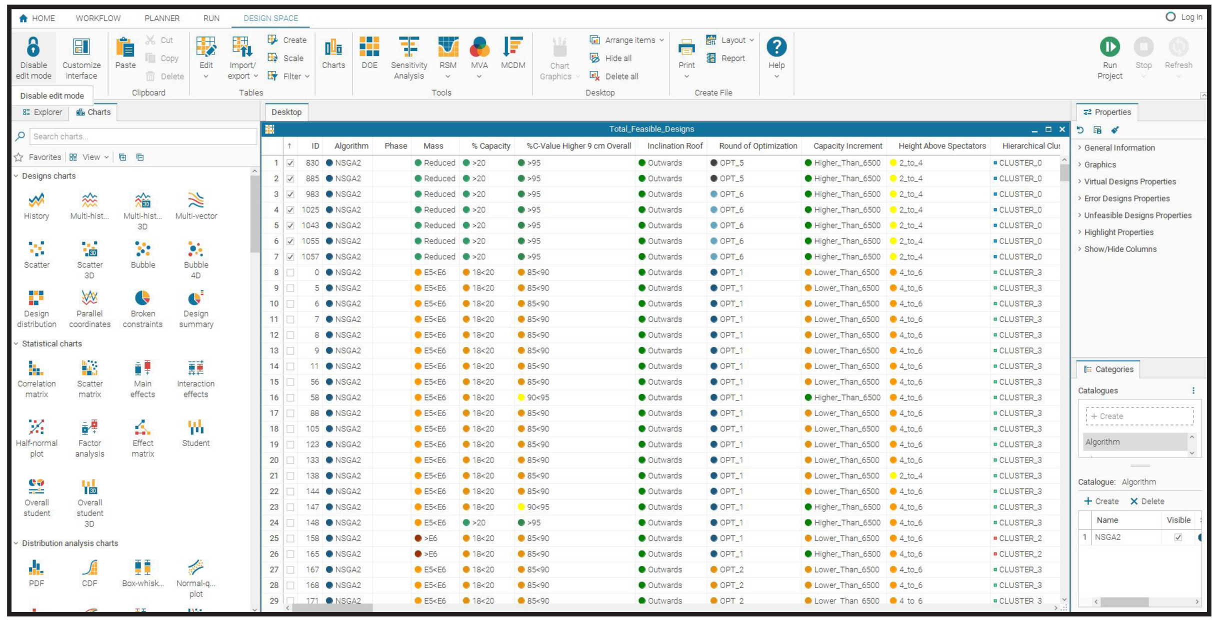


Figure 118. Example of the envisioned user-interface of the optimization and design exploration phase (Design Space). (Source: Self-made)

Considering the importance of the user interface, which facilitate the designer in the navigation within the computational tool and in the trade-off of the design alternatives, it can be improved by creating a custom graphic interface within Grasshopper. Indeed, this development can allow the designer to display the 3D Model of the stadium and the performances of both the initial and the alternative situations.

As an example, Human UI (Andrew Heumann et al., 2016) is a plug-in of Grasshopper that can be utilized to create custom user interfaces. As a future development, the user interface of the computational method can be envisioned to be realized. As a vision, the designer can be allowed to visualize the data of the initial situation and of the design alternative selected. Likewise, the 3D model of the design solution can be visualized alongside the data, providing therefore a complete overview of the design alternative selected. An example of the envisioned user interface for the post-optimization and design exploration phase is shown in figure 119.

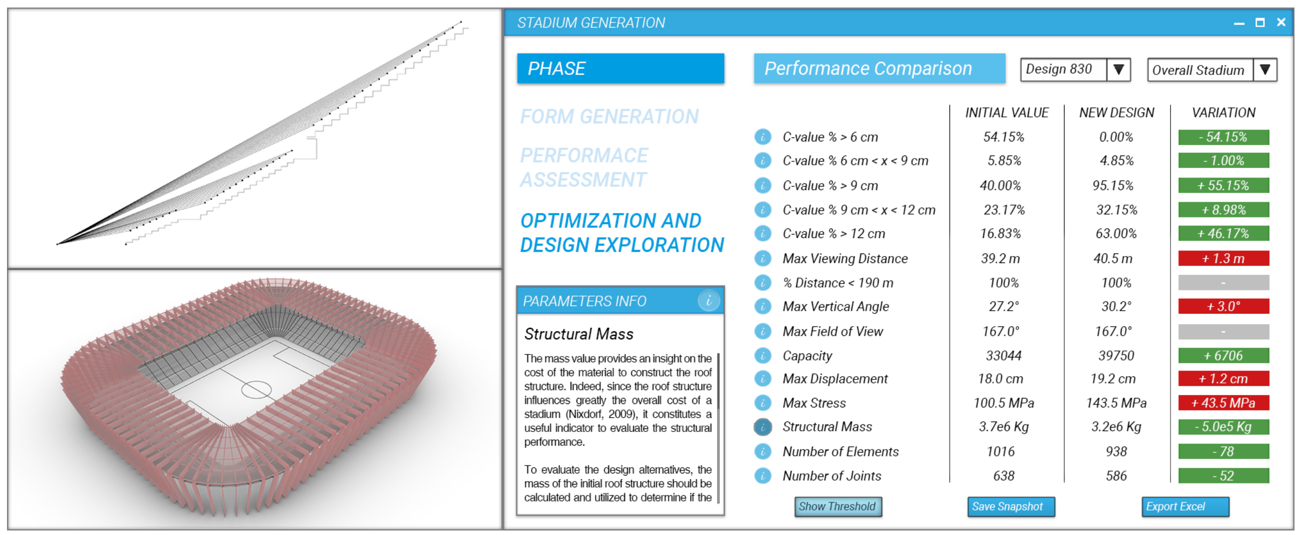


Figure 119. Example of the envisioned user-interface of the post-optimization and design exploration phase. (Source: Self-made)

09 | VALIDATION

9.1 Validation Case

As previously mentioned, the validation case can be an existing stadium, a simplified version of a case study or an arbitrary condition referenced to an existing case study based on the feasibility related to the boundaries of the computational method. In this case, the retrieval of the information related to the parameters of the stadium for the form generation rose problematics. Indeed, little literature is available on the data, since the information are confidential or not complete to generate the stadium within the computational method. Hence, a complete set of information was possible to be retrieved for few stadiums. However, since none of them was completely suitable for the developed computational method, one of the retrieved stadium was selected as a reference to set-up an arbitrary validation case.

In this case, the selected reference stadium is the Old Trafford of the city of Manchester (UK). Built between 1909 and 1910, the Old Trafford is the largest football stadium in the United Kingdom. The stadium is characterized by a rounded rectangle layout geometry and a cantilever structural system for the roof. Concerning the bowl geometry, stands are organized in a single tier for three of its sections (North-West, North and North-East stands), two tiers for four of its sections (South-East, East, South-West and West stands) and three tiers for one of its sections (South stand). Considering the first tier of stands, a parabolic stand typology is present, which is divided into two parts. Indeed, at half of the tier, the second part of the stands is slightly raised with a new riser value. Concerning the second and third tier, both stands have a parabolic rise. Lastly, considering the roof structure, three-dimensional trusses constitute the elements of the structural system. The trusses spans the entire length of the stands providing a full cover to the spectators. Moreover, the roof is inclined inwards. Considering these characteristics, the arbitrary validation case is realized by implementing the features matching with the boundaries of the computational method in order to approximate the bowl geometry of the stadium.

Firstly, the dimensions of the pitch are extrapolated and utilized as inputs in the parametric model. Secondly, a rounded rectangle layout geometry is shaped as in the Old Trafford. Thirdly, the configuration of the tiers of stands is maintained as in the reference stadium. However, considering that the stand typologies are all parabolic, a choice was taken to maintain the same inclination of the stands in the validation case. Hence, the values of the initial riser and the tread depth are implemented, while the value of the last riser of each tier is utilized as the constant riser height for the different tiers in the validation case. In addition, the starting row of each tier is set-up at the same height and the same cantilever distance of the ones in the Old Trafford. Concerning the vertical circulation, the number of gangways per section is approximated, while their dimensions are implemented as in the Old Trafford. Similarly, the dimensions of the seats and the gap between them is implemented as in the reference stadium. Considering the rows of seats, the number of rows is halved in the validation case compared to the Old Trafford. This choice was determined by taking into consideration the span of the structural elements of the roof. Indeed, trusses of approximately 10 meters high would have had to be utilized to cover the length of the stands when considering the number of rows of the Old Trafford for the validation case. Hence, this option was ruled out and half of the rows where considered for the validation case. Lastly, considering the roof structure, the position and the number of supports of the roof structure of the Old Trafford are maintained in the validation case, while trusses realized with UK CHSC circular hollow profiles are selected as structural elements for both the pillars and the cantilevers.

In conclusion, the validation case is realized by taking as a reference the Old Trafford of Manchester. Hence, the validation case will constitute the initial condition of which the computational method is applied for validation. Hence, by following the phases of the computational method, the designer can generate the geometry of the bowl and the roof structure and perform the evaluation of the performances. Then, the designer is able to individuate the portions of the stadium that are worth to be kept and develop concepts for a renovation. Therefore, multiple design alternatives can be produced through the optimization process. Subsequently, the produced designs can be explored and the trade-off of the alternatives can be realized to choose a suitable solution for further development.

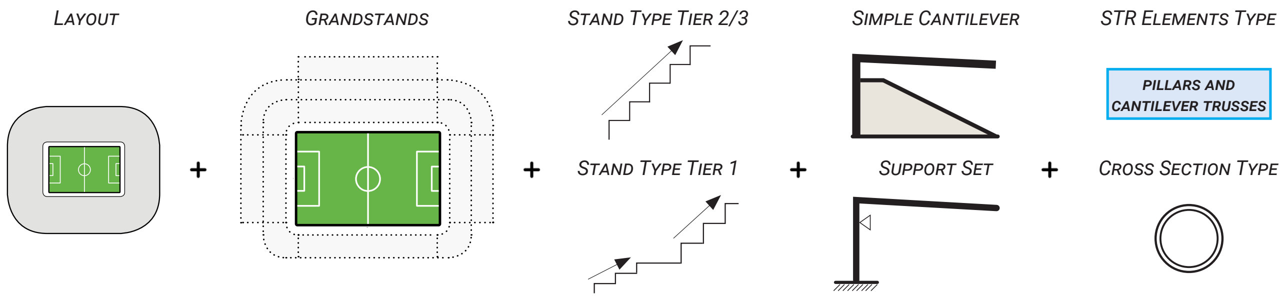


Figure 120. Overview of characteristics of the analysed Validation Case. (Source: Self-made)

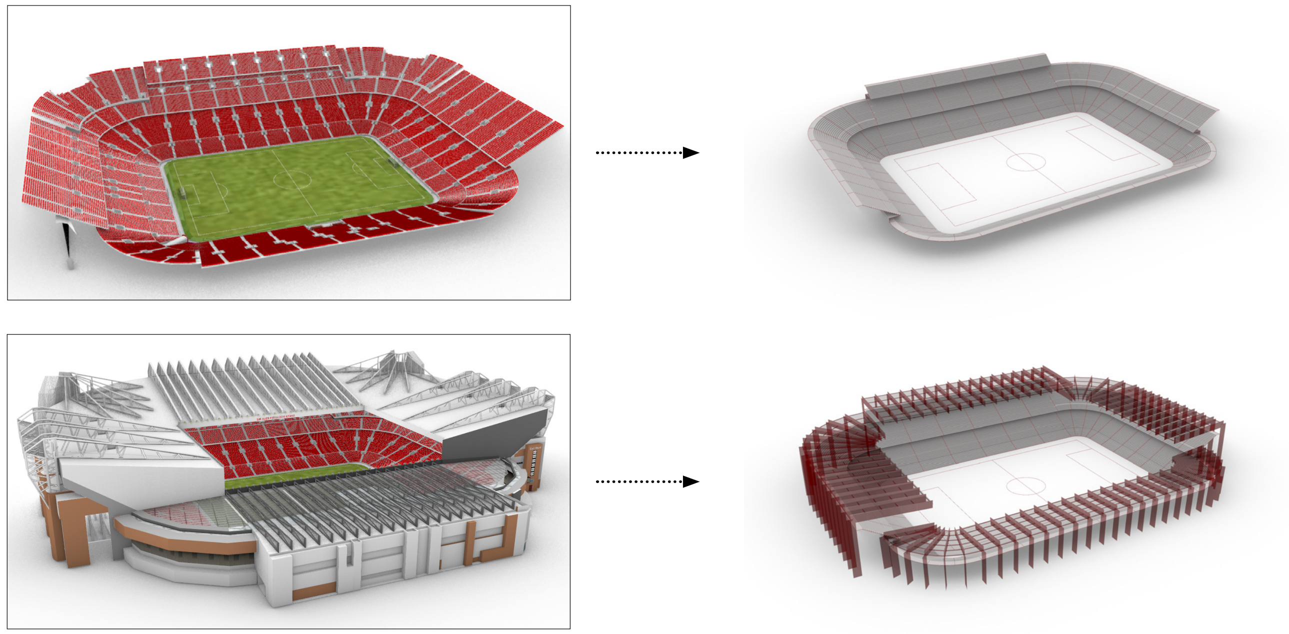


Figure 121. Comparison between the Reference stadium (Left) and the arbitrary validation case (Right). (Source: Self-made)

9.2 Form Generation

The validation case determined in reference to the Old Trafford stadium of Manchester (sub-section 9.1) is generated in Grasshopper by determining the values for the different inputs. Hence, the steps of the computational method are followed until the performance assessment phase to complete the form generation of the stadium.

Firstly, the playing area is set up by determining the dimensions of the pitch, which are of 105 m for the length and 68 m for the width. Then, the athletic track is not needed in the validation case. Thus, the input value is set to 0.

Secondly, the bowl of the stadium is constructed. Hence, 3 tiers are provided to the North section, two tiers to the North-East, the East, the West and the North-West sections, while a single tier is set for the South-East, the South and the South-West sections. Thirdly, a double linear stand stypology is applied to the first tier of stands, while a linear stand typology is set to the second and third tier of stands. In this case, the same parameters are utilized for each stand of the same tier. Subsequently, the number of gangways for each section and each tier of the stadium is inserted, as well as the width of the passages. Lastly, the dimensions of the seats and the gap between them are applied to complete the bowl geometry.

Subsequently, the roof structure is implemented. The simple cantilever system is applied and the number of supports is set. Hence, they are positioned on the ground directly below the end of the grnadstands. Hence, the structural pillars intersect perpendicularly the ground level. Then, a fixed support is applied to the ground supports at the base of the pillars and a hinge support is set in correspondance of the grandstands. Aftwerwards, the number of bracings is set to 6 and the rotation on the local y-axis is released at both ends of the beam. Subsequently, the inputs of the roof are implemented. The cantilever is set to span the entire length of the stands, while the cantilever starts 5 m above the grandstands' edges and terminates at 2.5 m above the horizontal sightline of the spectators. Hence, the roof structure is inclined inwards. Lastly, trusses are applied to the cantilever and the pillar elements. A UK CHSC cricular hollow cross section is applied to all the structural elements, while their dimensions are set based on rule of thumbs (L/10 for the trusses and L/25 for the bracings). Hence, the two trusses have a total height of 3.22 meters, with an internal height of 2.00 m. Concerning the bracings, the profile chosen is a UK CHSC 406.4 x 25.0. However, since the outputs for this profile were far below the limit values, the profile was then modified to a UK CHSC 329.9 x 16.0.

PLAYING AREA

INPUTS	PITCH
Width	68 m
Length	105 m
Track	-
Layout	1

INPUTS	LAYOUT
First Row Distance X	7.2 m
First Row Distance Y	5.5 m
Radius Corners	7.2 m

GRANDSTAND CONFIGURATION

INPUTS	NORTH	NORTH-EAST	EAST	SOUTH-EAST	SOUTH	SOUTH-WEST	WEST	NORTH-WEST
Tier 1	X	X	X	X	X	X	X	X
Tier 2	X	X	X	-	-	-	X	X
Tier 3	X	-	-	-	-	-	-	-
Stand Type Tier 1	2	2	2	2	2	2	2	2
Stand Type Tier 2	1	1	1	-	-	-	1	1
Stand Type Tier 3	1	-	-	-	-	-	-	-

FIRST PART TIER 1

INPUTS	NORTH	NORTH-EAST	EAST	SOUTH-EAST	SOUTH	SOUTH-WEST	WEST	NORTH-WEST
Initial Riser	0.20 m	0.20 m	0.20 m	0.20 m	0.20 m	0.20 m	0.20 m	0.20 m
Tread Depth	0.68 m	0.68 m	0.68 m	0.68 m	0.68 m	0.68 m	0.68 m	0.68 m
N Rows	9	9	9	9	9	9	9	9
Riser Height	0.30 m	0.30 m	0.30 m	0.30 m	0.30 m	0.30 m	0.30 m	0.30 m
Last Row Depth	0.60 m	0.60 m	0.60 m	0.60 m	0.60 m	0.60 m	0.60 m	0.60 m

SECOND PART TIER 1

INPUTS	NORTH	NORTH-EAST	EAST	SOUTH-EAST	SOUTH	SOUTH-WEST	WEST	NORTH-WEST
Initial Riser	0.50 m	0.50 m	0.50 m	0.50 m	0.50 m	0.50 m	0.50 m	0.50 m
Tread Depth	0.65 m	0.65 m	0.65 m	0.65 m	0.65 m	0.65 m	0.65 m	0.65 m
N Rows	16	16	16	16	16	16	16	16
Riser Height	0.40 m	0.40 m	0.40 m	0.40 m	0.40 m	0.40 m	0.40 m	0.40 m
Last Row Depth	2.40 m	2.40 m	2.40 m	2.40 m	2.40 m	2.40 m	2.40 m	2.40 m

TIER 2

INPUTS	NORTH	NORTH-EAST	EAST	SOUTH-EAST	SOUTH	SOUTH-WEST	WEST	NORTH-WEST
Initial Riser	0.20 m	0.20 m	0.20 m	-	-	-	0.20 m	0.20 m
Tread Depth	0.70 m	0.70 m	0.70 m	-	-	-	0.70 m	0.70 m
N Rows	20	20	20	-	-	-	20	20
Riser Height	0.43 m	0.43 m	0.43 m	-	-	-	0.43 m	0.43 m
Last Row Depth	2.40 m	2.40 m	2.40 m	-	-	-	2.40 m	2.40 m
Tier Height	1.80 m	1.80 m	1.80 m	-	-	-	1.80 m	1.80 m
Cantilever Distance	4.50 m	4.50 m	4.50 m	-	-	-	4.50 m	4.50 m

TIER 3

INPUTS	NORTH	NORTH-EAST	EAST	SOUTH-EAST	SOUTH	SOUTH-WEST	WEST	NORTH-WEST
Initial Riser	0.20 m	-	-	-	-	-	-	-
Tread Depth	0.65 m	-	-	-	-	-	-	-
N Rows	10	-	-	-	-	-	-	-
Riser Height	0.50 m	-	-	-	-	-	-	-
Last Row Depth	2.40 m	-	-	-	-	-	-	-
Tier Height	2.50 m	-	-	-	-	-	-	-
Cantilever Distance	8.00 m	-	-	-	-	-	-	

VERTICAL CIRCULATION

INPUTS	NORTH	NORTH-EAST	EAST	SOUTH-EAST	SOUTH	SOUTH-WEST	WEST	NORTH-WEST
Number Tier 1.1	9	3	6	3	9	3	6	3
Number Tier 1.2	9	5	6	5	9	5	6	5
Number Tier 2	9	5	6	-	-	-	6	5
Number Tier 3	9	-	-	-	-	-	-	-
Width	1.2 m	1.2 m	1.2 m	1.2 m	1.2 m	1.2 m	1.2 m	1.2 m

SEATINGS

INPUTS	SEATS
Width	0.45 m
Gap	0.05 m

STRUCTURAL SUPPORTS

INPUTS	NORTH	NORTH-EAST	EAST	SOUTH-EAST	SOUTH	SOUTH-WEST	WEST	NORTH-WEST
Number of Supports	16	6	10	6	16	6	10	6
Position of Supports	31 m	31 m	31 m	19.50 m	19.50 m	19.50 m	31 m	31 m

ROOF STRUCTURE OUTLINE

INPUTS	ROOF
Support Set	2
Material	S235
N Bracings	6
Start Cantilever	5.00 m
End Cantilever 2D	0.00 m
Clear Height	2.50 m

INPUTS	PILLAR	CANTILEVER	BRACINGS
Beam/Truss	Truss	Truss	Beam
Cross Section Type	UK CHSC	UK CHSC	UK CHSC
Cross Section	CHSC 610 x 30.0	CHSC 610 x 30.0	CHSC 329.9 x 16.0
Truss Height (h_1)	2.00 m	2.00 m	-

Figure 122. Inputs utilized for the form generation of the Validation Case and related values. (Source: Self-made)

9.3 Performance Assessment

Once the form generation is terminated, the performance assessment is carried out to extrapolate the results for the viewing quality and the structural performance. The overall workflow and the performance indicators were described in chapter 6 and it was followed to determine the outputs of the performance evaluation. Hence, the viewing quality is assessed and the results are listed in figure 108 and the results are visualized in figure 111.

OUTPUTS	TIER 1	TIER 2	TIER 3	OVERALL
Capacity	19326	11846	1872	33044
% C-value > 6 cm	100%	4.88%	11.11%	39.14%
% C-value > 9 cm	90.02%	4.88%	11.11%	55.03%
% C-value 6 cm < X < 9 cm	-	-	-	5.83%
% C-value 9 cm < X < 12 cm	-	-	-	24.61%
% C-value > 12 cm	-	-	-	30.42%
Max Vertical Viewing Angle	-	-	-	40.2°
Min Vertical Viewing Angle	-	-	-	10.7°
Max Field of View	-	-	-	167.0°
Min Field of View	-	-	-	63.4°
% Field of View < 120°	-	-	-	63.95%
Max Viewing Distance	-	-	-	34.00 m
Min Viewing Distance	-	-	-	5.98 m
% Spectators within Max Distance	-	-	-	100%
Inclination	31.0°/23.8°	31.6°	39.8°	-

Figure 123. Results of the viewing quality assessment of the Validation Case. (Source: Self-made)

Few aspects can be individuated. Firstly, the C-value of the second and third tier of stands results obstructed for most of the spectators, except for those seating in the first row of each tier. Hence, these stands necessitates a renovation to improve the performance. Concerning the comfort, the spectators are provided with the minimum requirements, except for the field of view. However, as expected, the spectators seating parallel to the pitch are the ones with a field of view greater than 120°. Hence, as mentioned in section 6.2, this aspect can be neglected since the activity is considered to be performed in half of the pitch at the time.

Then, the structural performance is assessed and the results are listed in figure 108 and the results are visualized in figure 111.

OUTPUTS	PILLARS	CANTILEVERS	BRACINGS	OVERALL
Max Displacement	0.8 cm	18.0 cm	1.9 cm	18 cm
Max Stress (My)	100.5 Mpa	100.5 Mpa	77.9 MPa	100.5 MPa
Max Stress (Mz)	18.0 MPa	2.82 MPa	18.6 Mpa	18.6 Mpa
Mass	-	-	-	3.7e6 Kg
Number of Elements	-	-	-	1016
Number of Joints	-	-	-	638
Roof Inclination	-	-	-	3.1°

Figure 124. Results of the structural performance assessment of the Validation Case. (Source: Self-made)

Firstly, it can be noticed that the bending moment diagram and the global displacement of the roof structure reflects the ones extrapolated from the initial analysis on the structural system realized in DIANA FEA. Moreover, as expected, the maximum displacements are located at the end points of the cantilever elements, while the maximum bending moments are located at the connection between the pillars and the cantilevers. In general, the most critical elements are the cantilever elements of the North section of the stadium, which have the higher values for both the displacement and the bending stress. Hence, the displacements and the stresses of the elements are confronted with their limit values to ensure the safety of the structure.

OUTPUTS	PILLARS	CANTILEVERS	BRACINGS
Displacement Limit	10.4 cm	20.7 cm	3.3 cm
Max Displacement	0.8 cm	18.0 cm	1.9 cm
Stress Limit	235 Mpa	235 Mpa	235 Mpa
Max Stress	100.5 Mpa	100.5 Mpa	77.9 MPa

Figure 125. Results of the structural performance assessment of the Validation Case. (Source: Self-made)

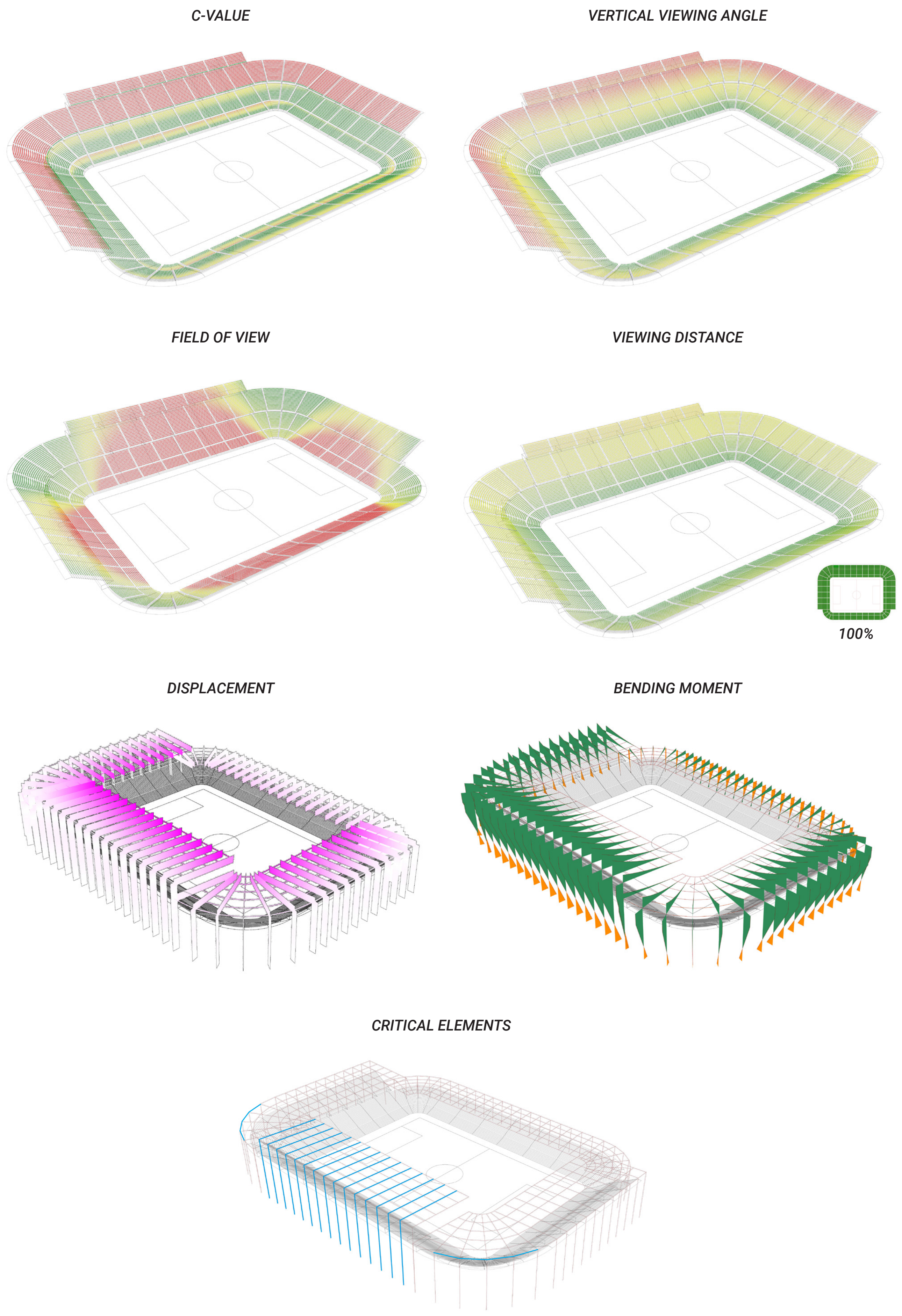


Figure 126. Visualization of the output of the performance assessment of the Validation Case. (Source: Self-made)

9.4 Optimization and Design Exploration

Once the performance assessment is terminated and the results are obtained, the optimization of the validation case is carried out. Considering the workflow described in chapter 7, before setting-up ModeFRONTIER, the portions of the stadium that needs to be renovated are individuated. Hence, the approach for the optimization is determined and the set-up of ModeFRONTIER is carried out. Lastly, the produced design alternatives are traded-off based on the hierarchical cluster and the categorization to individuate the optimal alternatives of the initial validation case.

9.4.1 Definition of Approach

In reference to section 6.4, the portions of the stadium that need renovation are individuated. Hence, the pitch and the layout are kept as in the initial condition of the validation case. Then, the first tier of stands is kept since the percentage of poor c-values (> 6 cm) is of 100%, meaning that no obstruction of the view is provided to the spectators. Moreover, the percentage of c-values higher than the recommended value of 9 cm is higher than 80%, meaning that the majority of the spectators is provided with a finer view of the action. Concerning the second and the third tier of stands, the percentage of poor c-values (> 6 cm) is of 4.88%, meaning that 95.12% of the spectators of the stadium have a view obstructed by the other spectators' heads. Then, the two tiers are considered to be modified. In relation to the maximum distance, 100% of the spectators are provided with the minimum distance to follow the activity. Considering the roof structure, the position and the number of the supports are maintained, while the structural elements, the materials and the number of bracings are considered to be modified. Indeed, the alteration of the grandstands modifies the outline of the roof structure. Therefore, the structural elements are considered to be modified to comply with the new configuration. Lastly, since the roof structure covers the entire length of the stands, the design alternatives are constrained to cover the whole stands as well.

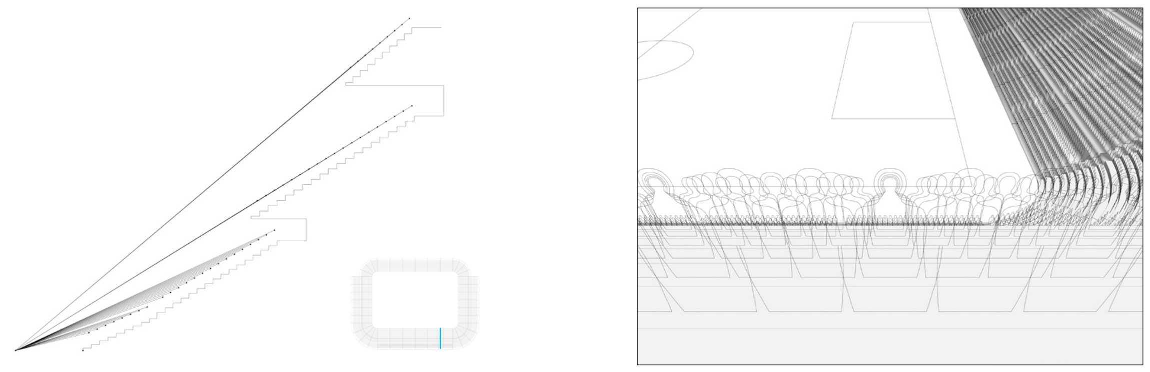


Figure 127. 2D Section of the North stand and an example of a spectator view from the 3rd tier of the Validation Case. (Source: Self-made)

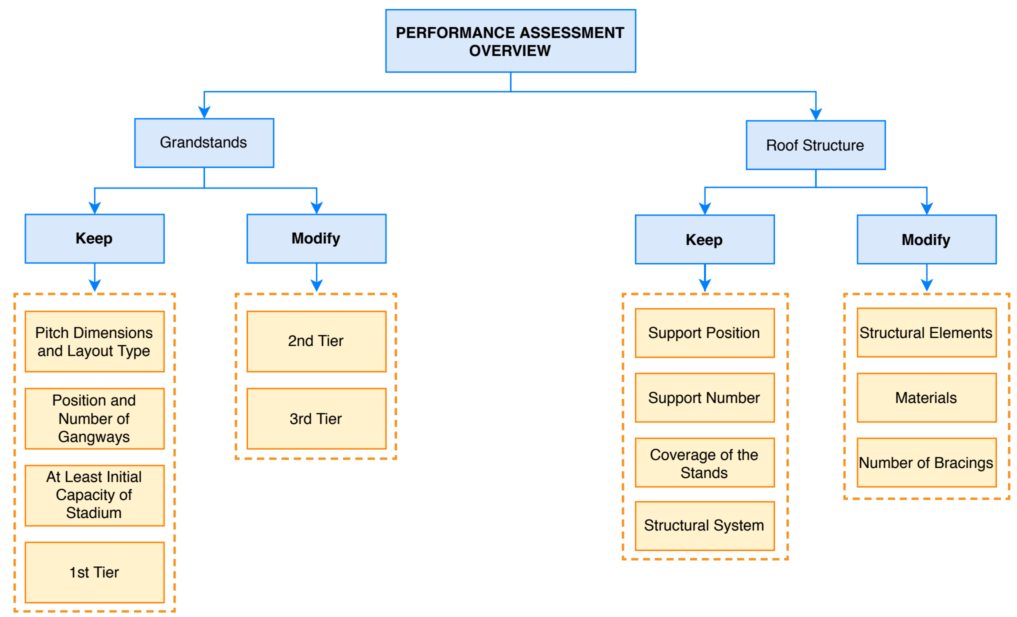


Figure 128. Overview of the components to be kept and to be modified for the optimization. (Source: Self-made)

Concerning the approaches for the optimization, two concepts are individuated to produce the design alternatives. In both cases, the structural system is kept as a constant to evaluate alternatives similar to the initial condition of the validation case. Moreover, considering the time-frame available and the computational time needed to produce the design alternatives, it was decided to focus mainly on the two individuated approaches to show the potential of the proposed computational method for both cases. In this case, the first approach was initially set-up and optimized. Hence, the outcome of this optimization led to the development of the second approach.

9.4.2 First Concept Approach

For the first approach, the concept is to renovate the validation case by optimizing the viewing quality of the second and the third tier of stands, while optimizing the roof structure accordingly. Hence, in this case the inputs of the two tiers are implemented within ModeFRONTIER, along with the parameters of the structural elements. In this case, the objectives are to improve the viewing quality of the stands and to reduce the mass of the new roof structure as much as possible. Concerning the constraints, few outputs are considered for the grandstands and the roof structure. On the one hand, the inclination of the stands is constrained to 35° to provide safety to the spectators and prevent dizziness. Then, the maximum distance allowed is limited to 45 m. Lastly, for both the second and the third tier of stands, the percentage of c-values higher than the poor value of 6 cm is set to 100%, while the percentage of c-values higher than the recommended value of 9 cm is set to 80%. Moreover, the percentage of c-values higher than the recommended value of 9 cm is set to 80% for the overall stadium in order to increase the efficiency of the design alternatives produced. It is notable that the maximum viewing angle and the percentage of the spectators within the maximum viewing distance are not included in the optimization. Indeed, considering the dimensions of the validation case, the constraints cannot be broken during the optimization. Hence, to reduce the computational time, these constraints were not included. Likewise, the initial capacity is not included as a constraint, but it is managed through the inputs of the optimization. Indeed, the cantilever distance and the tread depth, which affects this output, are limited in the range of values by setting the minimum value to the ones of the initial situation. Hence, the initial capacity is ensured to be maintained.

Considering the roof structure, the stress and the displacement are set to be higher than 0 Mpa and 0 cm respectively to ensure the structural safety (see section 6.2). Moreover, the roof inclination is constrained to 1.5° to ensure enough pendency to drain the rain. Lastly, two constraints are set to the height of the trusses of the pillars and the cantilevers. This solution is implemented as an aesthetic aspect to obtain design alternatives with smaller structural elements.

An overview of the configuration of the stadium (figure 114), as well as an overview of the inputs, the constraints and the objectives of the optimization is provided (figure 115, figure 116, figure 117).

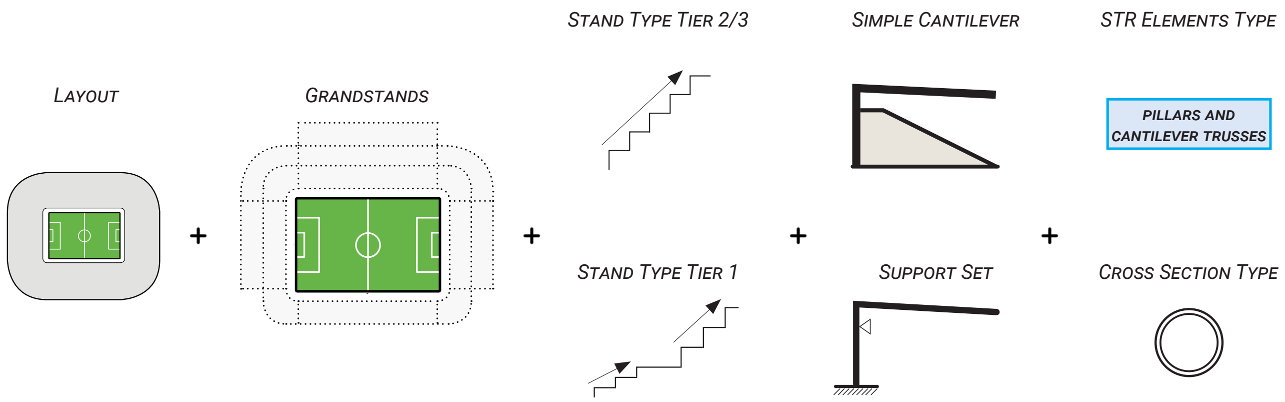


Figure 129. Overview of characteristics of the first concept approach of the optimization. (Source: Self-made)

OUTPUT	DESCRIPTION	CONSTRAINT
% > Recommended C-Value	Percentage of C-values > 9 cm of the Overall Stadium	HIGHER THAN 80%
% > Poor C-value Tier2	Percentage of C-values > 6 cm of the 2nd Tier	EQUAL TO 100%
% > Poor C-value Tier3	Percentage of C-values > 6 cm of the 3rd Tier	EQUAL TO 100%
% > Recommended C-Value Tier 2	Percentage of C-values > 9 cm of the 2nd Tier	HIGHER THAN 80%
% > Recommended C-Value Tier 3	Percentage of C-values > 9 cm of the 3rd Tier	HIGHER THAN 80%
Maximum Distance	Maximum distance of the spectators to the pitch of the overall stadium	LOWER THAN 45 m
Inclination Tier 2	Inclination of the stands of the 2nd Tier	LOWER THAN 35°
Inclination Tier 3	Inclination of the stands of the 3rd Tier	LOWER THAN 35°
STR_Stress	Maximum Allowed Stress Value of the Overall Roof Structure	HIGHER THAN 0 Mpa
STR_Deflection	Maximum Allowed Displacement Value of the Overall Roof Structure	HIGHER THAN 0 cm
Cantilever_Truss_Height	Height of the Truss of the Cantilevers	LOWER THAN 450 cm
Pillar_Truss_Height	Height of the Truss of the Pillars	LOWER THAN 450 cm
STR_Roof_Inclination	Minimum Inclination of the Roof Structure	HIGHER THAN 1.5°

Figure 130. Overview of the constraints of the first approach for the optimization in ModeFRONTIER. (Source: Self-made)

INPUT	LOWER BOUND	UPPER BOUND	STEP
Initial Riser T2	0.20	1.20	0.10
Riser Height T2	0.20	0.60	0.01
Tread Depth T2	0.60	1.00	0.01
Last Row Depth T2	0.60	2.40	0.10
Cantilever Distance T2	0.00	4.50	0.10
Tier Height T2	1.80	2.50	0.10
Initial Riser T3	0.20	1.20	0.10
Riser Height T3	0.20	0.60	0.01
Tread Depth T3	0.60	1.00	0.01
Last Row Depth T3	0.60	2.40	0.10
Cantilever Distance T3	0.00	4.50	0.50
Tier Height T3	1.80	2.50	0.10
STR_Start Cantilever	2.50	10.00	0.10
STR_Clear Height Above Spectators	0.00	7.50	0.10
STR_Bracing	4.00	10.00	1.00
STR_Bracing O Cross Section	14.00	36.00	1.00
STR_Cantilever O Cross Section	17.00	36.00	1.00
STR_Pillar O Cross Section	17.00	36.00	1.00
STR_Cantilever Truss Height	50.00	300.00	1.00
STR_Pillar Truss Height	50.00	300.00	1.00

Figure 131. Overview of the inputs of the first approach for the optimization in ModeFRONTIER. (Source: Self-made)

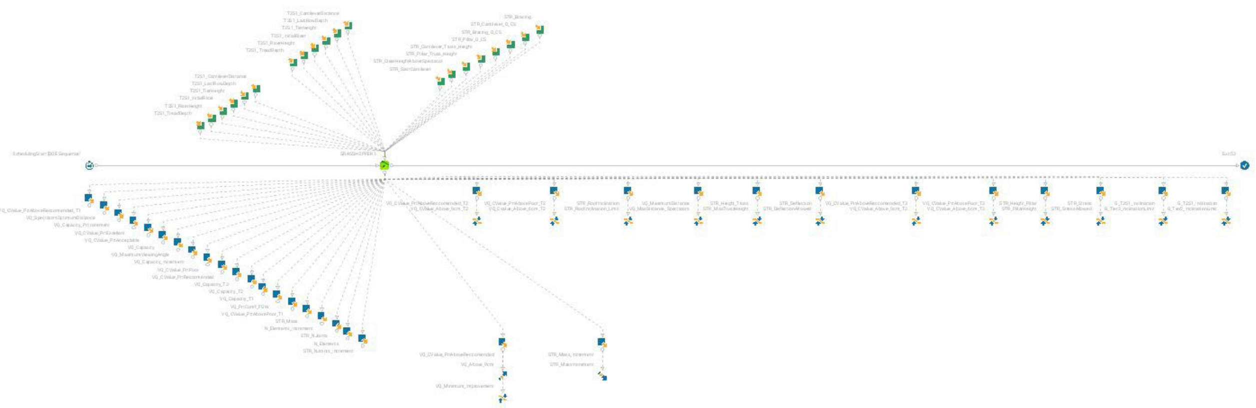
OUTPUT	DESCRIPTION	OBJECTIVE
% > Recommended C-Value	Percentage of C-values > 9 cm of the Overall Stadium	MAXIMIZE
STR_Mass_Increment	Difference Between the NEW and the INITIAL Mass of the Roof Structure	MINIMIZE

Figure 132. Overview of the objectives of the first approach for the optimization in ModeFRONTIER. (Source: Self-made)

A. Set-up

Once the approach is defined, the set-up of ModeFRONTIER can be initialized. Hence, Grasshopper file is uploaded in the Grasshopper-Node and the camera is set. Then, the introspection is run to import the inputs and the outputs of the optimization. Thus, the inputs, their boundaries and the steps between the values are inserted as in figure 117. Then, the constraints are applied to the respective output and the limit values are set for each one of them as shown in figure 116. Lastly, the objectives are connected to the correspondent output and their objective function is defined as in figure 118. It is notable that the number of elements and the number of joints are not set to be minimized since the minimization of the mass already drives the optimization algorithm towards the reduction of these aspects. Moreover, since the only bracings are allowed to be modified in number, the objectives would have been redundant and they would have simply increased the computational time needed for the optimization.

Afterwards, NSGA-II genetic algorithm is selected to solve the optimization problem. Indeed, this algorithm allows to explore the design space to find feasible solutions and performs better in presence of multiple design constraints that have to be matched. Hence, in the "scheduling start-node", the algorithm is self-initialized to produce 200 design alternatives for the first optimization run. In total, the optimization with 20 inputs, 13 constraints and 2 objectives required 6.5 hours to obtain the first batch of design alternatives.



APPROACH	INPUTS	CONSTRAINTS	OBJECTIVES
Concept Approach 1	20	13	2

OPTIMIZATION RUN	NUMBER OF DESIGNS	TIME FOR 1 DESIGN	TOTAL TIME
Run 1	200	120 s	6,5 h

Figure 133. Overview of the set-up of the first approach for the optimization in ModeFRONTIER. (Source: Self-made)

B. Results First Round Optimization

Once the first round of optimization is terminated, the design alternatives produced are analysed to reduce the range of values and to set-up the DOE of the subsequent round of optimization. In this case, the first round of optimization produced a total of 167 design alternatives, of which 100% are unfeasible. Hence, the broken constraints for the design alternatives are checked to individuate the aspects of major influence.

OPTIMIZATION RUN	DESIGN PRODUCED	FEASIBLE	UNFEASIBLE
Run 1	167	0	167

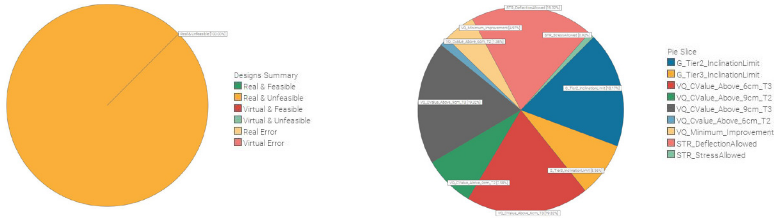


Figure 134. Overview of the results of the first run of optimization of the first concept approach in ModeFRONTIER. (Source: Self-made)

From the pie-chart, the most broken constraints results to be related to the C-values percentage of both poor and recommended values of the second and third tier. Moreover, also the inclination both tiers necessitate an evaluation. Hence, the sensitivity tool is utilized to evaluate the relation between the inputs and the mentioned outputs. Thus, the effect charts of the sensitivity tool are produced and the inputs are visualized to obtain the information. From the results, it is highlighted the influence that the tread depth and riser height of the have on the performances of the respective tiers.

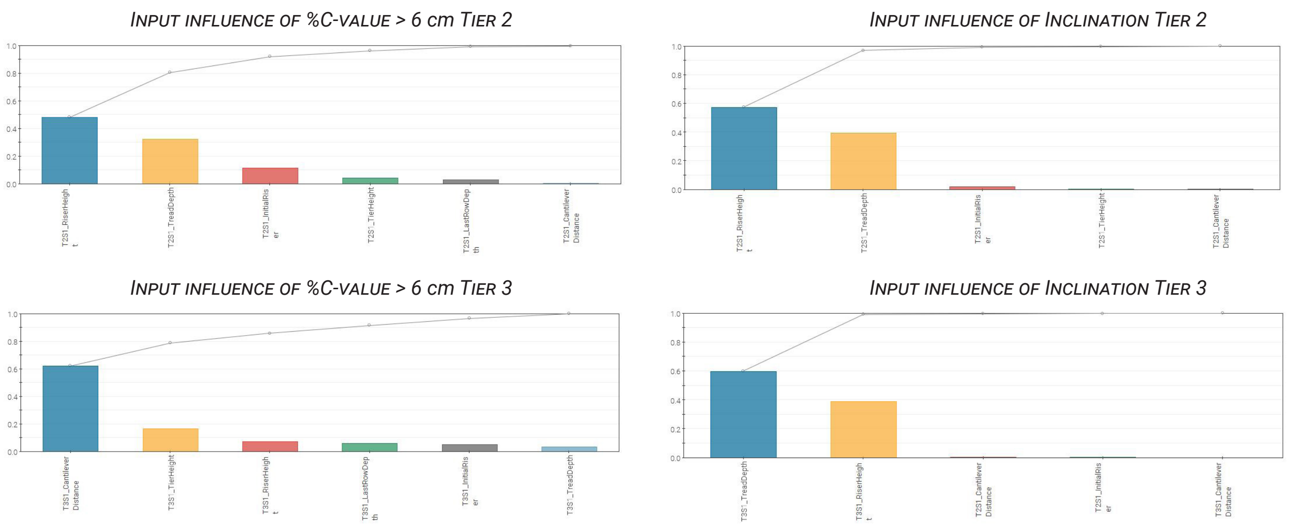


Figure 135. Sensitivity analysis to individuate the most influencing inputs for the 2nd and 3rd tier. (Source: Self-made)

Hence, a bubble diagram 4D is produced to evaluate the tread depth and the riser height of the two tiers with the respective objectives. The bubble diagram is set-up by plotting the tread depth on the x-axis, the riser height on the y-axis. In addition, the percentage of C-values higher than the recommended value (> 9 cm) is set as a color gradient, while the inclination of the tier is set as the diameter of the bubbles.

Concerning the second tier, it is noticed that the design alternatives that performs better in relation to the two outputs have a tread depth value lower than 0.75 cm and a riser height higher than 0.40 cm. However, the inclination of the tier mostly exceeds the limit value. Hence, it is decided to set 0.75 cm as a lower bound for the tread depth to obtain an increment in the percentage of C-values higher than the recommended value (> 9 cm) and to limit the possibility of breaking the inclination constraint.

Concerning the third tier, the results of the analysis show that there is no improvement in the percentage of C-values higher than the recommended value (> 9 cm), even though the inclination of the tier reaches the limit value. This output can be related to the limited amount of design alternatives produced. Moreover, similarly to the second tier, the inclination is mostly ensured with a tread depth value around 0.80 cm and a riser height higher than 0.40 cm.

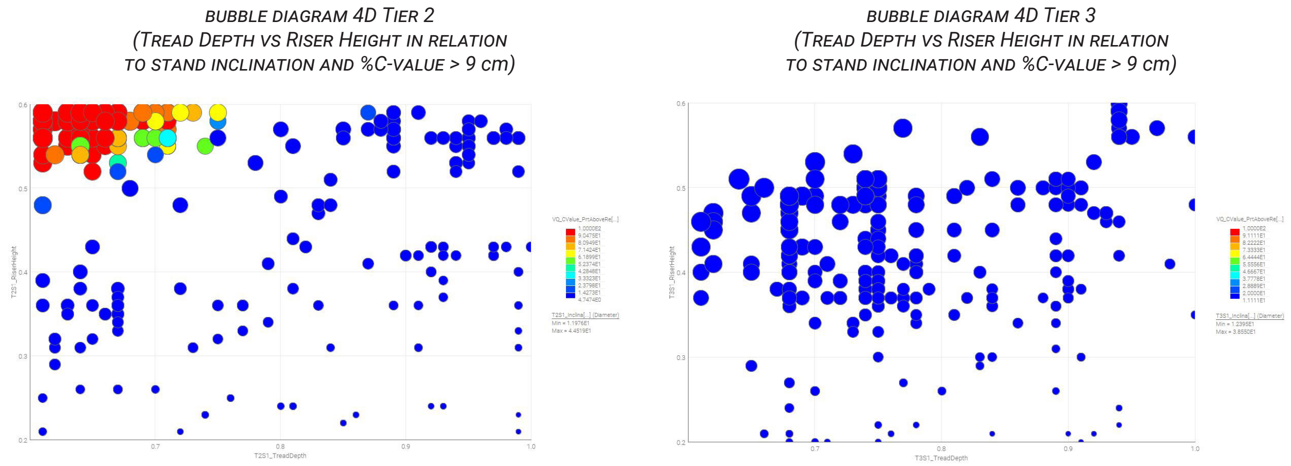


Figure 136. Bubble diagram 4D in relation to the 2nd and the 3rd tier. (Source: Self-made)

Hence, it is decided to reduce the range of values of the tread depth of the second tier between 0.75 cm and to 1.00 cm. Likewise, the range of values of the tread depth of the second tier between 0.80 cm and to 1.00 cm. In addition, the range of values of the riser height of the second and third tier is reduced between 0.40 cm to 0.60 cm. This decision is related to ensure the respect of the limit values of the inclination of the tiers, while driving the algorithm to search for the design alternatives that improves the percentage of C-values higher than the recommended value (> 9 cm).

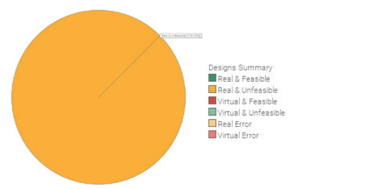
INPUT	LOWER BOUND	UPPER BOUND	STEP
Initial Riser T2	0.20	1.20	0.10
Riser Height T2	0.40	0.60	0.01
Tread Depth T2	0.75	1.00	0.01
Last Row Depth T2	0.60	2.40	0.60
Cantilever Distance T2	0.00	4.00	0.50
Tier Height T2	1.80	2.50	0.10
Initial Riser T3	0.20	1.20	0.10
Riser Height T3	0.40	0.60	0.01
Tread Depth T3	0.80	1.00	0.01
Last Row Depth T3	0.60	2.40	0.60
Cantilever Distance T3	0.00	2.00	0.50
Tier Height T3	1.80	2.50	0.10
STR_Start Cantilever	2.50	10.00	0.50
STR_Clear Height Above Spectators	0.00	7.50	0.50
STR_Bracing	4.00	10.00	1.00
STR_Bracing O Cross Section	14.00	36.00	1.00
STR_Cantilever O Cross Section	17.00	36.00	1.00
STR_Pillar O Cross Section	17.00	36.00	1.00
STR_Cantilever Truss Height	50.00	300.00	5.00
STR_Pillar Truss Height	50.00	300.00	5.00

Figure 137. Overview of the inputs with the refined range of values of the first approach in ModeFRONTIER.. (Source: Self-made)

From results of the first run, it seems that the first concept approach is inefficient. Indeed, the viewing quality of the third tier does not seem to improve, even though the inclination of the third tier is at its limit. Indeed, an inclination closer to the limit values improves the c-values. However, this outcome can be related to the smaller batch of design alternatives produced. Hence, it is decided to repeat the optimization for a total of four run to obtain a larger group of design alternatives.

C. Total Results of the Optimization

In total, 1209 design alternatives were produced. However, all the produced designs result to be inefficient. As cn be seen from the broken constraint pie chart (figure 125), the constraints of the percentage of C-values higher than the recommended value (> 9 cm) and the percentage of C-values higher than the poor value (> 6 cm) of the third tier are broken for 100% of the design alternatives.



OPTIMIZATION RUN	DESIGN PRODUCED	FEASIBLE	UNFEASIBLE
Run 1	167	0	167
Run 2	334	0	334
Run 3	358	0	358
Run 4	350	0	350
OVERALL	1209	0	1209

Figure 138. Overview of the resultsof the optimization of the first concept approach. (Source: Self-made)

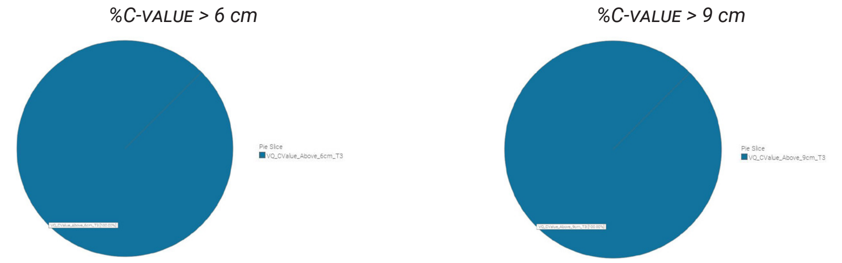


Figure 139. Broken constraints for 100% of the produced design alternatives (Source: Self-made)

Hence, the first concept approach results to be inefficient. As a confirmation, a bubble diagram 4D is produced to evaluate the tread depth and the riser height of the two tiers with the respective objectives. Even though the otpimization improved the performance of the second tier of stands, the third tier does not show any improvement, despite the inclination reaches the limit value of 35° and the values of the riser height and the tread depth are closer to the upper bound.

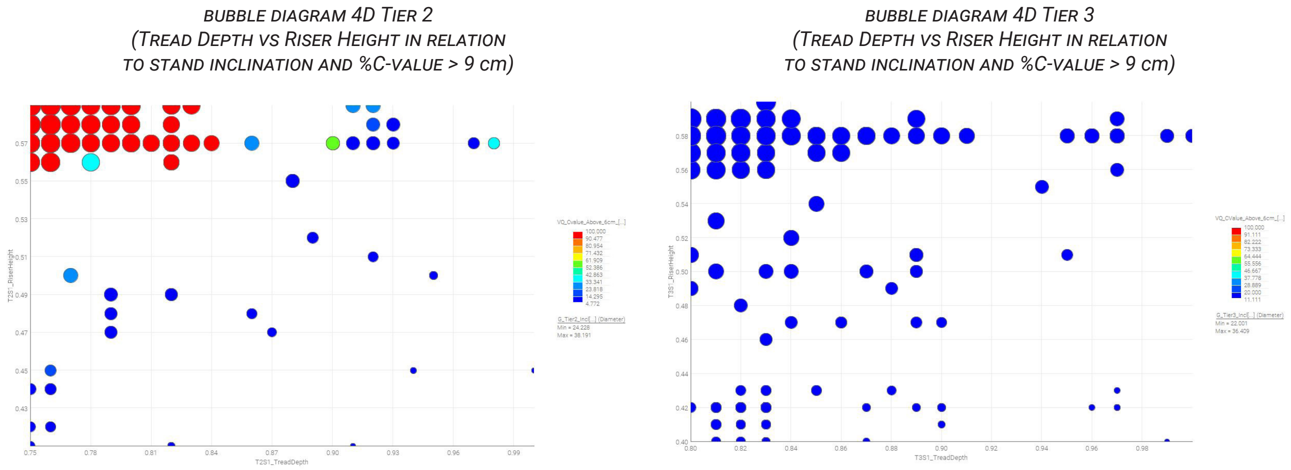


Figure 140. Bubble diagram 4D in relation to the 2nd and the 3rd tier (Source: Self-made)

Therefore, the first concept approach results to be inefficient. Hence, the optimization is interrupted and a second concept approach is developed. Even though the first approach results inefficient, it provides useful information that can be utilized to develop a second concept approach. Indeed, the second tier shows potential for improvement of the viewing quality.

9.4.3 Second Concept Approach

For the second approach, the concept is to renovate the validation case by completing the second tier of stands and eliminating the third tier of stands to even the roof structure and the overall stadium. In the meantime, the viewing quality of the second tier of stands is optimized, as well as the roof structure, which is optimized accordingly to the new configuration of the stadium. Hence, only the inputs of the second tier are implemented within ModeFRONTIER, along with the parameters of the structural elements. Moreover, considering the outcome of the optimization of the first design approach, the expansion of the stadium by completing the second tier supply to the loss of seats of the inefficient third tier. Thus, in this case the objectives are to maximize the C-value percentage higher than 9 cm of the overall stadium, to minimize the mass of the new roof structure and to maximize the capacity. Concerning the constraints, few outputs are considered for the grandstands and the roof structure. On the one hand, the inclination of the stands is constrained to 35° to provide safety to the spectators and prevent dizziness. Then, the maximum distance allowed is limited to 45 m. Lastly, for the second tier of stands, the percentage of c-values higher than the poor value of 6 cm is set to 100%, while the percentage of c-values higher than the recommended value of 9 cm is set to 80%. Moreover, the percentage of c-values higher than the recommended value of 9 cm is set to 80% for the overall stadium in order to increase the efficiency of the design alternatives produced. It is notable that the maximum viewing angle and the percentage of the spectators within the maximum viewing distance are not included in the optimization. Indeed, considering the dimensions of the validation case, the constraints cannot be broken during the optimization. Hence, to reduce the computational time, these constraints were not included. Likewise, the initial capacity is not included as a constraint, but it is managed through the inputs of the optimization. Indeed, the cantilever distance and the tread depth, which affects this output, are limited in the range of values by setting the minimum value to the ones of the initial situation. Hence, the initial capacity is ensured to be maintained.

Considering the roof structure, the position of the supports is harmonized to obtain a homogeneous structure for the overall stadium. Hence, the stress and the displacement are set to be higher than 0 Mpa and 0 cm respectively to ensure the structural safety (see section 6.2). Moreover, the roof inclination is constrained to 1.5° to ensure enough pendency to drain the rain. Lastly, two constraints are set to the height of the trusses of the pillars and the cantilevers. This solution is implemented as an aesthetic aspect to obtain design alternatives with smaller structural elements.

An overview of the configuration of the stadium (figure 127), as well as an overview of the inputs, the constraints and the objectives of the optimization is provided (figure 128, figure 129, figure 130).

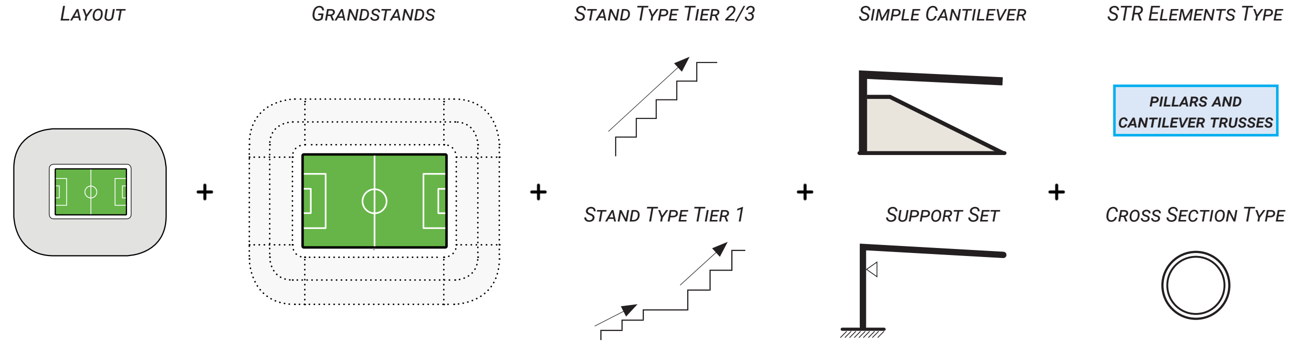


Figure 141. Overview of characteristics of the second concept approach of the optimization. (Source: Self-made)

INPUT	LOWER BOUND	UPPER BOUND	STEP
Initial Riser T2	0.20	1.20	0.10
Riser Height T2	0.40	0.60	0.01
Tread Depth T2	0.75	1.00	0.01
Last Row Depth T2	0.60	2.40	0.60
Cantilever Distance T2	0.00	4.00	0.50
Tier Height T2	1.80	2.50	0.10
STR_Start Cantilever	2.50	10.00	0.50
STR_Clear Height Above Spectators	0.00	7.50	0.50
STR_Bracing	4.00	10.00	1.00
STR_Bracing O Cross Section	14.00	36.00	1.00
STR_Cantilever O Cross Section	17.00	36.00	1.00
STR_Pillar O Cross Section	17.00	36.00	1.00
STR_Cantilever Truss Height	50.00	300.00	5.00
STR_Pillar Truss Height	50.00	300.00	5.00

Figure 142. Overview of the inputs of the second approach for the optimization in ModeFRONTIER. (Source: Self-made)

OUTPUT	DESCRIPTION	CONSTRAINT
% > Recommended C-Value	Percentage of C-values > 9 cm of the Overall Stadium	HIGHER THAN 80%
% > Poor C-value Tier2	Percentage of C-values > 6 cm of the 2nd Tier	EQUAL TO 100%
% > Recommended C-value Tier2	Percentage of C-values > 9 cm of the 2nd Tier	HIGHER THAN 80%
Maximum Distance	Maximum distance of the spectators to the pitch of the overall stadium	LOWER THAN 45 m
Inclination Tier 2	Inclination of the stands of the 2nd Tier	LOWER THAN 35°
STR_Stress	Maximum Allowed Stress Value of the Overall Roof Structure	HIGHER THAN 0 Mpa
STR_Deflection	Maximum Allowed Displacement Value of the Overall Roof Structure	HIGHER THAN 0 cm
Cantilever_Truss_Height	Height of the Truss of the Cantilevers	LOWER THAN 450 cm
Pillar_Truss_Height	Height of the Truss of the Pillars	LOWER THAN 450 cm
STR_Roof_Inclination	Minimum Inclination of the Roof Structure	HIGHER THAN 1.5°

Figure 143. Overview of the constraints of the second approach for the optimization in ModeFRONTIER. (Source: Self-made)

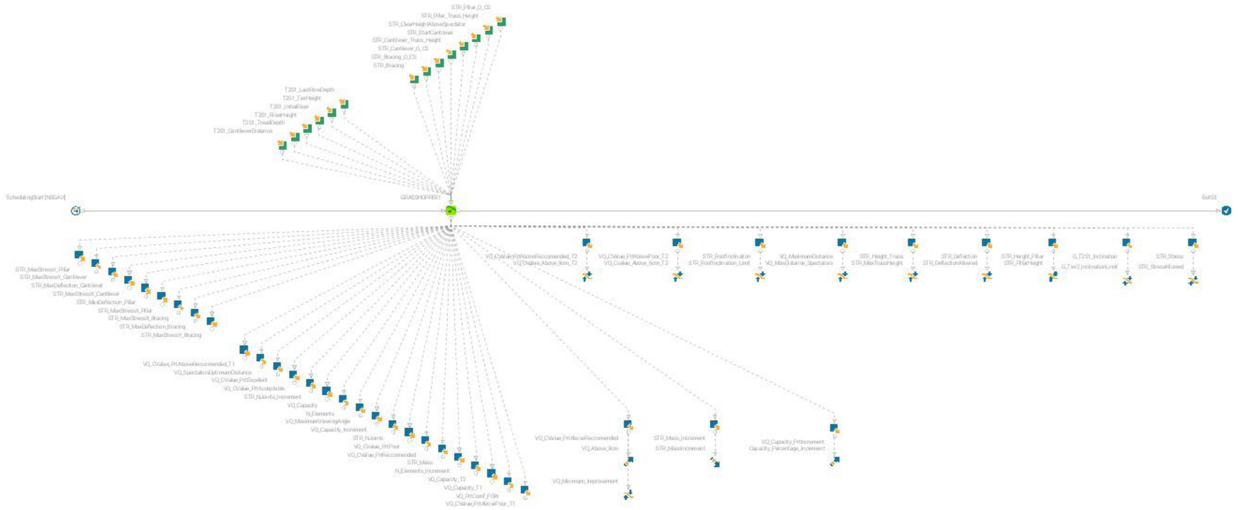
OUTPUT	DESCRIPTION	OBJECTIVE
% > Recommended C-Value	Percentage of C-values > 9 cm of the Overall Stadium	MAXIMIZE
STR_Mass_Increment	Difference Between the NEW and the INITIAL Mass of the Roof Structure	MINIMIZE
% Capacity Increment	Percentage of increment/decrement of Stadium Capacity	MAXIMIZE

Figure 144. Overview of the objectives of the second approach for the optimization in ModeFRONTIER. (Source: Self-made)

A. Set-up

Once the approach is defined, the set-up of ModeFRONTIER can be initialized. Hence, Grasshopper file is uploaded in the Grasshopper-Node and the camera is set. Then, the introspection is run to import the inputs and the outputs of the optimization. Thus, the inputs, their boundaries and the steps between the values are inserted as in figure 128. It is notable that, based on the information retrieved from the optimization of the first concept approach, the range of values is set accordingly. Indeed, the second tier showed potential for a full improvement of the viewing quality performance. Then, the constraints are applied to the respective output and the limit values are set for each one of them as shown in figure 129. Lastly, the objectives are connected to the correspondent output and their objective function is defined as in figure 130. It is notable that the number of elements and the number of joints are not set to be minimized since the minimization of the mass already drives the optimization algorithm towards the reduction of these aspects. Moreover, since the only bracings are allowed to be modified in number, the objectives would have been redundant and they would have simply increased the computational time needed for the optimization.

Afterwards, NSGA-II genetic algorithm is selected to solve the optimization problem. Indeed, this algorithm allows to explore the design space to find feasible solutions and performs better in presence of multiple design constraints that have to be matched. Hence, in the "scheduling start-node", the algorithm is self-initialized to produce 200 design alternatives for the first optimization run. In total, the optimization with 14 inputs, 10 constraints and 3 objectives required 5.5 hours to obtain the first batch of design alternatives.



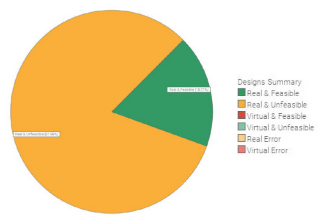
APPROACH	INPUTS	CONSTRAINTS	OBJECTIVES
Concept Approach 2	14	10	3

OPTIMIZATION RUN	NUMBER OF DESIGNS	TIME FOR 1 DESIGN	TOTAL TIME
Run 1	200	100 s	5,5 h

Figure 145. Overview of the set-up of the second concept approach for the optimization in ModeFRONTIER. (Source: Self-made)

B. Results First Round Optimization

Once the first round of optimization is terminated, the design alternatives produced are analysed to reduce the range of values and to set-up the DOE of the subsequent round of optimization. In this case, the first round of optimization produced a total of 161 design alternatives, of which 18% are feasible and 82% are unfeasible.



OPTIMIZATION RUN	DESIGN PRODUCED	FEASIBLE	UNFEASIBLE
Run 1	161	29	132

Figure 146. Overview of the results of the first run of optimization of the second concept approach in ModeFRONTIER. (Source: Self-made)

In this case, feasible design has been obtained in the first run of optimization. A parallel coordinates chart is produced to evaluate the inputs in relation to the objectives functions of the optimization. The percentage of C-values higher than 9 cm is set to 80% as a minimum value in the chart to highlight the solutions that respect this constraint. Since the values are spread along the range for all the inputs, no refinement is decided for the subsequent range of optimization. However, in order to drive the optimization towards the area of the design space where the feasible solutions are located, a DOE with the 29 feasible design produced in the first run is created to train the algorithm.

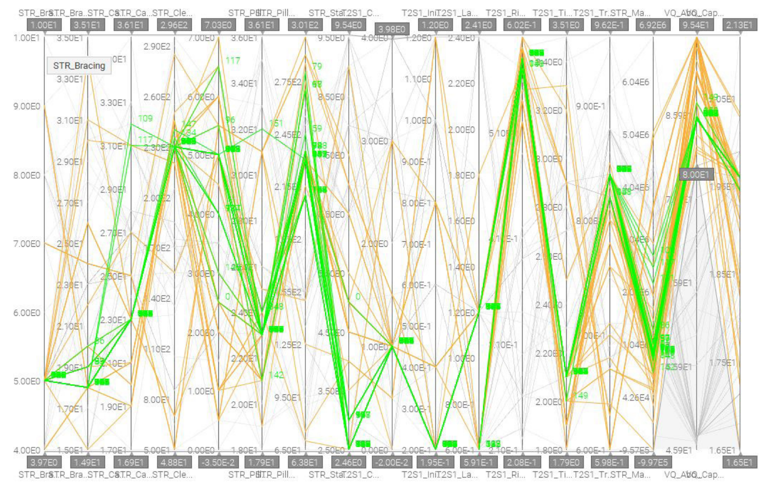
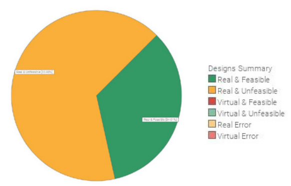


Figure 147. Parallel chart of the first run of optimization of the second concept approach in ModeFRONTIER. (Source: Self-made)

C. Total Results of the Optimization

In total, 2143 design alternatives have been produced. In total, 728 of the design alternatives produced are feasible, corresponding to the 34% of the overall designs. The individual overview of the results is shown in figure 133.



OPTIMIZATION RUN	DESIGN PRODUCED	FEASIBLE	UNFEASIBLE
Run 1	161	29	132
Run 2	440	141	299
Run 3	374	146	228
Run 4	349	135	214
Run 5	411	140	271
Run 6	408	137	271
OVERALL	2143	728	1415

Figure 148. Overview of the results of the optimization of the second concept approach. (Source: Self-made)

Hence, the design alternatives have to be traded-off to individuate the optimal solutions to solve the objective functions from all the feasible solutions. Hence, the unfeasible designs are discarded. Afterwards, a hierarchical clustering is performed to group the designs based on their proximity in the design space. In this case, a centroid-linkage algorithm is utilized to enhance the subdivision of the designs in a more robust manner. Then, from the produced dendogram, the design alternatives are divided into 6 clusters to spread the solutions among the groups.

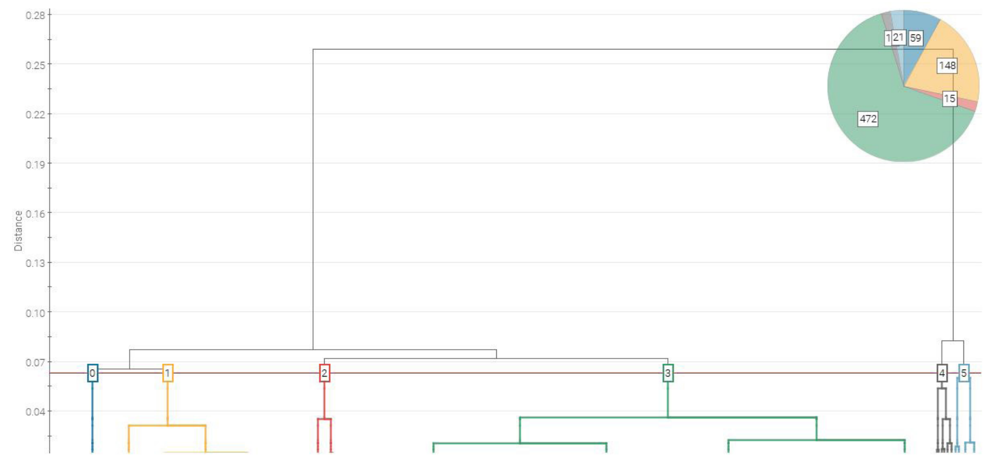


Figure 149. Dendogram of the hierarchical cluster of the second concept approach. (Source: Self-made)

Hence, a hierarchical table is produced and utilized to plot a bubble diagram 4D to evaluate the group of designs in relation to the objectives of the optimization. Hence, the mass increment is plotted on the x-axis, the percentage of c-value higher than 9 cm of the overall stadium is plotted on the y-axis. In addition, the capacity increment is utilized as color gradient and the percentage of c-value higher than 9 cm of the second tier determined the diameter of the bubbles.

		ID	Hierarchical Cluster
> 1	☑	0	CLUSTER_0
> 2	☐	1	CLUSTER_1
> 3	☐	2	CLUSTER_2
> 4	☐	3	CLUSTER_3
> 5	☐	4	CLUSTER_4
> 6	☐	5	CLUSTER_5

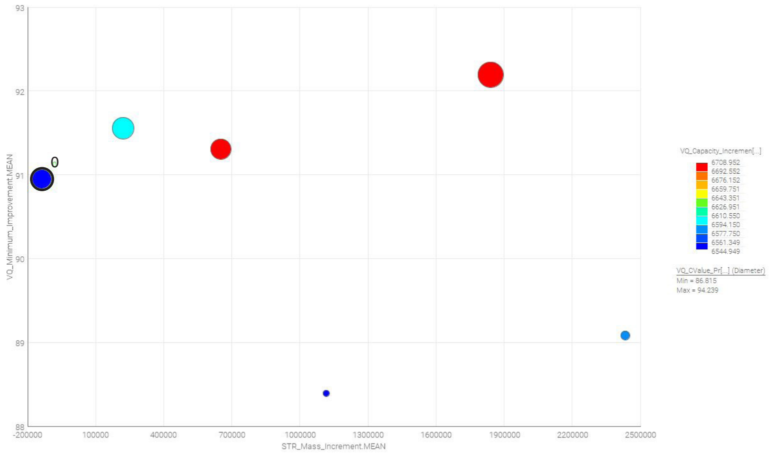


Figure 150. Hierarchical table and Bubble diagram 4D of the clusters. (Source: Self-made)

The hierarchical cluster facilitates the trade-off of the alternatives by reducing the amount of solutions to deal with during the evaluation. Indeed, the cluster represents an area of the design space that can be evaluated in relation to the different objectives. In this case, cluster 0 is selected since it is the group of solutions that reduces the mass of the structure more compared to the other groups. Indeed, the reduction of the mass is considered in this case a priority. In a second instance, the percentage of c-values higher than 9 cm is assumed as the second most important objective. Indeed, even though the approach followed should consider the increment of the capacity as a priority, the difference between the maximum and the minimum value is negligible.

Hence, from the initial 728 feasible solutions, a smaller group of 59 design alternatives is obtained. Therefore, the design alternatives are categorized based on their output based on their response to the objectives. Based on the categorization of the objectives, 10 design alternatives are selected from the initial 59 present in the hierarchical cluster.

MASS CATEGORIES	RANGE	COLOR CODE
Reduced	< 0 Kg	
E4 < E5	1e4 Kg < x < 1e5 Kg	
E5 < E6	1e5 Kg < x < 1e6 Kg	
> E6	x > 1e6 Kg	

C-Value CATEGORIES	RANGE	COLOR CODE
80 < 85	80% < 85%	
85 < 90	85% < 90%	
90 < 95	90% < 95%	
> 95	x > 95 %	

% Capacity CATEGORIES	RANGE	COLOR CODE
< 20%	< 20%	
> 20 %	> 20 %	

Capacity CATEGORIES	RANGE	COLOR CODE
< 6500	< 6500	
> 6500	> 6500	

Figure 151. Categories for the objectives utilized for the validation case in ModeFRONTIER. (Source: Self-made)

	↑	ID	Algorithm	Phase	Mass	% Capacity	%C-Value Higher 9 cm Overall	Inclination Roof	Round of Optimization	Capacity Increment	Height Above Spectators
1	☑	830	NSGA2		Reduced	>20	>95	Outwards	OPT_5	Higher_Than_6500	2_to_4
2	☑	848	NSGA2		Reduced	>20	>95	Outwards	OPT_5	Higher_Than_6500	4_to_6
3	☑	885	NSGA2		Reduced	>20	>95	Outwards	OPT_5	Higher_Than_6500	2_to_4
4	☑	983	NSGA2		Reduced	>20	>95	Outwards	OPT_6	Higher_Than_6500	2_to_4
5	☑	1025	NSGA2		Reduced	>20	>95	Outwards	OPT_6	Higher_Than_6500	2_to_4
6	☑	1043	NSGA2		Reduced	>20	>95	Outwards	OPT_6	Higher_Than_6500	2_to_4
7	☑	1048	NSGA2		Reduced	>20	>95	Outwards	OPT_6	Higher_Than_6500	4_to_6
8	☑	1055	NSGA2		Reduced	>20	>95	Outwards	OPT_6	Higher_Than_6500	2_to_4
9	☑	1057	NSGA2		Reduced	>20	>95	Outwards	OPT_6	Higher_Than_6500	2_to_4
10	☑	1079	NSGA2		Reduced	>20	>95	Inwards	OPT_6	Higher_Than_6500	0_to_2

Figure 152. Table of the design alternatives obtained from the categorization of the objectives. (Source: Self-made)

Moreover, the height of the roof above the spectators and the inclination of the roof are inserted as categories to provide an aesthetic criteria for the trade-off of the alternatives. In this case, the outwards inclination of the roof is preferred since the rain can be drained outside the stadium. Furthermore, the height of the roof above the spectators is preferred to be maintained between 2-4 meters to provide a more open view of the overall stadium to the spectators.

Roof Inclination CATEGORIES	RANGE	COLOR CODE
Inwards	-	
Outwards	-	

Clear height CATEGORIES	RANGE	COLOR CODE
0 m < 2 m	-	
2 m < 4 m	-	
4 m < 6 m	-	
> 6 m	-	

Figure 153. Categories for the aesthetic criteria utilized for the validation case in ModeFRONTIER. (Source: Self-made)

In general, the trade-off of the alternatives is completed. From 729 feasible designs obtained from the optimization, 7 design alternatives are obtained. In the next phase, one design alternative is selected for further detailing. Indeed, sectional drawings will be produced to confront the initial situation with the optimized new configuration.

	↑	ID	Algorithm	Phase	Mass	% Capacity	%C-Value Higher 9 cm Overall	Inclination Roof	Round of Optimization	Capacity Increment	Height Above Spectators
1	☑	830	NSGA2		Reduced	>20	>95	Outwards	OPT_5	Higher_Than_6500	2_to_4
2	☑	848	NSGA2		Reduced	>20	>95	Outwards	OPT_5	Higher_Than_6500	4_to_6
3	☑	885	NSGA2		Reduced	>20	>95	Outwards	OPT_5	Higher_Than_6500	2_to_4
4	☑	983	NSGA2		Reduced	>20	>95	Outwards	OPT_6	Higher_Than_6500	2_to_4
5	☑	1025	NSGA2		Reduced	>20	>95	Outwards	OPT_6	Higher_Than_6500	2_to_4
6	☑	1043	NSGA2		Reduced	>20	>95	Outwards	OPT_6	Higher_Than_6500	2_to_4
7	☑	1048	NSGA2		Reduced	>20	>95	Outwards	OPT_6	Higher_Than_6500	4_to_6
8	☑	1055	NSGA2		Reduced	>20	>95	Outwards	OPT_6	Higher_Than_6500	2_to_4
9	☑	1057	NSGA2		Reduced	>20	>95	Outwards	OPT_6	Higher_Than_6500	2_to_4
10	☑	1079	NSGA2		Reduced	>20	>95	Inwards	OPT_6	Higher_Than_6500	0_to_2

	↑	ID	Algorithm	Phase	Mass	% Capacity	%C-Value Higher 9 cm Overall	Inclination Roof	Round of Optimization	Capacity Increment	Height Above Spectators
1	☑	830	NSGA2		Reduced	>20	>95	Outwards	OPT_5	Higher_Than_6500	2_to_4
2	☑	885	NSGA2		Reduced	>20	>95	Outwards	OPT_5	Higher_Than_6500	2_to_4
3	☑	983	NSGA2		Reduced	>20	>95	Outwards	OPT_6	Higher_Than_6500	2_to_4
4	☑	1025	NSGA2		Reduced	>20	>95	Outwards	OPT_6	Higher_Than_6500	2_to_4
5	☑	1043	NSGA2		Reduced	>20	>95	Outwards	OPT_6	Higher_Than_6500	2_to_4
6	☑	1055	NSGA2		Reduced	>20	>95	Outwards	OPT_6	Higher_Than_6500	2_to_4
7	☑	1057	NSGA2		Reduced	>20	>95	Outwards	OPT_6	Higher_Than_6500	2_to_4

Figure 154. Table of the design alternatives obtained from the categorization of the aesthetic criteria selected. (Source: Self-made)

9.5 Design Representation

Starting from the 2143 design alternatives produced during the optimization, 10 optimal solutions were obtained after the trade-off process. In general, all the optimal designs generated improved the initial performances of the validation case. Indeed, the mass of the structure was reduced compared to the initial value of 3.7e6 Kg. In addition, the C-value percentage higher than the recommended value of 9 cm for the overall stadium was improved to over 95%, starting from the initial 55%. In particular, a recommended C-value is provided to all the spectators of the second tier, avoiding completely the obstruction of the view from other spectators' heads. Lastly, the capacity of the stadium was improved over 20% for all the design alternatives, with more than 6500 seats added to the initial 33044 seating.

Taking into consideration the aesthetic criteria selected during the trade-off process, the optimal solutions were reduced further. 7 design alternatives were individuated, which had the roof structure inclined outwards and a clear height over the spectators' sightline between 2 m and 4 m. In the end, the design alternative 830 is selected since it is the one that reduces the most the mass of the roof structure compared to the initial situation, while increasing the capacity and improving the C-value. In addition, the structural elements are slightly slimmer compared to the other optimal solutions.

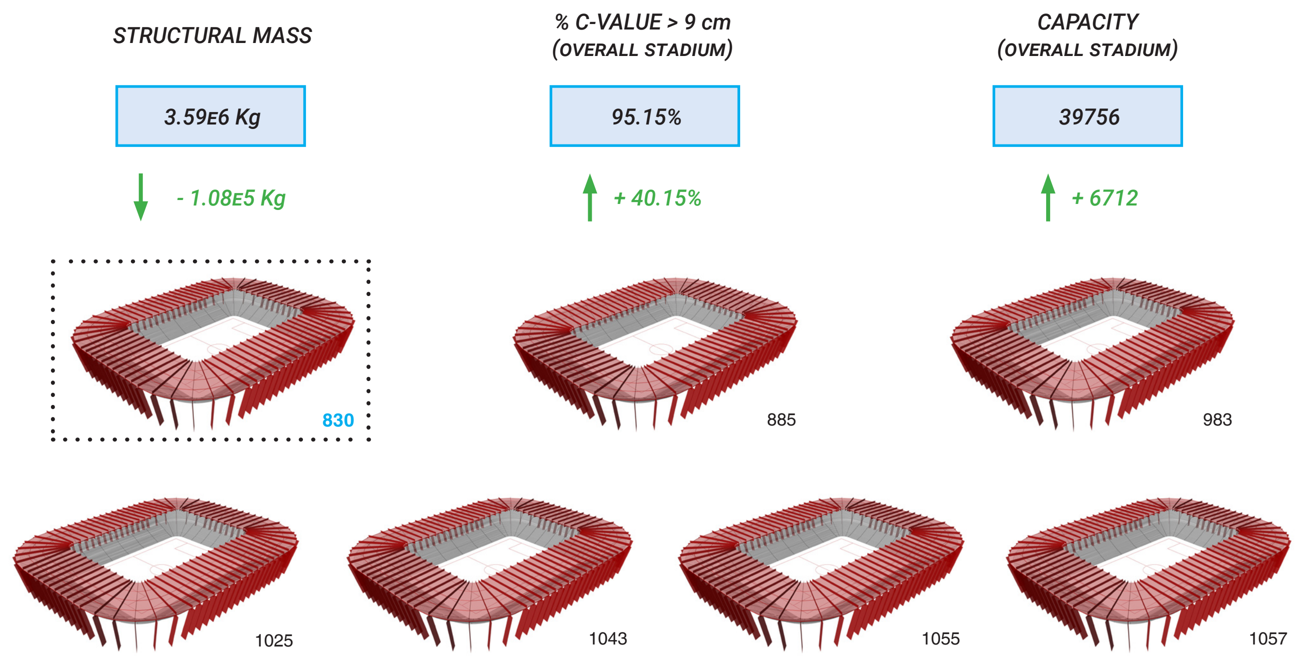


Figure 155. Selected design alternative and 3D model of the optimal solutions individuated during the trade-off process (Source: Self-made)

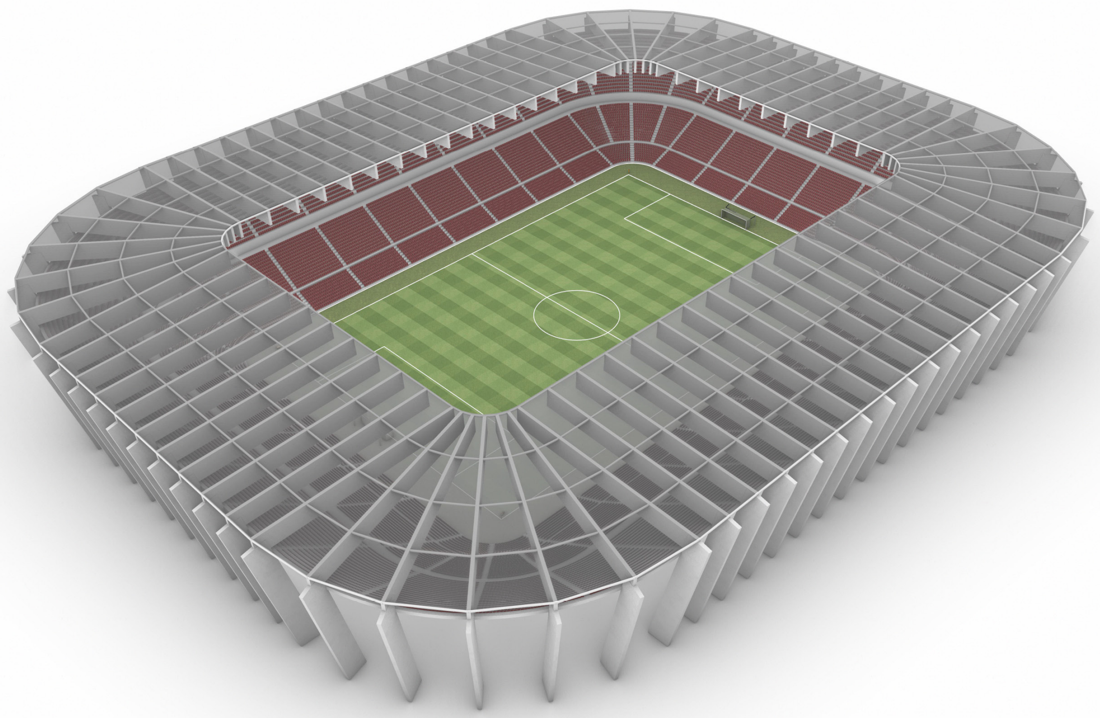


Figure 156. 3D impression of the selected design alternative (Source: Self-made)

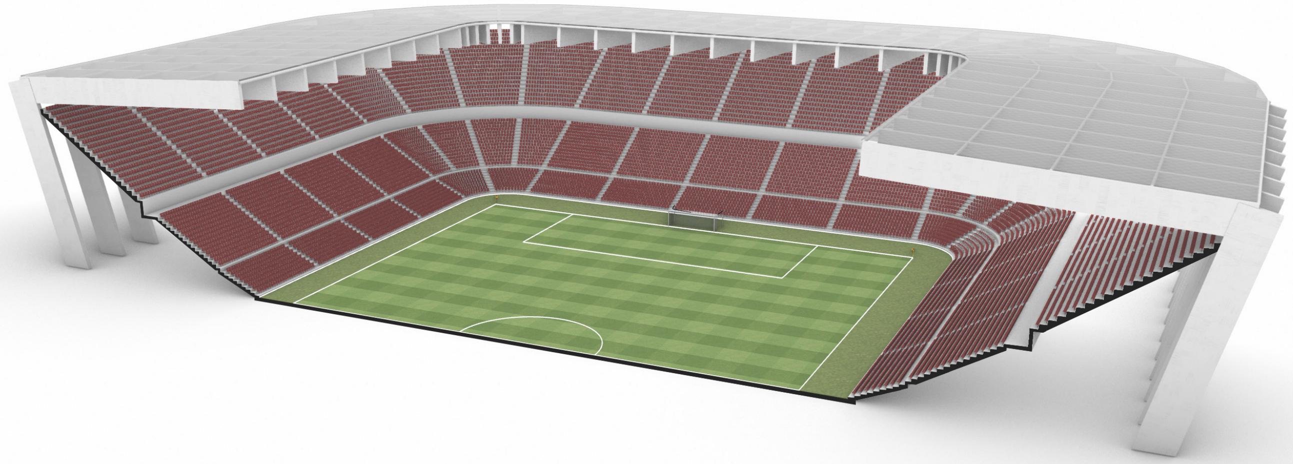


Figure 157. 3D section of the selected design alternative (Source: Self-made)

Figure 158. Perspective Section of the selected design alternative (Source: Self-made)

10 | CONCLUSIONS

CONCLUSIONS

The conclusions of the research are presented in this chapter. Hence, the research questions introduced in section 1.5 are answered to highlight the main findings of the research and the decision taken during the process. In addition the limitations of the computational method are presented in relation to the direction of the future research on the subject. as well as an overall reflection on the developed computational method is introduced.

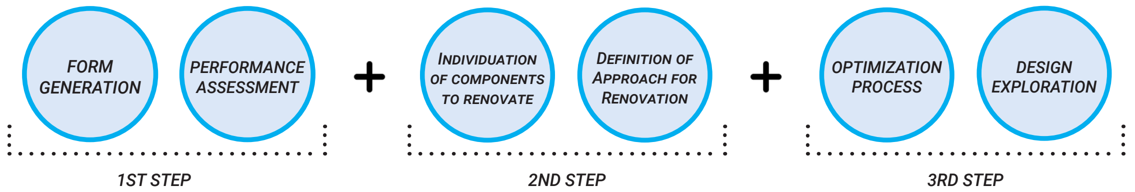
10.1 Answers of the Research Questions

As a conclusion of the research, the research questions formulated in section 1.5 are answered. The sub-questions are addressed first, while the main research question is answered as last.

SUB-QUESTIONS

1. *How is the computational method organized in order to implement stadium renovation?*

   Computational methods such as PCA are organized in three phases, which are the form generation, the performance assessment and the optimization and design exploration phase. In order to include stadium renovation, a further step have to be added to individuate the portions of the stadium to be renovated and to determine an approach for the renovation. This step can be inserted between the performance assessment phase and the optimization process. Indeed, the assessment allows to distinguish the portions of the stadium that are necessary to be renovated from the ones that are worth to be kept based on measurable criteria, while the optimization can be performed avoiding the modification of the parts that have to be kept unaltered. The test performed on the validation case showed the potential of the computational method in achieving this purpose.



2. *Which are the steps of the workflow to develop a computational method suitable for stadium renovation?*

   The renovation of a football stadium foresees the alteration of an existing stadium to obtain a new improved design. In the form generation, the steps of the workflow are individuated in the generation of the components of the existing stadium and in the implementation of the inputs parameters that control their geometries. In addition, a further step should be added to allow the designer to blend the components in different configurations to generate different existing stadiums and to increase the number of design alternatives that can be produced and therefore the applicability of the method.

   In the performance assessment, two main steps of the workflow are individuated. In general, the output values should be presented to the designer along with maps and diagrams to relate the data with a graphic visualization method. Hence, the designer can be facilitated in understanding the results of the assessment and in the individuation of the portions of the stadiums to be renovated, as observed in the test on the validation case. In this case, the color gradient maps can provide a valuable solution to achieve this goal.

   In the optimization and design exploration phase, the workflow allows to alter the inputs of the portions to be renovated and to define the constraints and the objectives of the optimization. The designer should be left free to determine these aspects based on the existing stadium and the renovation approach. Indeed, as observed in the test on the validation case, few objectives and constraints were left out from the optimization since they were negligible for the followed renovation approach.

   Concerning the trade-off of the alternatives, the performances of the initial configuration of the stadium can be utilized as a threshold for the optimization. Indeed, the performances of the existing stadium represent a threshold to determine whether the design alternatives produced are efficient or inefficient. Lastly, the designer should have the control over the trade-off process to prioritize an objective over the others and to consider aesthetic criteria along with measurable ones.

3. *Which tools are the most suitable to produce the workflow?*

   Considering the complexity of the geometries to be produced in the form generation and the volume of data to be generated, the workflow of the computational method should be maintained in the same computational environment as much as possible to facilitate the control over the generated data stream. In general, the computational tools should allow the designer to control the inputs, while providing an immediate feedback of the geometries produced and of the output of the performance assessment. In addition, a friendly user-interface should be provided to the designer to facilitate the navigation of the computational method.

4. *Which components of the stadium should be implemented in the computational method to assess the performances?*

   The components of the stadium should be selected based on the influence they exert on the performances to be assessed. Hence, the pitch should be included since it constitutes the point of focus of the spectators' view. Furthermore, the grandstands should be implemented, since the geometry and the dimensions of the stands affects both the viewing quality of the spectators and the structural performance of the roof. In fact, considering typologies of roof structure implemented, the geometry of the grandstands influences the position of the supports and the span they have to cover. Lastly, the roof structure should be implemented since it constitutes the principal component for the structural assessment. Moreover, its outline determines the area of the stands to which is provided cover from the weather and it can obstruct the view of the spectators.

5. *Which are the parameters that govern the components of the stadium to be implemented?*

   The number of parameters determines the dimensions of the design space and therefore the number of design alternatives that can be produced. However, a larger design space influences the computational time needed for the optimization and increases the complexity of the data stream. Hence, a balance should be found between the two aspects to exploit the potentiality of the computational method and its efficiency. In the computational method, few critical parameters were individuated for the components to provide a sufficient variety of alternatives, considering also the time-frame available. In general, the parameters should be selected to shape the geometries and to provide the possibility to create different configurations of the stadium, especially in the case in which the computational method is foreseen to be applicable on multiple stadiums. In this case, a priority should be given to the parameters that allows the creation of different configurations of a stadium.

6. *What are the constraints of an existing stadium in relation to the viewing quality and the structural performance of the roof?*

   The constraints of an existing stadium are the elements that should be maintained unaltered during the renovation process. *The output of the performance assessment can be evaluated in relation to a set of limit values to distinguish the parts that should be renovated from the ones that are worth to be kept. In the validation case, the set-up proposed resulted effective in determining the portions of the stadium to be maintained. However, the indicators utilized are restricted to the grandstands and to only the C-value and the maximum distance. Indeed, in relation to the* roof structure, the number and the position of the supports were considered to not be modified during the optimization process to avoid a complete alteration of the initial situation. *Thus, to provide additional support to the designer in the decision-making process, further indicators should be individuated.*

7. *How can the parameters that govern the components of the stadium be managed in the computational method?*

   The parameters that control the geometries and the configuration of the components of the stadium can be managed in two different phases. Considering the form generation, the parameters can be implemented as inputs. Hence, their range of values can be determined and the designer is able to define the value to apply within the set boundaries to control the components.

   Considering the optimization process, only the input parameters of the components to be renovated should be left free to be optimized. Indeed, as observed during the optimization of the validation case, the designer can maintain the control over the values to guide the optimization algorithm in searching for optimal solutions.

8. *How can the constraints of the existing stadium be managed in the computational method?*

The constraints of the existing stadium can be managed in two phases of the computational method. In the form generation, the elements should be implemented in a hierarchal order to determine the dependencies between them. Hence, the alteration of the components can affect the parts directly linked with each other, while maintaining unaltered the ones that need to be kept unaltered during the optimization. In the optimization, the elements that does not need renovation can be prevented to be altered by not allowing the alteration of their input parameters. However, this solution necessitate to create a complex data stream and increase the number of the parameters to be implemented, which can increase the computational time needed for the optimization.

9. *What is the viewing quality of the grandstand and the structural performance of the roof of a stadium?*

The viewing quality of the grandstand of a stadium is defined as the comfort of the spectators into following the activity held in the stadium. In this regard, two main aspects can be distinguished. On the one hand, a spectator should not have the view obstructed by any objects. *On the other hand, the comfort of the seats should be considered. Concerning the roof structure, it has to transfer the external loads to the ground and to provide cover to the spectators from the weather conditions. Hence, the principal requirement can be individuated in the structural stability to provide safety to the spectators, while sheltering them from the weather conditions in the mean time. In addition, the evaluation of the composition of the structure can provide a useful indicator to indicate its performance.*

10. *How can the viewing quality of the grandstand and the roof structure of a stadium be integrated together in a computational method?*

The viewing quality performance and the structural performance of the roof can be analyzed individually in relation to their performance indicators. However, few aspects should be considered to relate the roof structure to the grandstands. During the literature review, few indicators were proposed to evaluate features as the area of the stands sheltered by the roof and the obstruction of the spectators' view provided by the roof. Instead of performances indicators, these features can be managed during the form generation and the optimization phases. Indeed, the starting position of the roof structure can be set-up to not obstruct the view of the spectators and to cover the whole stands. Hence, in the optimization, the range of values can be utilized to ensure that the stands are fully covered and the spectators' view is not obstructed by the roof, as observed in the validation case, saving therefore computational time to perform the process.

11. *How can the structural performance of the roof and the viewing quality performance of the grandstand be evaluated?*

The performances should be evaluated with measurable criteria related to different performance indicators. Concerning the viewing quality, the field of view and the vertical viewing angle can provide an indication of the comfort of the spectators. In addition, further indicators as the maximum viewing distance and the c-value, can be evaluated in relation to the obstruction of the view. In general, the c-value can represent the principal indicator for the evaluation. As observed in the validation case, on the one hand, the evaluation of the c-value can provide a useful indicator to distinguish the portions of the stadium worth to be kept from the ones that necessitate renovation. On the other hand, the other indicators may be negligible based on the dimensions of the selected existing stadium.

Concerning the roof structure, the evaluation of the bending stresses and the maximum displacements should be performed to ensure the stability of the structure. However, these indicators can be considered as constraints to be respected in the renovation instead of objectives. Indeed, indicators related to the composition of the structure, such as the mass, can provide an insight on the cost of the structure, which is a critical aspect to be evaluated while renovating a stadium.

12. *How can the structural performance of the roof and the viewing quality of the grandstand be optimized jointly?*

In the computational method, the performances can optimized by selecting the outputs of the performance assessment and considering them as objectives functions to be maximized or minimized. In order to optimize the performances jointly, the objectives can be implemented together to perform a MOO. Hence, the optimization process can find a global optimal solution in case the objectives are consistent with each other or a set of optimal solutions in case the objectives are conflicting, which is the case of the objectives of the proposed computational method. Indeed, as observed in the validation case, a set of optimal solutions is obtained at the end of the trade-off process.

13. *How can the design constraints be implemented in the computational method?*

Based on the literature review, the design constraints can be individuated in the inclination of the stands to ensure the safety of the spectators and in the inclination of the roof to provide the drainage of the rain. Hence, in the computational method, the constraints related to design requirements of the components can be managed in the two phases. Firstly, their value should be evaluated in the performance assessment. Afterwards, the values can be utilized as constraints in the optimization to limit the design alternatives to be produced. In addition, further constraints should be included to ensure the structural stability of the roof.

14. *What is the objective of the optimization of the viewing quality performance of the grandstand?*

The objective functions of the viewing quality can be the maximization of the capacity to enhance the income of the venues, the c-value higher than 9 cm to avoid obstruction of the view and the minimization of the distance to improve the atmosphere of the stadium. In the validation case, the minimization of the distance was neglected considering the dimensions of the stadium. Moreover, it was observed how the range of values of the percentage capacity increment was small, with a variation of less than 2%. This can be due to the complexity of the parametric model and to the set-up of the optimization. Indeed, the number of rows of the tiers was not allowed to be modified in the optimization. Hence, based on the inputs implemented, a designer should evaluate the selection of this objective in the optimization process.

15. *What is the objective of the optimization of the structural performance of the roof?*

Concerning the structural performance, the objectives can be related to reduce the amount of elements and material necessary to construct the roof structure, containing therefore the cost of the project. In the computational method, the objectives considered are the minimization of the number of joints and elements and the minimization of the mass. However, the minimization of the mass drives already the algorithm in searching for solutions that reduce the amount of joints and elements present. Hence, these objectives can be neglected as in the validation case whether the mass is selected as an objective. In general, it should be necessary to set the objectives in relation to the initial performances of the stadium to provide the designer with an immediate understanding on how the performances have changed.

16. *Which process is most suitable to optimize the performances jointly?*

Initially, a set-up of the optimization problem should be carried out by implementing the inputs of the components to be modified, the objective functions and the constraints. Hence, a first optimization can be run to produce a first batch of design alternatives. Hence, the broken constraints can be evaluated whether only unfeasible solutions are present. Thus, the range of values can be reduced based on the responses of the objectives and the algorithm can be trained in searching in the direction of the area where the optimal solutions are located. The process should be repeated until a pareto-front is obtained. However in the validation case, due to the limited time-frame, the optimization was interrupted beforehand. As observed in the validation case, the group of optimal solutions determined was mostly composed of design alternatives obtained in the sixth and last run. Hence, more optimal solutions might have been present in the design space that could have been found with further rounds of optimization.

17. *How can the design alternatives be evaluated through the design exploration?*

The design alternatives can be evaluated in the design exploration to understand the relation between the inputs and the outputs of the optimization problem. Moreover, the trade-off of the alternatives can be performed in this phase to individuate the optimal solutions to the optimization problem. In general, the designer should have the control over the trade-off of the alternatives to prioritize an objective over the others and to consider non-measurable criteria, such as aesthetic criteria. In the computational method, a hierarchical cluster in combination with a categorization of the outputs of the objectives resulted to be effective in the validation case. Indeed, starting with a large group of design alternatives, a smaller group of optimal solutions that improve the performances of the stadium was obtained. In addition, the implementation of color codes facilitate the identification of optimal solutions. However, based on the existing stadium and the followed renovation approach, the designer should determine the hierarchy of the objectives. Furthermore, the categories can be created in the performance assessment phase to automate the trade-off, while letting the designer in control over the process.

MAIN RESEARCH QUESTION

> *"How can a computational method be designed for a stadia renovation process to provide designers and engineers with an overview of the current structural performance of the roof structure and the viewing quality performance of the grandstands, while offering them the possibility to optimize these features jointly?"*

The computational method developed and described in the previous chapters was applied to a validation case to determine whether, starting from an original condition of a stadium, multiple design alternatives which optimize the viewing quality of the bowl and the structural performance of the roof can be achieved. The computational method is organized in the three phases of PCA, to which is added a further step to include stadium renovation. This step can be inserted between the performance assessment and the optimization process. Indeed, the assessment allows to distinguish the portions of the stadium that are necessary to be renovated from the ones that are worth to be kept based on measurable criteria. In this instance, the evaluation should be performed in relation to the different parts of the stadium and not only to the whole building to determine the portions to be renovated. The test performed on the validation case showed the potential of the computational method in achieving this purpose.

During the design phase, it emerged the importance of keeping the data stream within the same computational environment as much as possible, to maintain control over the workflow of the method. In addition, it was understood the impact of the user-interface on the usability of the computational method. Indeed, a user-friendly interface can facilitate the navigation of the method, therefore improving the decision-making process of the designer by providing an immediate feedback on the geometries produced and on the performances of the stadium. Hence, the designer is facilitated in the individuation of the portions to be renovated and they can define an approach for the renovation, which is restricted in the method to a refurbishment or an expansion of the stadium.

In the form generation, since the computational method was envisioned to be applicable on different stadiums and not exclusively on a selected one, different typologies of the components had to be inserted. In this phase, the complexity of the stadium process emerged. Indeed, the alternatives that can be produced with the developed computational method constitute a small portions of the endless combinations that can be realized in practice. Therefore, the number of stadiums that can be implemented in the computational method is limited to the ones that have the same characteristics provided in the form generation. On the one hand, future research can enlarge the design space and the number of stadiums that can be implemented. However, a general method for the renovation of football stadiums will have to be updated continuously and there is the possibility that all the combinations will not ever be fully covered. However, the followed approach to develop the computational method highlighted the possibility to utilize it as a tool to design newly built stadium. Indeed, excluding the selection phase of the portions to be renovated, a designer can apply the method to generate multiple design alternatives for a new stadia.

In relation to the optimization process, the objectives and the constraints implemented in the method were individuated on the basis of the objectives of a renovation process. However, it was understood during the validation of the method that the application of the objectives, the constraints and the inputs is dependent on the existing stadium implemented and the objective of the renovation process to be followed. Hence, in practice a designer should determine the inputs, the constraints and the objectives based on the needs of the project to be developed. Likewise, the range of values of the inputs and the limit values for the constraints should be determined by the designer based on the needs of the project to be developed and in respect to the building regulations of the country where the stadium is located.

In general, the designer should have the control over the trade-off of the alternatives to prioritize an objective over the others and to consider non-measurable criteria, such as aesthetic criteria. *In this instance, the implementation of color codes can facilitate the identification of optimal solutions. However, based on the existing stadium and the followed renovation approach, the designer should determine the hierarchy of the objectives. In future research, the categories can be created in the performance assessment to automate the trade-off, while letting the designer in control over the process.*

A consideration have to be done in relation to the validation case. Indeed, the little literature available on the parameters of the existing stadiums led to the realization of an arbitrary validation case referenced to the Old Trafford of Manchester. In practice, a lidar scan of the stadium can be performed to obtain the information related to the parameters of the components of the stadium, which was not possible to be carried out during the thesis.

Hence, in this case, the reference stadium was selected on the basis of the layout typology and the structural system, which matched the boundaries of the computational method.

Considering the objective of the thesis and the outcome of its application on the validation case, the proposed computational method can be considered valid. Indeed, starting from an initial situation, multiple design alternatives that improve the initial performances can be produced. Moreover, inefficient designs can be individuated and discarded from further development. It must be stressed that the obtained alternatives can constitute a concept design that will be further developed in the subsequent phases of the design process.

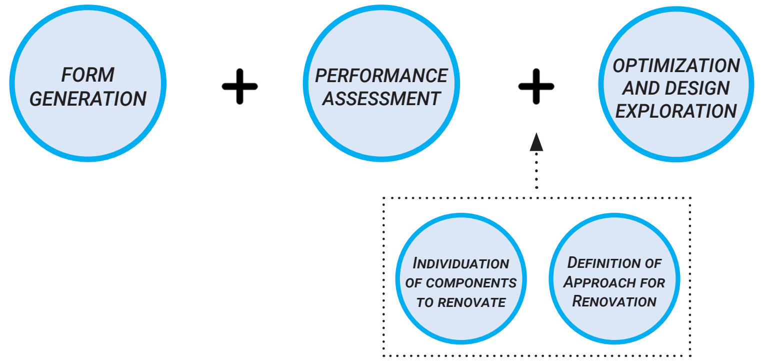


Figure 159. Location of the renovation process of stadium within the computational method (Source: Self-made)

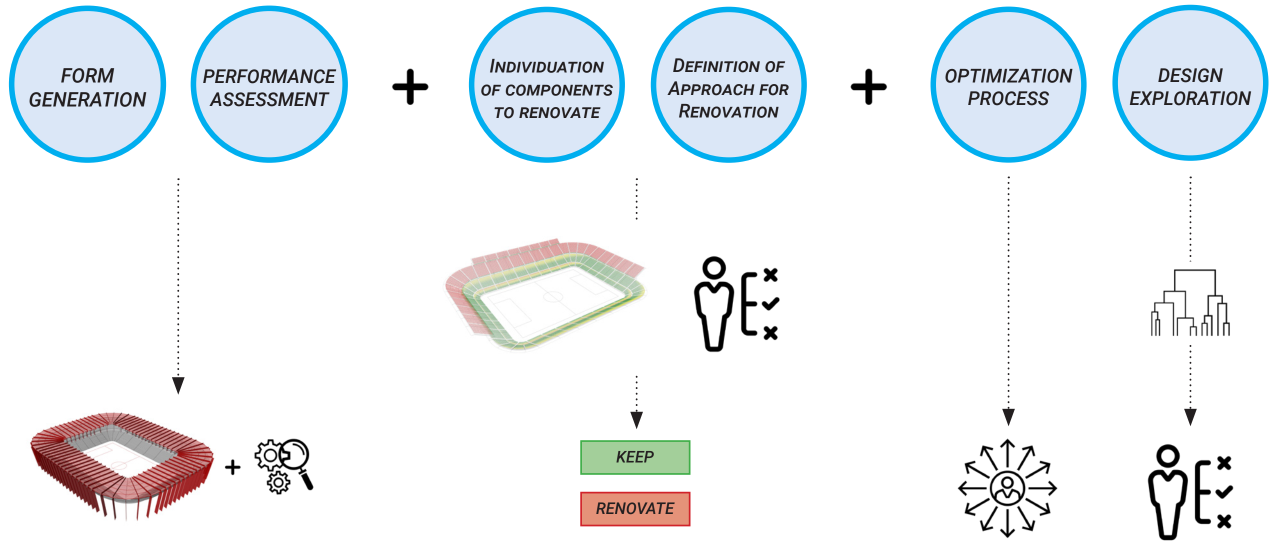


Figure 160. Overview of the developed computational method (Source: Self-made)

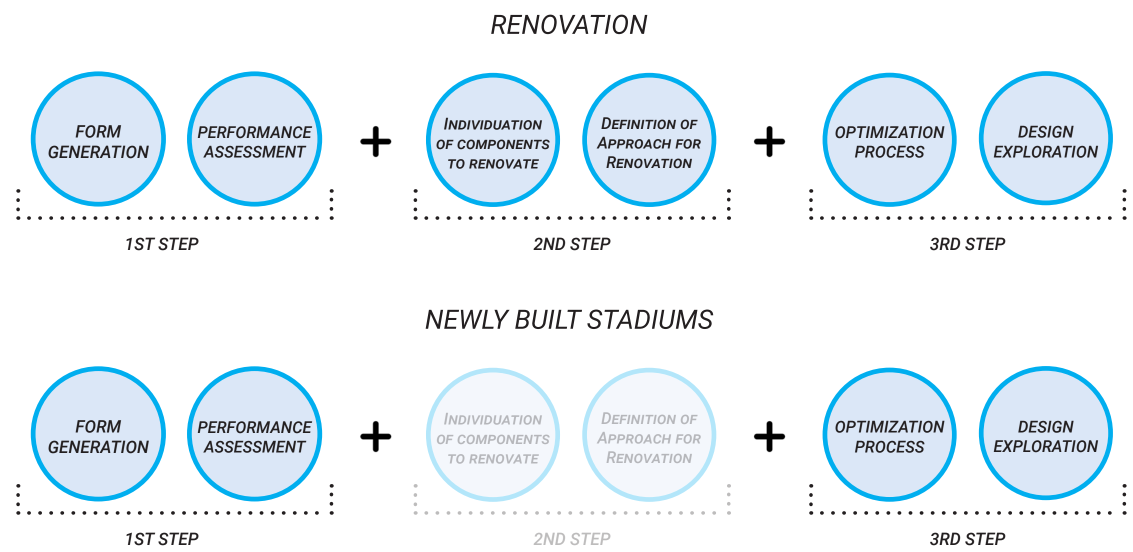


Figure 161. Comparison between the computational method for renovation and newly built stadiums. (Source: Self-made)

10.2 Limitations and Future Research

Along the design phase, few aspects emerged which can be evaluated in future research to refine the computational method and enlarge its design boundaries.

A. Form Generation:

In general, the complexity of the parametric model limits the number of existing stadiums that can be implemented within the computational method. Hence, as a future development, the design space can be expanded to implement a larger number of stadiums.

- Concerning the roof structure, it is limited in relation to its structural elements and its outline. Indeed, the same cross section is applied to the groups of structural elements independently from the span they have to cover. Hence, it is possible that the elements are over dimensioned as in the initial situation of the validation case. Therefore, as a future development, the roof structure should be developed further by applying a different cross section to the elements of the structure based on the span to be covered.

- Concerning the grandstands, the geometry is limited to the stand typologies with a linear riser. As a future development, more combinations of stand typologies should be evaluated for the implementation to enlarge the design space, therefore increasing the applicability of the computational method.

B. Performance Assessment:

- The performance assessment of the roof structure is limited to the dead weight, the snow load and the wind load. Hence, as a future development, further load conditions should be investigated for the implementation. As an example, the effect of the vibration of the stands on the roof structure can be investigated.

- Considering the overview of the performances, the results are presented in Grasshopper within panels and the visualization can be activated manually and one at the time. As a future development, a visualization method to display all the results simultaneously should be researched. Likewise, a solution to produce a table of the results of the performances within grasshopper should be evaluated.

- The performance assessment of the structural performance and the viewing quality is helpful in determining the portions of the stadium worth to be kept. Moreover, it provides an insight on the cost of the structure by assessing the mass of the structure and the capacity of the stadium. However, a cost evaluation of the structure should be implemented to enhance the assessment of the renovation from an economical point of view. As an example, a price can be assigned to the seats of the stadium based on the viewing quality to determine the income of the stadium. Furthermore, the material cost of the roof structure can be evaluated. Hence, a comparison can be carried out to determine the number of venues necessary to repay the cost of the renovation.

C. Optimization and Design Exploration

- The categorization of the design alternatives resulted an effective method to trade-off the alternatives produced during the optimization. However, the process has to be manually set-up by the designer in ModeFRONTIER. As a future development, the process can be automated in Grasshopper by producing an indicator based on the values produced in the performance assessment. Hence, these indicators can be utilized for both the measurable criteria and non-measurable criteria, such as the aesthetic quality of the produced solutions.

10.3 Applicability of the Computational Method

Considering the applicability of the method in practice, few reflections can be drawn. On the one hand, the problematic encountered in the individuation of the validation case due to the lack of literature available on the necessary parameters can be solved by performing a lidar scan of the existing stadium. On the other hand, the developed method focuses on few aspects related to the renovation of football stadium, which are related mainly to the viewing quality, the structural performance of the roof and their related components. Indeed, the number of stadiums that can be implemented in the computational method is limited to the ones that have the same characteristics provided in the form generation. Hence, even though the application on the validation case showed the potential of the computational method, it seems still premature to apply the proposed method in practice. However, future research to refine the typologies of the implemented components can be performed to enhance the computational method for a practical application. In addition, a cost evaluation can be individuated as a crucial feature for future research in order to provide a further valuable criteria to determine the efficiency of the design alternatives.

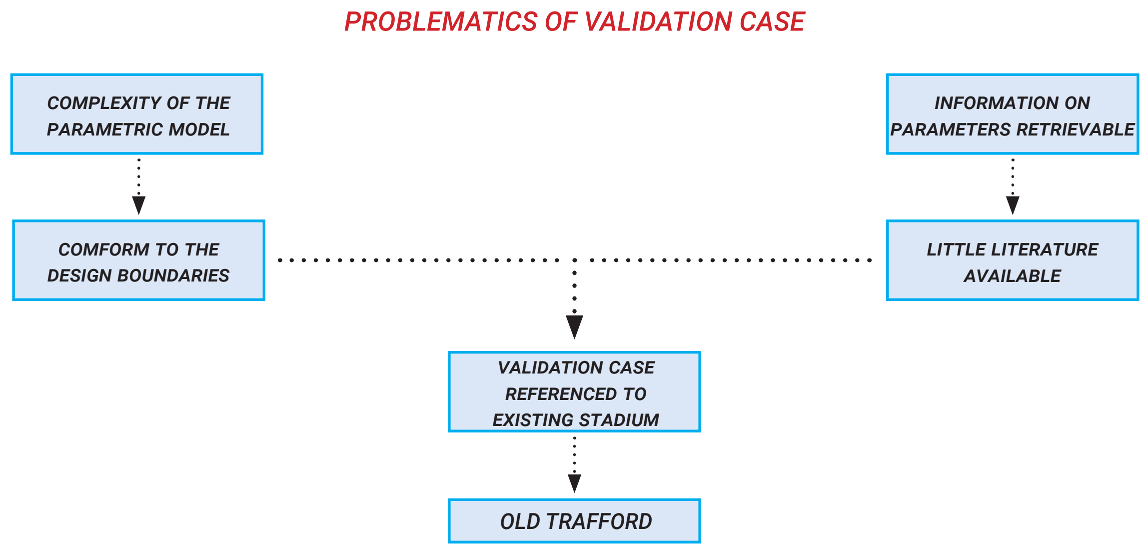


Figure 162. Scheme of the problematics rose in the selection of the validation case (Source: Self-made)

The developed computational method was envisioned to be applicable on multiple stadiums rather than exclusively on a selected one. On the one hand, the followed approach led to the definition of a computational method that has potential in relation to the renovation process of a stadium. However, the combinations that can be achieved are a small portions of the endless combinations that have been realized in practice. In addition, the computational method has the potential to be utilized as a tool to produce multiple different types of newly built stadiums. Indeed, excluding the selection phase of the portions to be renovated, a designer can apply the method to generate multiple design alternatives for a new stadia. On the other hand, the development of a computational method focused on a selected stadium could have allowed to implement and evaluate more features, but the complexity of the parametric model would have been still restricted to the specific case and/or similar stadiums.

The design space can be enlarged in future research to increase the number of stadium on which the method can be applied, as well as the different design alternatives that can be found in the design space. However, the computational time needed to perform the optimization will increase, affecting therefore the functionality of the computational method. Indeed, as observed in the validation case, a single optimization run necessitates various hours to produce a small batch of design alternatives. Hence, increasing the complexity of the parametric model can enhance the applicability of the method, but it can slow down the entire process, reducing therefore its functionality.

Lastly, the computational method can be utilized to develop optimal design alternatives for a stadium to be renovated in the early design phase. Hence, the obtained alternatives can constitute a concept design that can be further developed in the subsequent phases of the design process. As observed in the validation case, the proposed computational method can be applied to evaluate the feasibility and the efficiency of a concept design for a renovation of a stadium. Indeed, inefficient designs can be individuated and discarded from further development, allowing the designer to concentrate on more efficient one.

11 | REFERENCES

REFERENCES

Adams, Duncan, *"The Essential Football Fan: The Definitive Guide to Premier and Football League Grounds",* Aesculus Press Limited, 2003

Bradner, E., Francesco I., and Mark D., *'Parameters Tell the Design Story: Ideation and Abstraction in Design Optimization'*, in Simulation Series, 2014, XLVI, 172–97
Doi: https://www.researchgate.net/publication/275831167

Citerne D., *Parametric design for better buildings*, 2019
Doi: https://www.arup.com/perspectives/parametric-design-for-better-buildings

Department for Culture Media and sports, *'Guide to Safety at Sports Grounds'*, Department for Culture, Media and Sport, 2008

Ekici, B, Cubukcuoglu C., Turrin M., and Sariyildiz I.S., '*Performative Computational Architecture Using Swarm and Evolutionary Optimisation: A Review',* Building and Environment (Elsevier Ltd, 2019), 356–71
Doi: https://doi.org/10.1016/j.buildenv.2018.10.023

Engel, H., and Rapson R., '*Tragsysteme - Structure Systems*', 2007

FIFA, *'Football Stadiums - Technical Recommendations and Requirements*', in FIFA Fédération Internationale de Football Association, 2011
Doi:https://it.scribd.com/doc/100501692/FIFA-Football-Stadiums-Technical-recommendation-and-requirements-5th-edition

John G. and Heard H., *Handbook of sports and recreational building design*, architectural press, 1981

John G., Sheard R. and Vickery B., *Stadia: The Populous Design and Development Guide*, Routledge, 2013

Göppert, K., & Stein, M. (2007). *A spoked wheel structure for the world's largest convertible roof - The new commerzbank Arena in Frankfurt*, Germany. Structural Engineering International: Journal of the International Association for Bridge and Structural Engineering (IABSE), 17(4), 282–287.
https://doi.org/10.2749/101686607782359155

Gough C., *Average attendance of major soccer leagues around the world 2018/2019*, 2019
Doi:https://www.statista.com/statistics/270301/best-attended-football-stadiums-in-the-world-by-average-attendance-2010/

Hudson, R., *'Strategies for Parametric Design in Architecture.*', Civil Engineering, 2010, 274

Jones T., *Trends in Stadium Design and Renovation*, 2019
Doi: https://populous.com/trends-in-stadium-design-and-renovation

Joseph D., Kim A., Butler A., and Haeusler H., '*Optimisation for Sport Stadium Designs'*, Proceedings of the 20th International Conference of the Past, Present and Future of Digital Architecture, Proceedings of the 20th International Conference of the Association for Computer-Aided Architectural Design Research in Asia CAAD, 2015, 573–82
Doi: http://papers.cumincad.org/data/works/att/caadria2015_054.content.pdf

McCormick C., Fergus, FIStructE Director, and Uk Pottinger A. BEng, *Introduction: Appointment and Brief,* 2016
Doi: www.thestructuralengineer.org

Miller, N. (2009). P*arametric strategies in civic architecture design.* ACADIA 09: ReForm(): Building a Better Tomorrow - Proceedings of the 29th Annual Conference of the Association for Computer Aided Design in Architecture, 144–152.

Millls D.E., *Planning: Buildings for Administration, Entertainment and Recreation*, Newnes-Butterworths; 9th edition (1976)

Nixdorf S., *Stadium Atlas: Technical recommendations for Grandstands in Modern Stadia*, Wiley-VCH Verlag GmbH, Berlin, 2009

Palvarini P. and Tosi S., *Stadiums as Studios: How the media shape space in the new Juventus Stadium,* 2013
Doi: https://firstmonday.org/ojs/index.php/fm/article/view/4959/3791

Pan W., Turrin M., Louter C., Sariyildiz S., and Sun Y., *'Integrating Multi-Functional Space and Long-Span Structure in the Early Design Stage of Indoor Sports Arenas by Using Parametric Modelling and Multi-Objective Optimization'*, Journal of Building Engineering, 22 (2019), 464–85
Doi: https://doi.org/10.1016/j.jobe.2019.01.006

Patz r., Brinkmann j., Aziz S., and Marschall M., *Immersive Interfacing in Large-Scale Design Embodied Knowledge and Vagueness Assisting Intuition-Prospects for Computer Aided Architectural Design View Project,* 2016
Doi: https://www.researchgate.net/publication/306095111

Reuters (2007), *Platini wants Champions League final at weekend*, Retrieved 30 August 2007
Doi:https://uk.reuters.com/article/soccer-uefa-platini/update-1-soccer-platini-wants-champions-league-final-at-weekend-idUKL3082273420070830 (Reuters, 2007)

Rodriguez Garcia A., *Computational design method based on multidisciplinary design optimization and optioneering techniques for energy efficiency and cost effectiveness,* 2018
Doi: http://resolver.tudelft.nl/uuid:efd1c23f-4ab7-41dd-88e4-e9a1683c4ccc

Sariyildiz I.S., *'Performative Computational Design',* Keynote Speech in: Proceedings of ICONARCH-I:, 2012, 15–17
Doi: http://repository.tudelft.nl/assets/uuid:b637bb68-7e90-44f7-9c45-74a05e29a69d/289840.pdf

Shepherd P., '*On the Benefits of a Parametric Approach to Stadium Design*', Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2015, Amsterdam Future Visions, 2015
Doi: https://people.bath.ac.uk/ps281/research/publications/amsterdam_preprint2.pdf

Statista (2013), *Stadium projected costs of the EURO 2016 in France*, Retrieved 30 April 2013
Doi: https://www.statista.com/statistics/285229/stadium-construction-renovation-costs-uefa-euro-2016/

The Nielsen Company, *Fan Favorite: the global popularity of football is rising,* 2018
doi: https://www.nielsen.com/eu/en/insights/article/2018/fan-favorite-the-global-popularity-of-football-is-rising/

Turrin M., Von Buelow P., and Stouffs R., '*Design Explorations of Performance Driven Geometry in Architectural Design Using Parametric Modeling and Genetic Algorithms*', Advanced Engineering Informatics, 25.4 (2011), 656–75
Doi: https://doi.org/10.1016/j.aei.2011.07.009

Turrin M. (2014). **Performance Assessment Strategies: A computational framework for conceptual design of large roofs.** In A+BE | Architecture and the Built Environment (Vol. 1, Issue 1).
Doi: https://doi.org/10.7480/a+be.vol1.diss1

Turrin M, Sariyildiz S., and Paul J., *Interdisciplinary Parametric Design: The XXL Experience Optimus: Metaheuristic Optimization for Grasshopper 3d View Project Configraphix: Graph Theoretical Methods for Design and Analysis of Spatial Configurations View Project Interdisciplinary Parametric,* 2015
Doi: https://www.researchgate.net/publication/281118921

UEFA, '*UEFA Guide to Quality Stadiums'*, 2011

UEFA, '*UEFA Stadium Infrastructure Regulations Edition 2018',* 2018
Doi: https://www.uefa.com/MultimediaFiles/Download/uefaorg/Stadium&Security/01/48/48/85/1484885_DOWNLOAD.pdf

Wortmann T. and Nannicini G., *'Introduction to Architectural Design Optimization'*, in Springer Optimization and Its Applications (Springer International Publishing, 2017), CXXVIII, 259–78
Doi: https://doi.org/10.1007/978-3-319-65338-9_14

Yang D., Turrin M., Sariyildiz S. and Sun Y., *'Sports Building Envelope Optimization Using Multi-Objective Multidisciplinary Design Optimization (M-MDO) Techniques'*, in 2015 IEEE Congress on Evolutionary Computation, CEC 2015 - Proceedings (Institute of Electrical and Electronics Engineers Inc., 2015), pp. 2269–78
Doi: https://doi.org/10.1109/CEC.2015.7257165

Yang D., Ren S., Turrin M., Sariyildiz S. and Sun Y., *'Multi-Disciplinary and Multi-Objective Optimization Problem Re-Formulation in Computational Design Exploration: A Case of Conceptual Sports Building Design',* Automation in Construction, 92 (2018), 242–69
Doi: https://doi.org/10.1016/j.autcon.2018.03.023