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Generative Design for Constructability improvements with BIM|Lean approach

Generativno načrtovanje za izboljšanje izvedljivosti gradnje pri uporabi pristopa BIM |Lean

BIM A+ European Master in Building Information Modelling

Master thesis No.:

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BIBLIOGRAFSKO – DOKUMENTACIJSKE STRANI IN IZVLEČEK

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Izvleček:

Gradbena industrija zaostaja pri uvajanju sodobnih tehnologij, zaradi česar gradbeništvo sodi med najbolj neučinkovite industrije z eno najnižjih stopenj produktivnosti med sektorji. Osrednji vidik, ki vpliva na nastalo stanje, je pomanjkanje integracije skozi življenjski cikel gradbenega projekta. Pomanjkanje integracije povzroča ponovno delo na posameznih projektih, brez da bi temeljito preučili zahteve za izvedljivost gradbenih del. Študija izvedljivosti gradbenih del je tehnika, ki sistematično preučuje logiko gradbenih del od začetka do konca, s ciljem, da zniža stroške, potreben čas za izvedbo in količino odpadnega materiala projekta. Vitka proizvodnja in BIM sta mehanizma, ki podpirata proces, ki je nujen, če želimo izboljšati izvedljivost gradbenih del. Pričujoča disertacija integrira te mehanizme, na način, da najprej identificiramo vrednost mehanizmov za reševanje najbolj pogostih težav pri izvedbi gradbenih del in jih nato vgradimo v študije izvedljivosti gradbenih del v fazi načrtovanja.

Poleg tega naloga tudi obravnava, kako bi lahko z uporabo vitke proizvodnje in BIM odpravili ne-tehnične težave. Med tehničnimi težavami ima racionalizacija načrtovalskih rešitev ključen pomen pri izboljšanju izvedbe in zmanjšanju stroškov. Pristop je prikazan na študiji primera Arene Stožice, kjer je prikazana optimizacija oblike z uporabo orodij za generativno načrtovanje, ki omogoča iskanje optimalnih načrtovalskih rešitev. V sklepnem delu študije prikažemo tudi uporabnost strojnega učenja za standardizacijo in združevanje konstrukcijskih sistemov fasadnega ovoja.

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BIBLIOGRAPHIC– DOCUMENTALIST INFORMATION AND ABSTRACT

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Abstract:

The construction industry suffers from the lack of adoption of advanced technologies. As a consequence, construction is among the least productive industries across various sectors. The researchers often point out that the critical issue is the lack of integration throughout the building project life cycle. Lack of information integration causes reworks unexpected changes, lower construction quality, delays, and on-site conflicts, which could be addressed in advance by a proper constructability study executed already in the design phase. Constructability is a technique that examines the logic of construction from the beginning to the end, seeking technical solutions that reduce project cost, time, and waste. The central part of the thesis provides a comprehensive overview and analysis of non-technical and technical constructability issues. Special attention is given to Lean and BIM approaches, which may serve as driving mechanisms that substantially improve constructability. The presented work tries to identify the value and integration of mechanisms for the improvement of constructability issues. Among the technical issues, the rationalization of the design plays an essential role in improving the execution and reducing project costs and delays.

The final part of the thesis focuses on the rationalization of design addressing constructability issues by employing Generative Design. This approach is demonstrated in a case study of a complex building –Stožice Arena. The Arena case study shows the design rationalization techniques using generative design and machine learning, enabling informed shaping and clustering of the building envelope. The presented solution contributes to the evolving field of future architectural-structural design methods.

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RESUMEN

DISEÑO GENERATIVO PARA MEJORAS DE CONSTRUCTIBILIDAD CON ENFOQUE BIM | LEAN

La industria de la construcción sufre de la falta de adopción de tecnologías avanzadas. Como consecuencia, la construcción se encuentra entre las industrias menos productivas en varios sectores. Los investigadores a menudo la falta de integración a lo largo del ciclo de vida del proyecto de construcción como problema clave. La falta de integración de la información provoca modificaciones inesperadas en el trabajo, menor calidad de la construcción, retrasos y conflictos en el sitio, que podrían abordarse de antemano mediante un estudio de constructibilidad adecuado ejecutado ya en la fase de diseño.

La constructibilidad es una técnica que examina la lógica de la construcción de principio a fin, buscando soluciones técnicas que reducen el costo, el tiempo y el desperdicio del proyecto. La parte central de la tesis proporciona una descripción y un análisis exhaustivo de los problemas no técnicos y técnicos de constructibilidad. Se presta especial atención a dos enfoques, Lean y BIM, que pueden servir como mecanismos impulsores que mejoran sustancialmente la constructibilidad. El trabajo presentado intenta identificar el valor y la integración de mecanismos para la mejora de los problemas de constructibilidad. Entre los aspectos técnicos, la racionalización del diseño juega un papel fundamental para mejorar la ejecución y reducir los costos y retrasos del proyecto.

La parte final de la tesis se centra en la racionalización del diseño abordando problemas de constructibilidad mediante el empleo del diseño generativo. Este enfoque se demuestra en un estudio de caso de una infraestructura compleja: Stožice Arena. En el caso de estudio de Stožice Arena, mostramos las técnicas de racionalización del diseño utilizando el diseño generativo y el Machine Learning, lo que permite una estandarización y agrupación informada de la envolvente de la infraestructura. La solución presentada contribuye al campo en evolución de los futuros métodos de diseño arquitectónico-estructural.

Palabras Clave: Constructabilidad, BIM, Lean, Diseño Generativo, Machine Learning, Diseño Paramétrico, Racionalización, Problemas no técnicos en la construcción

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This thesis had a collaborative flow of creation since it was sought as far as possible to manage and learn from experts, for which I thank every one of those involved who served as support and consultancy during its creation: Andrej Lavrič, Marko Završki, Veljko Janjić, Lorenzo Comaron, Chi-Li Cheng, Marko Završki and Juan Pedro Cortes. Thanks for your contribution, professional field knowledge added practical value to this document, and I learned a lot from their feedback.

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I want to thank all my subscribers and students that I have had throughout this trajectory where I have shared my knowledge in BIM; you have made me never stop learning and question myself, above all, to improve and teach what is better.

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"*This is the beginning of an exciting path to continue learning and improving, thanks to all who have been part of my personal growth.*"

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1. INTRODUCTION

"Every great journey begins with a single step…." **— Chinese Proverb**

The construction industry is full of areas for improvement, which allows us to seek to increase productivity and offer a better product to the end customer. There are different mechanisms to optimise construction projects. This thesis exposes the construction sector's current problems, as Lean and BIM reduce the risk of many non-technical problems within construction. The main point of the thesis focuses on taking advantage of the constructability technique and using available technology to solve technical problems. Through algorithms, BIM tools and standardised processes can optimise construction processes, which allows offering solutions with the help of generative design and the automation of creating multiple scenarios in planning.

This thesis develops the Stožice Arena as a practical case using generative design to optimize the shape of a structure, using construction techniques as inputs and constraints, resulting in a rationalized solution that reduces construction processes and material cost.

1.1. Background and Problem Statement

The construction field is one of the sectors most defragmented and lagging in technology adoption. This has resulted in low productivity, which is reflected in poorly paid wages.

Non-technical problems such as the lack of knowledge about the scope of the project, no collaboration and a lack of transparency in the activities have made businessmen, academics, and organizations rethink the current way of working.

Among the technical problems in construction, the rationalization of the design is an essential pillar in its development. Unfortunately, the lack of rationalization, a wrong notion of structural honesty, has led the projects to increase their cost by 80% and even more.

Finally, we find ourselves with less and less natural resources and accelerated population growth. This concern has led entire countries to set goals to reduce carbon emissions by 90% by 2050.

Suppose we want to reduce these, grow as an industry, and leave a better place for our children. In that case, it is crazy to continue doing things like our ancestors and expect different results.

1.2. Goals and Aims

The aim is to identify how Generative Design and Lean | BIM management help improve construction projects' Constructability processes.

To achieve this described goal, the objectives are:

1. Define the main construction problems attached to the lack of constructability approach and segment them into technical and non-technical.

2. Define the main points within the construction that help to improve the constructability of the project.

3. Describe how Lean and BIM will help reduce the risk of non-technical problems within a project.

4. Describe how Generative Design helps design rationalization through automation and standardization using constructability criteria.

5. Evaluate the results obtained in the implementation of the case study.

1.3. Research Questions

To identify the objectives to be achieved in this thesis, the following questions were asked during the investigation:

- What is the current situation in construction?
- Why are there delays and cost overruns in construction?
- What are the proposals offered to mitigate these problems within a project?
- Why is constructability a technique that is not implemented in most projects?
- What makes BIM and Lean a solution to solve construction problems?
- Why are these mechanisms not used by professionals, and what is being implemented in projects?
- How can generative design help to improve constructability processes within a project?
- What are the constructability principles that can be parameterised and used in the generative design?
- How can all this be integrated into a project?

Answers to these questions are offered within the thesis. Finally, constructability solutions are implemented in the Stožice Arena case study, supported by generative design models.

1.4. Scope and limitations

The classification of construction problems was reduced to those directly related to the lack of constructability criteria and secondary factors. The practical case focused on obtaining the optimal geometry to allow a uniform transmission of forces and optimise panelisation. Due to the project's complexity, the creation of the structural solution is shown within a conceptual design phase, so it does not have all the assumptions of load combinations nor the specific details of structural connections.

This thesis aims to show how the combination of constructability, generative design and BIM can improve the efficiency of the design process. It is carried out using various optimization tools.

1.5. Methods of research

The first part consisted of carrying out a general review of the problems of the construction sector, the main topic of the thesis (Constructability), and the application of Lean | BIM as a framework for improvement. Keywords were identified to search for scientific documentation; relevance and agreement were filtered, the information was read to determine the area where a significant contribution could be made, and the specific proposal to be addressed in the thesis was generated.

Once found, a specific search was generated by topics such as the proposal made. Then, a statement was developed to support the suggestion that will be addressed in the case study. Next, the knowledge bases of the proposal were created, forming a synthesis of the literature, and focusing it on the practical case. After, the element breakdown structure of the problem to be solved in the case study was carried out. Finally, the project was developed to respond to the initial hypothesis. Finally, the conclusions obtained from the case study were generated.

The complete workflow used to create this document is shown in Figure 1.

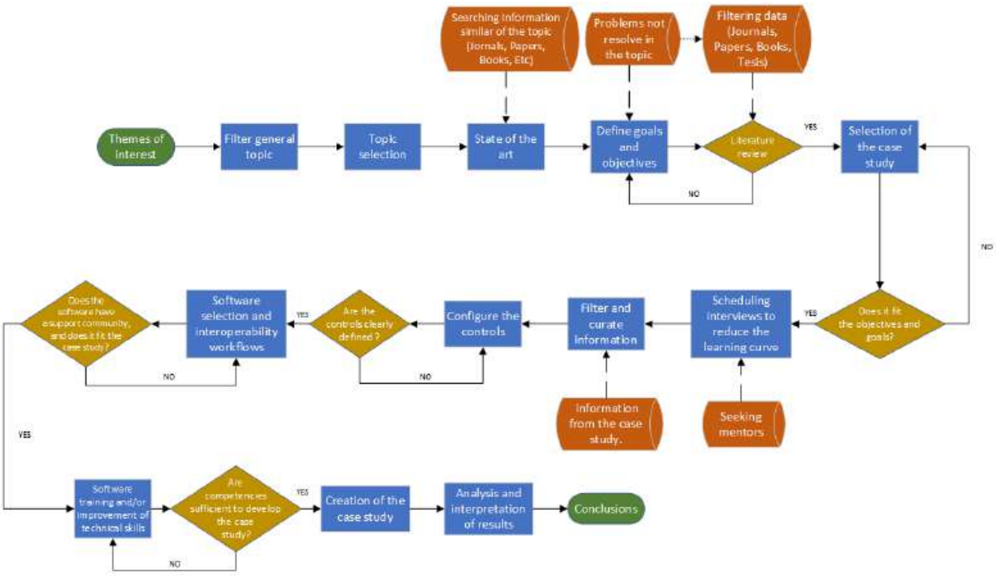


Figure 1 Thesis Workflow

1.6. Content Structure

The structuring of the thesis is composed of eight chapters, beginning with the introduction of the proposed topic; the introduction has indicated the general perspective of the construction industry and the main problem that motivates the creation of this document. Next, the goals and aims that answer the questions are established. Finally, it has delimited the practical case developed in the thesis.

Chapter 2 describes the current state of construction, how the sector is in terms of productivity and technological adoption, the challenges that the European Union proposes for the coming years and its approach to mitigating them. Then it has introduced the problems that affect the industry within a general aspect. Finally, give an opinion and describe proposals that help reduce the issues related to the big picture.

Chapter 3 describes why Constructability should be considered within the project creation process. It establishes the basic definition of Constructability and explains how it is being applied in some countries. It describes the principles on which this technique is based, and a table is generated consolidating those principles exposed by various authors on the subject. Finally, the implementation problems of this technique are described and how the review process helps control the adoption of constructability within a project.

Chapter 4 describes what is Lean and what are the principles on which this philosophy is governed. What are the tools Lean uses to reduce waste and improve collaboration within the organization? Then it is discussed how BIM is being adopted in various countries and how they have shown benefits within the public sector. Next, what are its definitions as a methodology and as a product? When is it that this collaborative methodology began to develop? Then it describes all those tools and standards that help BIM as a single language translator within project collaboration. Finally, the connection that

BIM | Lean has with each other and how they use the constructability technique to reduce waste, increase the commitment of those involved in the project and reduce execution times.

Chapter 5 describes non-technical problems in construction, focusing on those that can be controlled and mitigated through different mechanisms offered by BIM | Read. First, non-technical issues, according to Griffith, are described. Then, specific proposals on mitigating non-technical problems using Lean tools are later described | BIM, such as Integrated Project Delivery, Common Data Environment, BIM Execution Plan and Last Planner System. Finally, the author makes the conclusions of this chapter.

Chapter 6 describes the meaning of technical problems and then focuses on the problem related to the lack of rationalization of the design. First, it is defined what rationalization and its importance within the project is. Later, examples of platforms that use Artificial Intelligence and Procedural Modeling are shown to reduce the time in the search for the rationalization of the design. Finally, the author makes the conclusions of the mentioned chapter.

Chapter 7 defines the meaning of procedural modelling to later focus on computational design and the skills required for this activity. Then it is described what the parametric design is, what are the bases that define this activity. In addition, the tools that allow parametric designs and what type of programming is used in these are described. Finally, the progression of the parametric design is defined and how the generative design using the genetic algorithm allows creating multiple designs following a computational logic that must be configured from the problem statement. This subchapter explains the topic, identifies the approaches to carry out this activity, and defines why NSGA II was used as the execution engine algorithm for the practical case.

Chapter 8 focuses on the practical case of Stožice Arena, where it begins by describing the project and the scope of the case study, describing the assumptions made for it. Then, the methods, the Lean tools used, and how to subdivide the case study are related to better understanding the reader. Finally, this chapter describes the creation of parametric designs for the stadium roof and facade.

Once the algorithms for parametric design have been defined, the variables and constraints used for the generative designs are explained. Then, explaining their choice, describing the techniques and methods used to optimise computational time for the search for the optimal result. This step explains how Machine Learning was used to filter the results to reduce the Pareto front noise. Finally, in this step, comparisons are made on the results obtained in the structural pseudo-analysis tool vs a software dedicated exclusively to structural design for the corroboration of results and verification of the optimal solutions found.

Grouping and creation of standardized panels are also described using mesh rationalization techniques, mesh relaxation, and Machine Learning as a proposal aligned with the constructability technique's objectives.

Finally, the creation of the BIM model is described based on the results obtained from the visual programming tool. Thus, the final information model is established that will allow information to be received within the conceptual phase in the construction elements developed during the practical case.

In the end, general conclusions found from the development of the practical case are described, also giving a proposal on lines of work related to the document.

As additional documents, it provides the appendices that contain relevant information about the project, such as the questions asked to stakeholders, a table with more extensive content on the synergy that Lean and BIM have proposed by Hamdi and Leite and finally, examples of the documents created from the BIM model.

2. STATE OF ART IN THE CONSTRUCTION

“The more you know about the past, the better prepared you are for the future.”
— Theodore Rosevelt

The construction sector is of utmost importance in the European Union (EU) since it can generate twenty million jobs and 10% of GDP, so the development of this activity plays an essential role in the economy and natural resources. However, due to climate change, it is necessary to reduce carbon emissions. The EU has the objective of reducing it by up to 90% in 2050 (Comisión Europea, 2012), so it is essential to rethink what we can do to change as a sector, increase our productivity and reduce our waste to improve the economy and reduce emissions from the construction field.

2.1. The current state of productivity

With about $10 trillion spent on construction-related goods and services every year, our sector is one of the largest in the world economy. However, in terms of productivity, construction worldwide has only grown by 1%. Comparing the last 80 years, we could realise that our sector is stagnant, while agriculture and manufacturing have increased fifteen times. Even worse, we have been consistently declining since the 1960s (McKinsey Global Institute, 2017).

Compared with other sectors, ours lacks investment in time dedicated to creating added value to the final product, as shown in Figure 2. That causes us to lose profits in Engineering and Construction, like construction machinery and significant equipment directly support the earnings from 2002 to 2008 in our sector (Santhanam *et al.*, 2020). The lack of productivity causes a poor economic benefit for companies dedicated to the construction sector, which leads to low-paid salaries, having a gap of more than double compared to manufacturing.

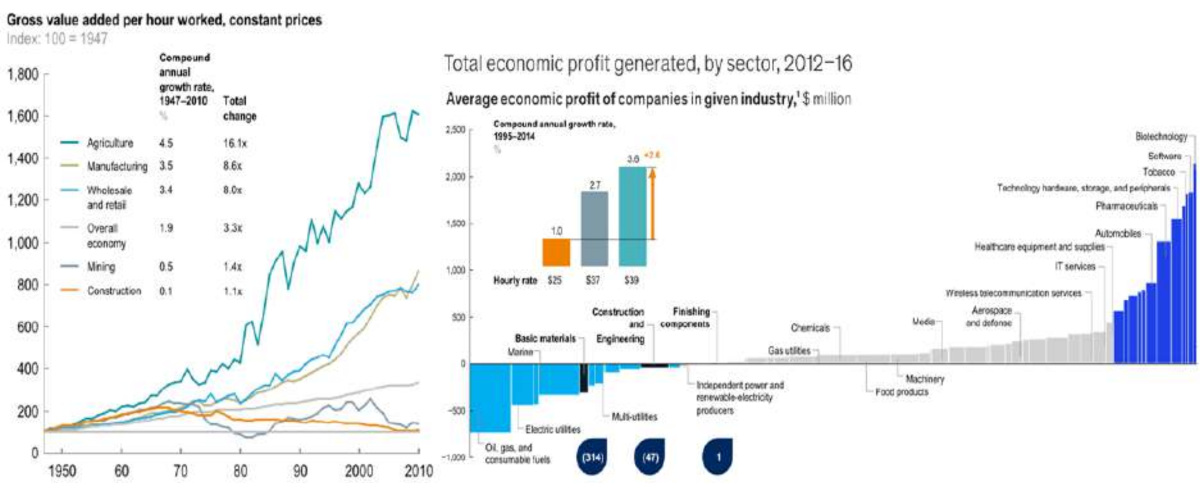


Figure 2 Adaptation of reports conducted with lack of productivity (McKinsey Global Institute, 2017; Santhanam *et al.*, 2020)

Some problems of the lack of productivity are because construction is among the most fragmented industries in the world. As a result, contracting structures governing projects are rife with mismatched risk allocation, creation of inefficient designs, insufficient investing time spent on planning and thinking on the management and execution of the project, and the corruption role is the cherry on the cake.

The good news is that if construction productivity were to catch up with the entire economy, the industry's value-added could rise by $ 1.6 trillion a year (McKinsey Global Institute, 2017), causing a beneficial change for society. Currently, seven areas can help increase productivity by up to 60%; this thesis describes how to improve through Lean | BIM, infusing technology and innovation within the constructability technique.

2.2. The current state of technology adoption

Productivity today is strongly related to technology adoption; it was not strange to identify that part of the lack of productivity is associated with the inferior technology adoption that our sector compared to others it has had throughout these 50 years. For example, as shown in Figure 3, construction suffers a significant delay in technological adoption, regarding the use of assets, interaction with end-users and finally, the insertion within activities related to work on-site (McKinsey Productivity Sciences Center, 2018).

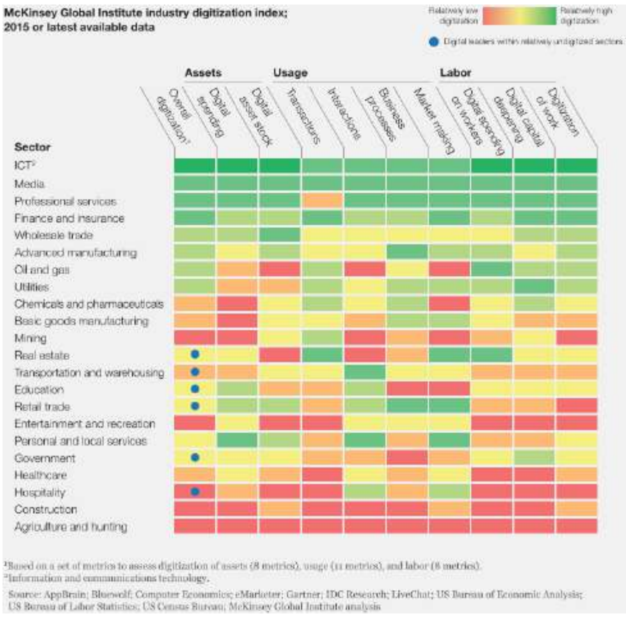


Figure 3 Index digitalisation among industries (McKinsey Productivity Sciences Center, 2018)

Within the unfortunate facts of COVID, the good news is that there is exponential growth within the digitisation of activities. An example is the potential benefit of remote work has been seen, increasing in the following years up to 20%, thus showing an additional benefit that digitisation brings concerning the relocation of jobs in our sector (McGraw Hill Construction, 2021).

Companies' main problems during the digital transformation process involve investing a considerable amount in software and hiring personnel more qualified. Nevertheless, mainly, it is the lack of knowledge and investment in research on the uses and benefits of this adoption. As a form of support, the EU has launched the "Digital Europe" program. 7.5 billion euros will be allocated to support technology development, implementations, research and innovation in our sector (European Construction Sector Observatory, 2021). Within the report carried out by the EU, 12 leading technologies that could help generate more significant benefits in our industry were identified; within these are BIM and Artificial Intelligence, these being fundamental pillars for our proposal for improvement on constructability in this thesis.

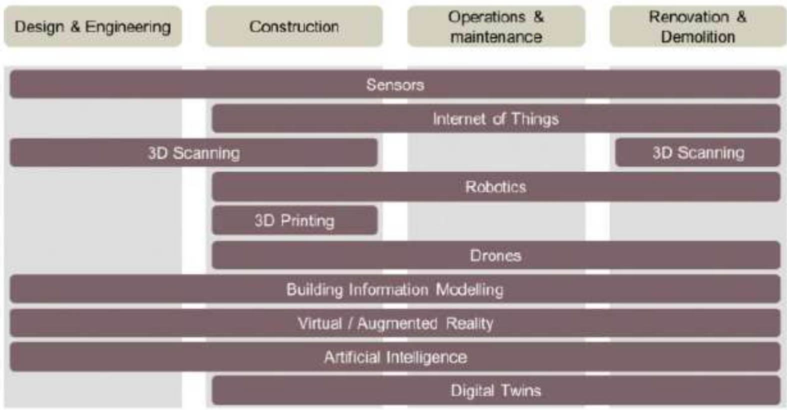


Figure 4 Proposal on the application of technologies in the construction sector (European Construction Sector Observatory, 2021)

2.3. Construction Issues

Construction issues mainly affect the execution time during the construction phase cycle, which leads to a considerable cost increase in the project. For example, in a study carried out by KPMG, it was obtained that only 25% of the projects came within 10% of the original deadline. Furthermore, Mckinsey Global Institute indicated that long projects usually take 20% longer to finalise than scheduled and are up to 80% over budget (Ellis, 2021).

The construction sector faces a more significant problem when seeking to industrialise the processes within it. Unlike the manufacturing industry, our product requires generating a unique and unrepeatable project; additionally, this process usually separates those involved within the two project creation phases, design vs construction. This situation occurs because clients mainly opt for the Design-Bid-Build contracting system, distancing designers from the constructor's contribution to the construction execution process (Anumba, Chimay J, Egbu, Charles O, Carrillo, 2005).

Issues like the collaboration between stakeholders, rework for inconsistent design options, unreal duration imposed by the clients, poor site management, weak planning, unpredicted site conditions are part of the problems that it can be found in our sector (Sepasgozar *et al.*, 2019), those issues can be separated by two main factors: Technical and Non-Technical.

One of the most common non-technical factors on the projects is that one person's critical decisions' power remains. In some cases, we face this type of action that can increase too much the project budget.*" I do not care what it cost, I do not care what scandal it causes, I do not care how long it takes, but that is what I want" – Jorn Utzon in the main discussion with Arup and Zunz. Related with the Sydney Opera House project that increased the cost in +14x of the initial budget* (Murray, 2003)

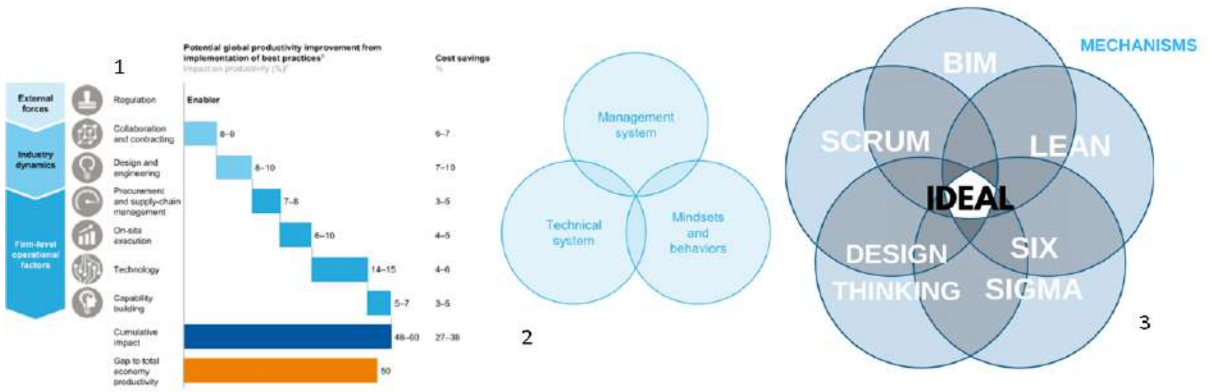
An example of a technical factor would be poor project planning and scheduling; usually, technical and non-technical factors are found in project development. This thesis develops these factors in more detail, focusing mainly on those solved using the Constructability technique. The reduction of risks and problems within the projects is related to the increase in productivity. The mechanisms proposed by various institutions to change the current construction situation are described below.

2.4. Proposal of mechanism for improving the productivity

McKinsey Global Institution and World Economic Forum agree that one of the main aspects of improving our sector's productivity is taking advantage of Industry 4.0 and integrating technology in construction. Some technologies and techniques proposed are (World Economic Forum, 2018):

- Prefabrication and Modularisation
- Advance building materials
- 3D printing and additive manufacturing
- Autonomous Construction
- Augmented reality and Virtualisation
- BIG data & Predictive analytics
- Wireless monitoring & connect equipment
- Cloud and real-time Collaboration
- 3D Scanning and Photogrammetry
- BIM is like an enabler of all these technologies.

Additionally, McKinsey proposes seven critical areas of improvement to increase the productivity shown in Figure 5 image 1, where if those are correctly implemented, the productivity gap between the construction industry and the entire economy could be closed by 2030, increasing the productivity until 60% (McKinsey Global Institute, 2017).



1,2 Adaptation of McKinsey Global Analysis 3 Proposal by the Author

Figure 5 Proposal of mechanism for improving the productivity (Seven areas of action, operating system, frameworks, and methodologies)

In Figure 5, image 2, the main problems are caused by these main aspects, and if they are handled correctly, they can offer a solution. How to take the example of the manufacturing sector and seek to create a production system, standardise processes and take advantage of the human capital and value it within the supply chain. This mindset is used within the Lean Production System.

Figure 5, image 3, shows the mechanisms that have enormous potential within our sector from the author's perspective, which could well be adopted in the future as a single integrated framework (Rodríguez Hernández, 2019). These methodologies and frameworks proposed by academia, researchers, government sectors, professionals, and entrepreneurs seek to correct the technological and productive recession that the construction sector has sought to reduce times and improve the precision of our projects and work execution.

Design Thinking is an agile framework that looks to improve the product, giving the Project Owner what he needs and wants, investing more time in visualising the problem and seeking multiple viable solutions for the product by participating in everything from moment to the Project Owner. As a result, it is intended to deliver the product without rework caused by a wrong concept of the client’s need (Friis Dam, Rikke, Siang, no date).

SCRUM focused on generating a virtuous circle from the beginning rather than extensive documentation that may be obsolete in the future. Therefore, the product is its primary focus. Furthermore, it involves the client actively in decision-making to avoid rework on the project due to an omission of Information (Ormeño, 2017).

Lean is a philosophy used in construction. Its primary function is to reduce waste and increase the product’s added value through continuous improvement. The Six Sigma methodology is more abstract and measurable.

The most extended and with more time in construction than the previous ones, BIM uses the collaboration and standards framework where interested parties are involved from the early stages of the project. Its primary focus is creating a digital model that serves as a database during the design, construction, and operation (Kensek, 2014a). It allows us to centralise the Information and make the process transparent for all those involved.

The similarity between them is that they use available technology to improve their workflow, collaboration, communication as a critical aspect of the project, and standards as communication support between stakeholders. Our thesis focuses mainly on BIM and Lean, which propose improvements to the constructability technique to improve creating projects.

3. CONSTRUCTABILITY

"Good buildings come from good people, and all problems are solved by good design."
— Stephen Gardiner

The process within the construction is a task that requires much knowledge to carry out a successful execution; now, we even have more challenging projects in our sector. With a complex process where the variables change for each new product, we find a possible risk caused by traditional contractual systems such as Design-Bid-Build that the client chooses. This Contractual System further separates the design and construction processes.

The design specialists, in most cases, focus more on aesthetics and does not think about the construction process, mainly because they do not have the guidance and support of the person in charge of the execution and construction, increasing the cost and deadlines being overrun (Griffith and Sidwell, 1995). This problem usually happens because designers lack construction knowledge and experience, forgetting constructability as an essential design consideration (Lam, Wong and Chan, 2006).

3.1. Defining Constructability

The concept of Constructability emerged in the late 1970s due to research into cost efficiency and quality in the construction industry (Griffith and Sidwell, 1995). Buildability defines a more specific concept but can be interchangeable for constructability in the U.K.

Buildability refers to which a building design facilitates construction's ease, focusing more on the design phase. At the same time, constructability embraces both design and management functions, dealing with the project management systems using the construction knowledge and experience to enhance project delivery efficiency (Alzayd, 2015).

Constructability is a project management technique that examines construction logic from beginning to end to identify obstacles, restrictions, and potential problems (Samimpey and Saghatforoush, 2020). This technique looks to increase the quality of built products and use the construction knowledge and experience in different project stages to achieve the overall project objectives (Lam, Wong and Chan, 2006).

Constructability musk seeks to alleviate the problems of separation and demarcation between the contractual parties and the process involved; the main goal is to incorporate information and skills of different parties involved in a project to reach a practical and efficient solution satisfying all project needs (Mohsenijam, Mahdavian and Shojaei, 2020).

Critical points are: rationalisation of the design, referring to the simplification of the process, seeking the repetition and modularisation of the design details, using the available construction technology, planning and programming the project considering that not only the ease of construction but also consider how this will affect the use or maintenance of the building in the future (Griffith and Sidwell, 1995).

Suppose the constructability is genuinely recognised, accurately understood, and consciously implemented. In that case, the project is empowering with standards and principles of design oriented to constructability, awareness, dialogue, interaction, teamwork, Knowledge-sharing, additional information development, feedback and create an environment of education to promote the constructability approach across the disciplines involved (Griffith and Sidwell, 1995).

As a result of these principles applied in the project, the following are obtained: decrease order changes, improvement construction quality, efficient work scheduling, promotion of construction safety and as a global result, reduction of the final cost of the project (Ugwu, Anumba and Thorpe, 2004). Studies in the USA show that the saving cost goes around 6 to 20% with the applicability of this technique (Chasey and Schexnayder, 2000; Nascimento *et al.*, 2017).

3.2. Constructability principles

Due to benefits proposed, countries such as: United States(USA), Australia, United Kingdom(U.K.), Malaysia, and China have invested and developed guides dedicated to establishing the principles of Constructability or Buildability (Nima *et al.*, 2001; Holoroyd M., 2003; Lam, Wong and Chan, 2006).

Singapore is even the pioneer country in qualifying using the Buildable Design Appraisal System (BDAS) to submit building plans and is mainly composed of three core principles: Standardisation, Simplicity, and Single Integrate Elements (Lam, Wong and Chan, 2006). The Construction Industry Research Information Association (CIRIA) in the U.K. established seven "Guidelines for Buildability", which were later expanded into 16 "Design Principles" for practical buildability were Adams (1989) added more detail and added the other principles (Holoroyd M., 2003; Mohsenijam, Mahdavian and Shojaei, 2020).

In Malaysia, Nima et al. (2002) reported 23 constructability concepts distributed on conceptual planning, 8 for consideration during the design, engineering, and procurement stages, and eight concepts for review during field operations (Mohsenijam, Mahdavian and Shojaei, 2020).

The Construction Industry Institute in the USA(CII) subdivides the improvement process into four phases: Conceptual Planning, Design and Procurement, and Operations. Finally, after three significant studies (CII 1986[a]; 1986B; 1988) and after improvements, CII (1992) take into count 17 constructability concepts (Gambatese, 2007).

Likewise, CII in Australia (CIIA), within them principles' proposal, was found (Griffith and Sidwell, 1995):

- Integration of constructability in the project plan.
- Use of construction knowledge and team skills appropriate for the project
- Establishment of corporate objectives to involve and commit to carrying out
- Use technology, resources, and available skills

- Control external factors with Risk Management.
- Create realistic and construction sensitive programs.
- Considerate in the construction methodology and accessibility in the different stages.
- Integrate innovation within the construction processes and document the successes and failures to have them as a reference in future projects.

Finally, Arash Mohsenijam, Amirsaman M, and Alireza S. made a compilation of 40 principles which we will take as the primary basis, as it is the union of all the proposals made divided into three tables.

Table 1 Adaptation of Constructability Principles for Conceptual Planning Phase by (Mohsenijam, Mahdavian and Shojaei, 2020)

Concept #	Concept Stage	Concept Stage #	Brief
1	C1	C1-1	Constructability programs are made an integral part of project execution plans through the participation of all project team members.
2	C1	C1-2	A project team with representatives of the owner, engineer, and contractor formulated & maintained to consider constructability issues in all phases.
3	C1	C1-3	Project planning actively involves construction knowledge and experience to avoid interference between design and construction.
4	C1	C1-4	Early construction involvement is considered in the development of contracting strategies.
5	C1	C1-5	Project schedules are construction-sensitive and assigned as early as possible.
6	C1	C1-6	Basic design approaches consider effective construction methods.
7	C1	C1-7	Site layouts promote efficient construction, operation and maintenance.
8	C1	C1-8	Advance information technologies are applied throughout the project.
9	C1	C1-9	Primary construction methods should be analyzed in-depth as early as possible. to accomplish the field operations quickly and efficiently
10	C1	C1-10	Operability and maintainability phases are integrated into project planning and design stages.
11	C1	C1-11	Political and legal factors are reviewed before the design stage.
12	C1	C1-12	Environmental factors are reviewed and addressed.
13	C1	C1-13	Construction methods are comprehensively reviewed to include the recovery and recycling methods and sustainable and final disposal planning.
14	C1	C1-14	Simplify and separate building systems and components to facilitate maintenance and future renovations

Table 2 Adaptation of Constructability Principles for Desing and Procurement by (Mohsenijam, Mahdavian and Shojaei, 2020)

Concept #	Concept Stage	Concept Stage #	Brief
15	C2	C2-1	Design and procurement schedules are construction sensitive and considered in project sequencing
16	C2	C2-2	The project technical specifications are simplified and configured to achieve efficient construction without sacrificing the project performance level or efficiency.
17	C2	C2-3	Design simplification by designers and design review by qualified construction personnel must be configured to enable efficient construction.
18	C2	C2-4	Design elements are standardized.
19	C2	C2-5	Construction efficiency is considered in specification development.
20	C2	C2-6	Module/preassembly designs are prepared to facilitate fabrication, transportation, and installation.
21	C2	C2-7	Designs considering construction accessibility of personnel, material, & equipment.
22	C2	C2-8	Designs facilitate construction under adverse weather conditions and consider an increase of prefabricated elements.
23	C2	C2-9	Design & construction sequencing must facilitate system turnover & start-up.
24	C2	C2-10	Safety and health reviews are considered comprehensively within the design specifications.
25	C2	C2-11	Project design considers the operability and maintainability of the project.
26	C2	C2-12	Standardize repeatable components.
27	C2	C2-13	Ensure proper sizing and specification of equipment, products, and materials
28	C2	C2-14	Optimize dimensions to utilize the entire product/material.
29	C2	C2-15	Use methods and materials that allow for ease of reconfiguration, renovation, or deconstruction.
30	C2	C2-16	Designs are reviewed by construction personnel regarding minimizing material waste, recycling, and cost-effectiveness.

Table 3 Adaptation of Constructability Principles for Field Operation by (Mohsenijam, Mahdavian and Shojaei, 2020)

Concept #	Concept Stage	Concept Stage #	Brief
31	C3	C3-1	Constructability will be enhanced using innovative construction methods.
32	C3	C3-2	Tasks Sequencing is configured to minimize rework of project elements, scaffolding needs, the formwork used, or congestion of labours & materials
33	C3	C3-3	Innovation in temporary construction materials/systems that the design drawings and technical specifications have not defined.
34	C3	C3-4	Innovative methods for using the available equipment or modification of the available equipment to increase their productivity.
35	C3	C3-5	Innovative methods for using the available equipment or modification of the available equipment to increase their productivity.
36	C3	C3-6	Use preassembly to increase productivity, reduce the need for scaffolding, or improve the project constructability under adverse weather conditions.
37	C3	C3-7	Evaluation, documentation, and feedback on the issues of the constructability concepts should be maintained throughout the proj ect and as lessons learned.
38	C3	C3-8	Reduce packaging and mobilizing waste.
39	C3	C3-9	Document prefabricated and modularized components for reuse.
40	C3	C3-10	As-built documentation to facilitate any required reconfiguration or renovation.

In the last part of the paper, “Contribution of designers to improving buildability and constructability”, the authors developed a breakdown structure of buildability attributes (Lam, Wong and Chan, 2006). Within the annexe are the 66 points divided into Site, Underground, Weather, Coordination and Rationalisation of Design Information, Detailing, Flexibility, Safety, Use of Resources, Material Systems, Installations, Standardization and Prefabrication. Our case study took the points with the most impact to seek to implement them in it.

Finally, those concepts can be divided into different ways to phase constructability. Programmatic constructability focuses on whether the project scope reaches to improve the desired time frame and focuses on the early phases of the project development. On the other side, Technical Constructability addresses the technical details of the project: methods, techniques, sequences, and procedures by which the project can be built (Transportation Building, 1999).

The case study focuses on programmatic constructability using generative design to improve the design rationalization.

3.3. Constructability Issues and Review process

Constructability looks to ensure the project is buildable, cost-effective, biddable, and maintainable. For the practice in the project, constructability reviews are necessary. A constructability review is a systematic process to ensure that the project possesses the preceding attributes of constructability. This process is integrated around all the project stages, and the combination of those comprise the constructability review process (Transportation Building, 1999).

Washington Department of Transportation developed a manual for implementing the constructability review process, explaining how to set the Constructability review for each project stage. One of the common elements that have proved to be more successful for the proper implementation are:

- A constructability Champion to oversee its implementation.
- A multidisciplinary team composed of Construction professionals, internal construction staff, Constructability Consultants, Regulatory representatives, Utility representatives, Material suppliers and maintenance representatives.
- Frequency reviews are performed at different stages of project development.
- Focus on the significant issues involved in the project and correctly use the following resources: workforce, funding, and time.
- A structured review process controls the type and length of review meetings, checklist, responsibilities, and dissemination of review comments like lessons learned for future reference.
- Tracking and measuring the results and benefits from constructability review.
- Post constructability reviews to eliminate repeated mistakes and reuse the knowledge gain in previous projects.

Furthermore, during its implementation program, Construction Industry Institute (CII USA) identified seven critical components for adopting the constructability technique, resulting in the following. (Griffith and Sidwell, 1995):

- Self-assessment to identify the achievement of the organisation in constructability.
- The development of a written policy towards constructability.
- Assign an executive sponsor to lead the implementation of constructability in the company.
- Commitment to the adoption of constructability in the organisation.
- Develop concept procedures and how to implement constructability.
- Improvement continuous evaluating the actions carried out in the projects and documenting them in good practices.
- Generation of a database with constructability information in previous projects to save it as a reference in new projects.

As an additional point, and because the most significant barrier to implementation is Change Management, the CII (USA) developed the “Starter Kit Implementation” as a guide to implementing this technique in public and private sectors (Construction Industry Institute, 2021). Being aware that each process change within the organisation requires new responsibilities for stakeholders and prerequisites that must be covered, Rozita Samimpey and Ehnsan collected the Information. They compressed the prerequisites for implementing constructability in Table 4; such is shown below.

Later chapters show the relationship in which the problems can be mitigated with tools and workflows that enable Lean / BIM and align with the constructability technique.

3.4. Constructability Implementation Barriers

Each workflow change entails implementation barriers, and constructability is one of them. The success or failure of the implementation will depend on mitigating the risks within the implementation. Constructability is only done by identifying the barriers and looking for mechanisms of control.

The barriers are divided into corporate and project levels; according to O'Connor and Miller (1995), the control is divided into three phases: identification, mitigation and review (Gambatese, 2007).

The most prominent barriers are (Griffith and Sidwell, 1995; Holoroyd M., 2003): due to the resistance of the client, the lack of knowledge about the benefits and the use of traditional contracting systems that fragment the design, professionals not used to collaborating in early stages, inadequate management of priorities in the project, lack of incentives and training, finally and related to the previous point, the shortage of qualified personnel oriented to constructability.

Table 4 Prerequisites code adapted from (Samimpey and Saghatforoush, 2020)

Factors	**Constructability prerequisites codes**
Managerial	(1) Increasing communications, integration, coordination, and mutual respect among all project stakeholders
	(2) Sharing and exchanging Information through a database, documenting previous projects and lessons learned, and fast and easy access to them by all of the team members
	(3) Creating a strong support program and its development
	(4) Existence of correct planning to achieve project objectives
	(5) Using development tools and equipment
	(6) Knowledge of project stakeholders about constructability and its advantage
	(7) Enhancing team-building skills
	(8) Increasing integration among all project stakeholders
	(9) Using new methods of information and communication technology
	(10) Preferring new contracts to traditional ones
	(11) Allocating cost for constructability training and implementation
	(12) Commitment and participation of employers and understanding their needs
Technical	(13) Familiarity with and using new and creative methods of construction and new technologies
	(14) Using experts experienced in the field of designing
	(15) Integrating knowledge and experience of all team members
	(16) Identifying, visualising, and reviewing the project environment before construction
	(17) Reviewing plans and presenting feedback to designers
	(18) Participation and presence of contractors in the initial stages of the project to transfer construction knowledge and experience
	(19) Using computer models for better identification of project situation
	(20) Using related checklists
Environmental	(21) Paying attention to design and construction standards
	(22) Considering environmental factors (technology, economic, and social, …)

4. LEAN AND BIM

***"If you are not willing to risk the usual, you will have to settle for the ordinary." —* Jim Rohn**

These two mechanisms are currently changing how projects are developed and have proven to be much more efficient than traditional methods. It will address the basic concepts summarised and how they integrate constructability into their improvement process.

4.1. Lean brief

Lean Production System (LPS) is a production philosophy that originated in the automobile industry, which is now replicated in sectors, such as consumer products, I.T., metal processing, aerospace, healthcare, and construction, named Lean Construction. This philosophy approach encompasses many different practices to eliminate the construction process that is understood as resources or tasks that do not add value, such as inventories and transportation. Lean is based on four main pillars philosophy (Long-Term Thinking), Process (Eliminate Waste), People & Partners (Respect, Challenge & Grow) and Problem Solving (Continuous improvement and learning). In addition, LPS identifies eight primary wastes that should seek to reduce within our processes to be more productive. Table 5 are from "The Toyota Way", which summarises those critical aspects of this philosophy.

Table 5 Lean Fourteen principles adapted from (Liker, 2021)

#	Principles of Lean	Identification of Waste
1	Base management decisions on a long-term philosophy, even at the expense of short-term financial goals.	Defects
2	Create continuous process flow to bring problems to the surface.	Overproduction
3	Use "Pull" system to avoid overproduction.	Waiting
4	Level out the workload (Work like tortoise, not the hare).	Non-Utilized Talent
5	Build a culture of stopping to fix problems, get the right quality the first time.	Transportation
6	Standardize task as foundation for continuous improvement & empowerment	Inventory

7	Use visual control so problems are not hidden	Motion
8	Use reliable, tested technology that serves your people & processes	Extra Processing
9	Grow leaders who understand work, live philosophy & teach others	
10	Develop exceptional people & teams who follow your philosophy	
11	Respect your extended network of partners by challenging them & helping improve	
12	Go & see to understand the situation thoroughly	
13	Make decisions slowly by consensus, considering all options, implement rapidly	
14	Become a learning organization through relentless reflection & continuous improvement	

As support, Lean use several instruments to reaching continuous improvement; the most important are: Multifunctional task group, simultaneous engineering, Kaizen, Just-in-time-deliveries, Co-makership, Customer orientation, Information, Communication and Process Structure (Alarcón, 2013). Those instruments have operating methods divided into production, design development, information manager, scope, and cost. However, as it is a philosophy where its fundamental pillar is people, it also has organisational methods divided into team-organisation, problem-solving, decision-making, and continuous improvements (Bhawani, 2019). All those are grouped in Table 6.

Table 6 Methods in Lean Construction, adapted to (Bhawani, 2019)

	Production	**Design Development**	**Scope & Cost**	**Information Manager**
Operating System Methods	Last Planner System	Set-based Design	Target Value Design	Big Room Planning
	SISP/Takt Planning	Agile Planning	Design Structure Matrix	Visual Management
	Modularisation	Value Stream Mapping	Conditions of Satisfaction	BIM Execution Plan

	Additional Techniques used in Lean Implementation			
	First Run Studies	Poke-Yoke	5-S (Sort, Set, Shine, Standardise, Sustain)	3P (Production-Preparation-Process)
Organisation Methods	**Team Organization**	**Problem-Solving**	**Decision-Making**	**Continuous Improvement**
	Onboarding	A3 thinking (PDCA) (Plan-Do-Check-Adjust)	Choosing by Advantages	Quality Circles
	Work Cluster			
	Additional Techniques used in Lean Implementation			
		5 WHY Analysis	PICK Chart	Spaghetti Diagramming
		Ohno Circles		Gemba Walk

According to those interviewed in the Lean survey for McGraw Hill Construction (2010), lack of knowledge and lack of understanding of the industry is the main barrier to implementation; it is a philosophy that requires a change of mindset for monitoring maintenance so that improvement actions are not truncated within the company.

Among the most relevant benefits that Lean practitioners have found are: Cost reduction, increased productivity, improved construction quality, improved Risk Management and improved safety (McGraw Hill Construction, 2010)

4.2. BIM brief

BIM is in a moment of traction where several countries are seeking to obtain the benefits of integrating them in public tenders; a case of success is the U.K., where 60% of the public sector and 70% times within the private sector is requested by the clients(McGraw Hill Construction, 2014). In addition, countries like USA, Australia, China, France, Germany, Hong Kong, New Zealand, and many more have decided to create guidelines and protocols to help improve BIM adoption within their countries (Hore, McAuley and West, 2017).

Since its inception, the acronym BIM has had different definitions because it can well be categorised into various activities, the best known are as a **product**, as a technological enabler, as an open standard database, as a collaborative process and as a **requirement to manage any infrastructure** (Keyes, Swartz and Loehr, 2015). BIM as an interdisciplinary collaborative methodology combines tools, processes, and digital technologies, allowing us to generate information and documentation on the project throughout its life cycle (Rodríguez Hernández, 2019).

On the other hand, there is a product definition which is the result of our research. In this case, Building Information Model (BIM) is defined as the digital representation of the physical and functional characteristics of infrastructure, creating a knowledge resource shared to obtain information about it and forming a reliable database for decisions during its life cycle, from the first conception to demolition. This will be the meaning to which this document will refer whenever discussing BIM as a product (Chuck EastMan, Paul Teicholz, Rafael Sacks, 2008).

According to Jason & Umit, this digital model must have the following characteristics: It must contain compressive data and rich information within it, it must be oriented to natural objects in the construction, it must be a three-dimensional model with established spatial relationships and rich in semantics, and finally, this model must generate support views for construction documents (Underwood, Jason, Isikdag, 2010).

This methodology was born in the ’70s as a Building Description System; initially, it focused on using libraries as a database within a model (Eastman *et al.*, 1974). So on many occasions, BIM is often confused with the use of 3D models only; even in American documents, they usually treat it this way (AIA, 2007).

Because in USA, from the beginning, the meaning of BIM associated with software prevailed, it has been challenging to switch the paradigm to the industry entirely. That is why now at this time, especially in the United States of America, they are changing and adopting an improvement of the framework called Virtual Design Construction that seeks to erase those errors of the past where it focused on the use of software as the main objective of BIM (Khanzode *et al.*, 2006).

One of the fundamental aspects of BIM is the definition of processes, this being the main point to have the same communication language and avoid ambiguities. Therefore, this methodology has created multiple workflow standards such as the ISO 19650 series dedicated to managing Information throughout the life cycle (International Organization for Standardization, 2012, 2018; UK BIM Framework, 2020), contractual documents such as the BIM Execution Plan (BEP)(Computer Integrated Construction Research Program, 2011), Exchange Information Requirement(EIR) and its derivatives (AIR, OIR) (April, 2015; International Organization for Standardization, 2018).

In addition, modelling standards such as those exposed by BIM Forum Level of Development Specification (LOD)(BIM Modelling)(Bedrick *et al.*, 2020) and Level of Acceptance Specification for BIM Reality Capture Simulation(LoA) (Ikerd *et al.*, 2020), Information Exchange standards such as Industry Foundation Classes(IFC) (*IFC Overview summary — Welcome to buildingSMART-Tech.org*, no date), Construction Operations Building Information Exchange(Cobie). Have also been developed, BIM Collaboration Format(BCF)(*BCF 2.0 BIM Collaboration Format*, 2013) and finally, digital models can separate their constructive elements with established classification systems such as

Uniformat, MasterFormat, OmniClass, Uniclass, among others (BuildLACCD, 2010; Kassem *et al.*, 2015; OCCS Development Committee Secretariat, 2017).

In addition, BIM is a technological enabler that helps to improve the design, construction, and maintenance processes; this technology must be used through well-defined processes for it to be functional, without forgetting that people are the ones who will use this (Succar, 2009; McKinsey Productivity Sciences Center, 2018). Therefore, the correct use will fall mainly on the social factor for the collaborative process of utmost importance in this methodology. So, making a summary, its main pillars are more complex since they are composed of very different elements: processes, actors, and technology.

4.3. The connection between Lean | BIM and Constructability

As previously discussed, these two ideologies have similarities and seek the same objective, "to be a more productive industry", improving efficiency, quality, cost, and time tracking within the project. When BIM is adopted adequately from the early stages, this can eliminate wastes exposed by the Lean philosophy, including waiting time, over-processing, overproduction, wasted for defect (rework) using a centralised Common Data Environment (CDE) and a BIM model. Related to the overproduction, transportation waste, and inventory waste, the 4D(Scheduling) and 5D(Cost Estimation) BIM models help reduce them (Ningappa, 2011; Sampaio, 2018).

The creation of the BIM model within the early phase helps to conceptualise how it will be built using the virtual information model, so the constructability issue is associated with BIM. The clash detection process in the design phase plays a crucial role within the constructability review; this allows making better decisions and requesting changes from designers at an early stage when part of their design interferes with one or more disciplines (Seo *et al.*, 2012). In some BIM guides and BEPs, constructability is one of the points to review within the BIM model (Computer Integrated Construction Research Program, 2011; Kensek, 2014). Regarding Lean activities such as collaboration and constructability, they are considered partial parts of the implementation of the Last Planner System, this being a controlled workflow, which coordinates the planning of design, supply, and installation throughout the production of the project (Alarcón, 2013; Spitler, 2014). The interaction between the BIM and Lean tools as implementation support is shown in Annex II obtained from the author Olfa Hamdi(Hamdi and Leite, 2012).

One of the main areas where Lean | BIM and constructability converge is when the 4D use is established. 4D BIM models can be used for multiple services such as phase planning, site utilisation planning, cost estimation, safety management, site layout, clash detection over time, activity monitoring and constructability management over time. This is because the 4D visualisation of construction schedules reduces the abstraction of the activity, allowing it to visually represent the overall view of the construction process and critical activities on the site (Boton, 2018). In addition, it shows some of the benefits that the visual communication Lean tool and 4D models can bring to the project (Spitler, 2014).

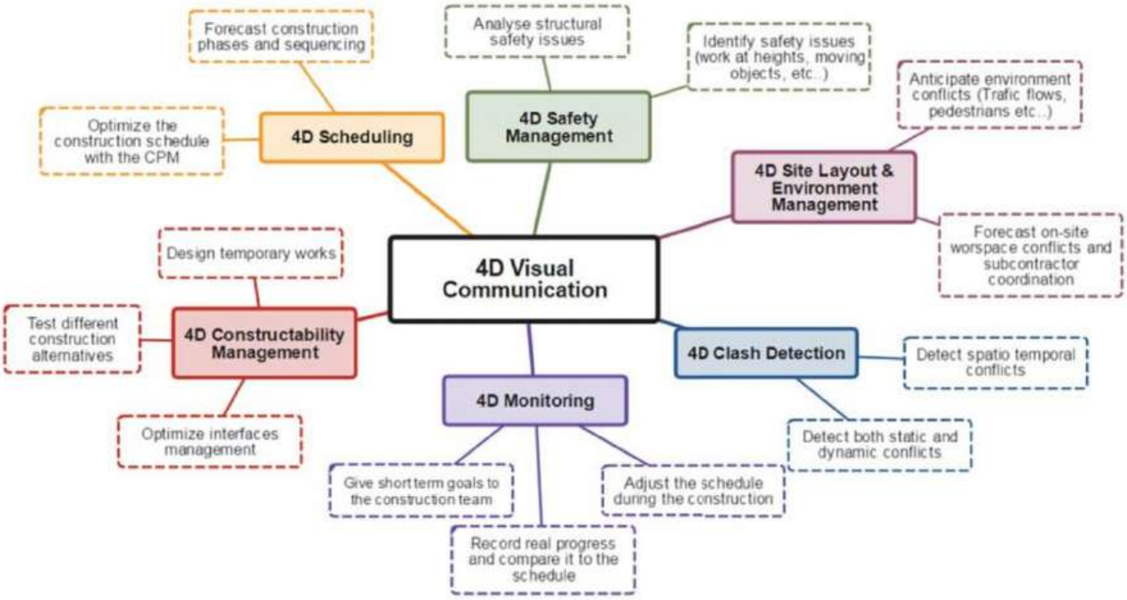


Figure 6 Integration of Visual Communication and 4D models from (Spitler, 2014)

Finally, within the contractual systems in which the Lean philosophy and BIM models are required is the Integrated Project Delivery (IPD). IPD is a project delivery approach that integrates people, systems, business structures, and practices into a collaborative process, harness the talents and insights of all participants to optimise project results, increase value to the owner, reduce waste through the project phases (AIA, 2007). The following chapters will address how these tools help mitigate the most common technical problems in construction.

5. NON-TECHNICAL CONSTRUCTION PROBLEMS

“Change almost never fails because it is too early. It almost always fails because it is too late.”
— Seth Godin

In construction, we found social, political, economic, environmental, technical, and technological problems. Non-technical factors greatly influence the success or failure of a project. Those that cannot be controlled are discarded during this chapter.

5.1. Description of non-technical construction problems

Based on the definition obtained by the Cambridge Dictionary, a problem is “something that causes difficulty or that is hard to deal with”, and “Technical refers to “involving or needing special skills or knowledge, esp. in science or engineering “. Therefore, it is recognized that a non-technical problem does not apply special knowledge or skill and is still difficult to handle, causing a delay or failure in the activity.

Within buildability, non-technical factors are defined by management systems, personalities and others (Griffith and Sidwell, 1995). In the management systems, the problems found to consist of a late involvement of the members, that communication fails during the project, which causes the team not to identify the direction in which it should go; finally, the ignorance of the flow used. In personalities, the problems found are related to lack of knowledge of capacities and experience of the personnel, attitudes about assigned activities and compatibility of people in a team. While in others, waiting times are defined as a problem due to a bad relationship with providers and site restrictions (Dastbaz, Gorse and Moncaster, 2017).

Additionally, in his paper, Pradeep defines non-technical issues that decrease the quality of a project as a lack of awareness of various activities and human behavioural issues (Pradeep and Preeja, 2018).

5.2. Proposal for mitigating non-technical construction problems

For decades they have sought to mitigate these problems using different mechanisms; some have been implemented in Lean and BIM. Regarding the central issue of communication and late involvement, BIM proposes an improvement as it is a methodology based on collaboration and early involvement of stakeholders. BIM suggest a change of workload and involvement represented on the MacLeamy chart in Figure 7. This curve represents how the IPD contractual system, which involves Lean and BIM tools, reduces the extra costs associated with the previously mentioned problems. (Wang, 2014).

IPD is a structured, trust-based collaboration that encourages parties to focus on project results rather than their individual goals. So it is because it is based on the value-added by an organization and rewards "best for the project" behaviour, such as providing incentives linked to project objectives. (AIA, 2007).

The tools that enable collaboration in real-time are collaborative digital models, a Common Data Environment that is a centralized place to work with a defined standard based on project phases and divisions by disciplines (International Organization for Standardization, 2018). Additionally, the BIM Execution Plan defines the roles and responsibilities of the project members, allowing everyone involved to collaborate to define the goals to be achieved in the project and when they should be met. (Penn State CIC Research Team, 2010).

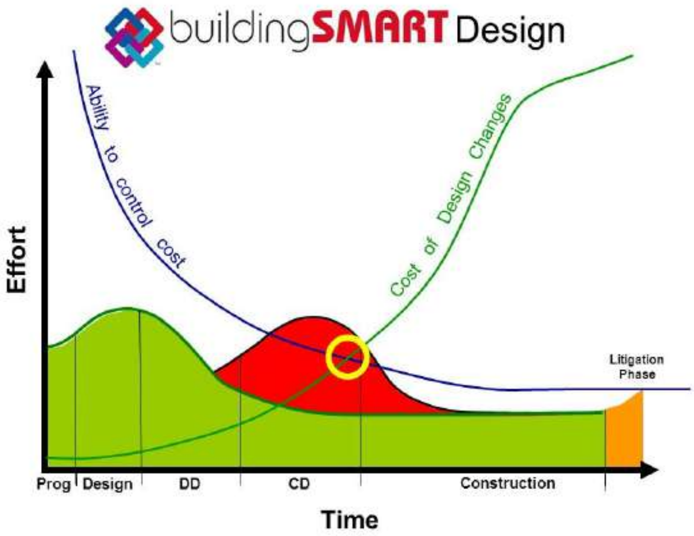


Figure 7 MacLeamy Curve obtain from BuildingSMART

On the other hand, Lean helps clarify and understand the project through its Last Planner System. This seeks to reduce project noise by focusing on "what should be done" - "what can be done" - "what will be done" - "what was actually done". In addition, this planning system adds a production control component based on team collaboration and commitment (Pons Achell, 2014). The Last Planner System is created collaboratively. The main actors are involved in a session known as the BIG Room (Dave, Koskela and Kiviniemi, Arto, Tzortzopoulos, Patricia, Owen, 2013). The master plan is defined where milestones are marked.

Then in the Lookahead Planning, the selection, sequencing, and size of the work that can be done are made. Here determines how far in advance of the scheduled start date the activities are considered in the master schedule to enter the anticipation. They are governed by a detailed master schedule of activities to be carried out (Explosion), a follow-up of the activity (Projection) and the actions necessary to remove the restrictions so that the Job Done (Make ready) (Messner, Leiht and Bhawani, 2019).

Finally, in Weekly Work Planning, a record is kept of the number of activities completed, and the percentage of the plan carried out, making a more detailed subdivision to clarify the scope of the team involved. Here the production units commit to select the activities that SHOULD be carried out to complete the project and decide for a given framework what WILL be done—recognizing that due to resource limitations, some activities CAN not be done according to the master plan. This planning methodology uses other Lean tools during its process, such as PDCA, Kanban and 5 Why? (LCI, 2007), Figure 8 summarizes how the Last Planner System is subdivided during its planning and project execution process.

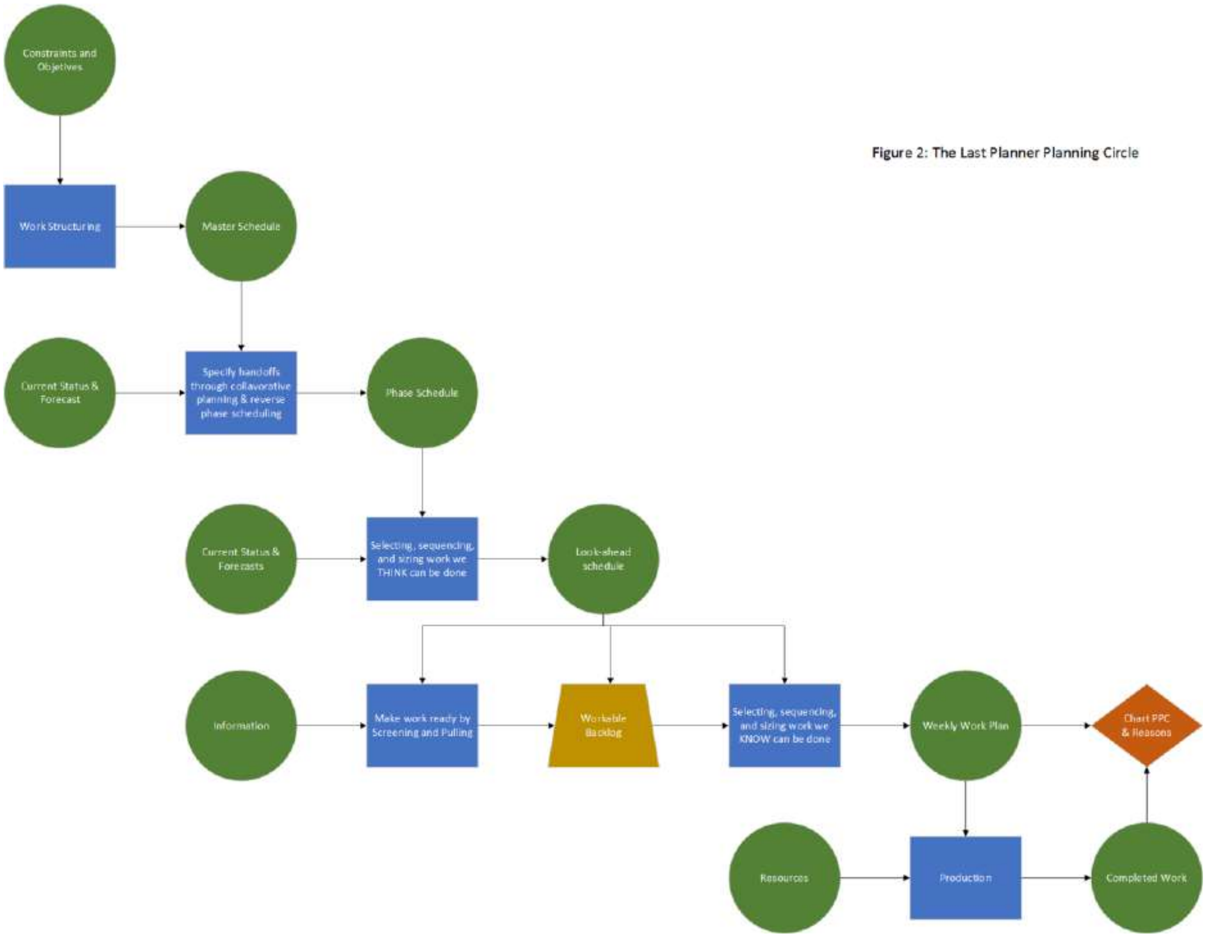


Figure 8 Last Planner Planning Circle adapted from (LCI, 2007)

One software that correctly implements Last Planner System to work in BIM models is BEXEL. This software allows the creation of detail 4D task reports, schedule comparison, plan vs actual analysis, Look a Head analysis, resourcing monitoring and KPI tracking. Therefore, BEXEL allows the automation of certain implicit activities within the Last Planer System methodology.

Finally, concerning personalities, the Lean philosophy promotes a culture that thinks in the long term, so human relationships play an essential pillar within this. This action is reflected in these principles (Liker, 2021):

- Two, "Connect people and process through continuous process flow to bring problems to the surface".
- Six "Build a culture of stopping to identify out-of-Standard conditions and build quality".
- Eight "Adopt and adopt technology that supports your people and processes".
- Nine, ten, and eleven principles are focus on people: "Respect, Challenge, and Grow your people and partners toward a vision of excellence".
- Thirteen "Improving the energy of your people through aligned goals at all levels".

Its entire philosophy is based on improving relationships with the people involved to identify with the company and bring the best of them; having aligned goals reduces internal conflict between what the employee wants vs what they are doing within the organization. Figure 9 shows how this philosophy is divided into a 4P model where one of the fundamental pillars of the Toyota Production System, creator of lean, is focused exclusively on people.

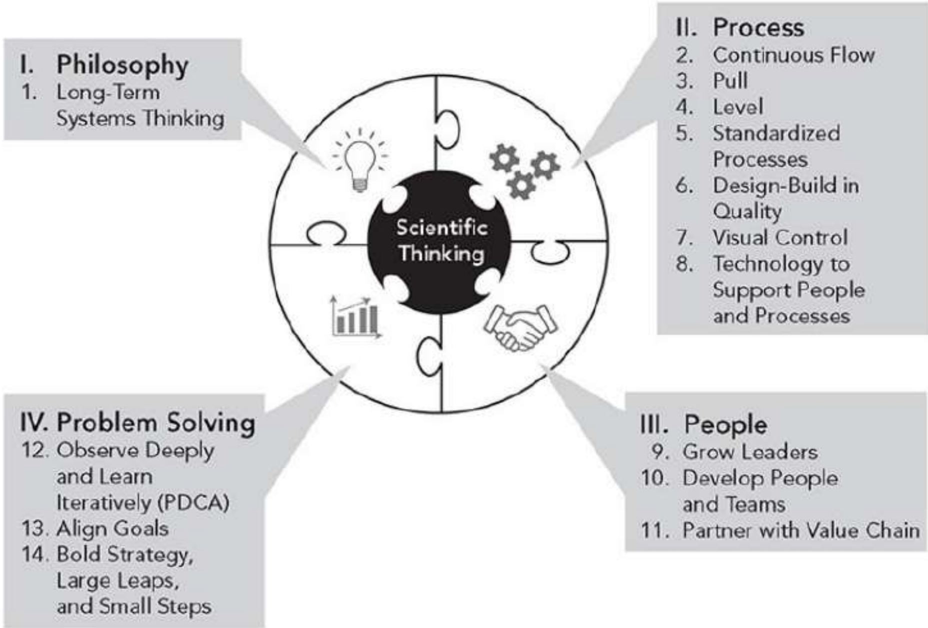


Figure 9 4P model of Toyota way from (Liker, 2021)

5.3. Conclusions of non-technical construction problems

In conclusion, existing mechanisms to mitigate non-technical problems exposed; in the industry, its adoption has been incipient in most cases. However, these proposals can reduce delays and cost overruns associated with management and people behaviour problems.

Furthermore, BIM offers a standardized framework to reduce the language barrier between those involved since its main factor is structuring information through all the standards based on industry good practices, making collaboration have a clear and specific language, thus reducing misinterpretation.

Finally, Lean is a philosophy that focuses mainly on people and identifies that for a company to be successful, it must nurture its employees through a long-term philosophy aligned with the employees' objectives. In addition, this philosophy seeks to improve its processes through the trust and collaboration of those involved, a differentiating factor among other more analytical workflows.

6. TECHNICAL CONSTRUCTION PROBLEMS

"Insanity is doing the same thing over and over again and expecting different results."
— Albert Einstein

As seen in chapter 5, this document identifies technical problems as those that refer to "involving or needing special skills or knowledge, esp. in science or engineering". Although the construction industry has multiple areas for improvement, it was decided to focus on a problem that seeks to be solved through Buildability and available technology. Therefore, this chapter will address a specific technical problem, "Design Rationalization," (Griffith and Sidwell, 1995), to which the case study applies practically.

These problems are more direct of the solution because they can be solved using technical forms or tools. While these tools continue to function through user and implementation, technical issues can be easily identified and mitigated.

6.1. Description of problems in Design Rationalization

Design can be understood as the rationalization of decisions that are guided to solve a problem. The rationalization of the design involves modularization, repetition, and simplification. Additionally, the design should be thought of for the construction from the beginning. A good rationalization of the design allows minimizing construction task interdependencies.

Within the simplification, an iterative process is required to find the minimum number of components, elements, parts to assemble, activities that traditionally require time, and a designer with several years of experience in the system to be built. (Khan, 2019).

A clear example of a lack of rationalization at the beginning of conception is the Sydney Opera House; the design was not easy to construct and had an "inappropriate" notion of structural honesty; for this reason, it had a 1400% cost overrun (Murray, 2003; Fischer, 2012). Furthermore, the design is complex, and projects always have different aspects; compromises and strategies must be sought to be economically viable. In addition to this, the traditional method of rationalization can become very abstract since having only two-dimensional views creates a bias in how one system can affect another.

Parametric models play an essential role in the quest for rationalization as they allow us to generate dynamic geometry and numerical relationships, offering us the opportunity to observe multiple scenarios. In addition, technology now allows us to create mathematical logic models on geometric operations and create generative designs. The main objective is to reduce the time in geometric, spatial, and mathematical operations.

Technological evolution has allowed us that through procedural modelling and parameterization, be able to make digital replicas of the project, allowing multiple iterations within a computer. Therefore, BIM proposes the use of three-dimensional models to reduce geometric abstraction.

6.2. Examples in the market that help reduce time in Rationalization

The issue of digitization in design and construction processes is raised to improve productivity, reduce project delays, improve safety, and enhance the quality of the projects. For this reason, in June 2018, the European Construction Industry Federation (FIEC) created a manifesto to accelerate and lead digital transformation in construction (European Construction Sector Observatory, 2021).

Aware that digitization is an essential pillar in improving construction, development companies have opened possibilities to reduce the time to create design proposals and even rationalize the construction process. Therefore, there is now an offer of platforms, software and plug-ins that use Artificial Intelligence (AI) to carry out parametric and generative design procedures; some examples are shown in Figure 10.

Figure 10 Overview of solution that tries to reduce time in the process design using AI

One example is Test Fit, a company that develops algorithms dedicated to producing buildings in seconds, not weeks, as their website says. Their case study explains how they helped Novin Development Corp choose the best site for its development, setting goals to compete with each other, such as proximity to pharmacies, schools, senior centres, high-quality traffic and pedestrian accessibility, and community (TestFit, 2020).

Schnakel Engineers uses AI to generate the best design solution accurately and quickly on the MEP side. In a study with DominaLaw, their solution saved 15% from an office building design improvement (Schnackel, 2020).

In addition to simplifying the construction process, Alice Technologies uses AI to create construction schedules that reduce project risk and cost by creating and exploring multiple scenarios. For example, the case study with Ananda Development reduced 32% in the Elio del Nest project (Alice Technologies, 2019).

Then we have BEXEL Manager, established software and winner of the buildingSMART International Innovation Award 2020 (BEXEL Manager, 2020; buildingSMART, 2020). BEXEL has several case studies that demonstrate the value of the intelligent programming methodology powered by BIM models. As evidence, there was a 40% reduction in the quantities of concrete in the Punta Cana Hotels and resort project in the Dominican Republic (BEXEL Consulting, 2018). This was made possible through an extensive review with tools that allow obtaining a reference schedule intelligently linked with elements of the BIM model and built-in price and cost information that helps 4D / 5D simulations.

Finally, Autodesk company is developing a wide range of solutions to improve and optimize design processes. Among these Space Maker, is proclaimed as a platform that allows to analyse, simulate and visualize design alternatives in residential development (Stockholm, 2020). Then within the Civil 3D software, the Grading Optimization tool allows optimizing processes in site grading in zones, building pads, drain lines, sidewalk, and transition zones (Autodesk, 2020). In addition, within the BIM Revit software, a generative design engine is integrated. The success story with Autodesk's Generative Design was the design of Toronto's MaRS Discovery District innovation hub with about 60,000 square feet. It was sought to optimize the design considering the users and their requirements for accessibility and comfort, among others (Gerfen, 2018).

6.3. Rationalization Problems Conclusions

The rationalization process requires extensive knowledge of the subject and considerable time within the design. Therefore, technology adoption within these processes helps reduce human error in complex operations where the computer has a more significant advantage and speed. Thus, the proposed solutions work as a complement and tool for the designer, not replacing his experience and creativity.

Each tool helps reduce time in a specific task and field, so it will be up to the designer to make the right choice for the design rationalization phase. For this reason, it has been decided to focus on generative design engines for the case study proposed in this document.

7. PROCEDURAL MODELLING & PARAMETRIZATION

"You are an idiot if you are not using the best tool possible" — Manfred Fisher

The market always seeks to have more profits from its activities, so evolve, reducing operating costs. More than 50 years ago, the search for process automation began to develop; in the design area through procedural modelling.

Procedural modelling is a process that explicitly uses instructions to produce a model output; within our field, it is expressed as the design of geometry expressed descriptively, mainly through a digital medium. The first development of the applied use of procedural modelling was with Ivan Sutherland and his Sketchpad application in the 1950s. (Cadazz, 2003).

7.1. Computational Design

Procedural modelling is found within Computation Design. Computation is the expression of a computer system that reports through transformation, modification, or the ordering of observed physical or symbolic entities. In this way, a computational design must be seen as a producer of information in composition, going beyond translational representation through a transformation process (Menges, Achim, Ahlquist, 2011). The nature of computational design rests at a particular confluence of domains ranging from philosophy, biology, mathematics, and computer sciences.

The skills of a computational designer are not traditionally part of the discipline's repertoire, as it requires additional knowledge in scripting and programming. However, a critical aspect of this discipline is developing critical thinking, seeing the problem as a set of variables and unknowns that algorithms can solve. An algorithm is a set of rules and instructions in a step-by-step procedure to calculate. For example, in Figure 11, a graphical algorithm of how to make tea is represented.

Figure 11 A cup of tea making algorithm by (Khabazi, 2012)

The computational design within architecture and engineering allows us to explore design variations, defined by fixed and variable parameters, thus creating parametric models. Although this workflow has existed for years, it has recently increased its use exponentially, mainly because computing functionalities have increased, and the democratization of technology has allowed costs to be reduced.

When approaching a design computationally, the computer does the iteration process through options and data. Therefore, the designer would develop the procedure that would create a design, not the design itself. This action allows us to invest more time in the design process than activities that do not add value to the project, thus saving time, money, and effort.

7.1.1. Parametric Design

Parametric is the term used to describe those techniques that define procedural modelling deployments; these can be applied throughout the design, only the elements that change or the tooling of the modelling. Suppose we translate the definition of the parametric equation to a parametric model; in that case, it is defined by a set of equations represented geometrically and has explicit parameter functions. As an essential part of the design, the parametric schema plays a necessary pillar within parameterization. It allows reducing the abstraction of the mathematical model using a graphic representation. Thus, a parametric schema is a tool that focuses on the visual and geometrical representation of the object (Oxman, 2017).

The designers of the parametric models write their own rules referring mainly to the modelling of geometry on geometric elements. This action allows them to acquire a broader knowledge of the design because they must predict their geometrical function's effects within the model. Furthermore, unlimited model alternatives can be generated in parallel once the rules are implemented in the parametric design process allowing play with all the variations that the designer wishes to explore within the smallest dimensionality possible (Davis, 2013). Figure 12 shows an example of the Hangzhou Olympic Sport project's parametric design, developed by the computational designer Nathan Miller.

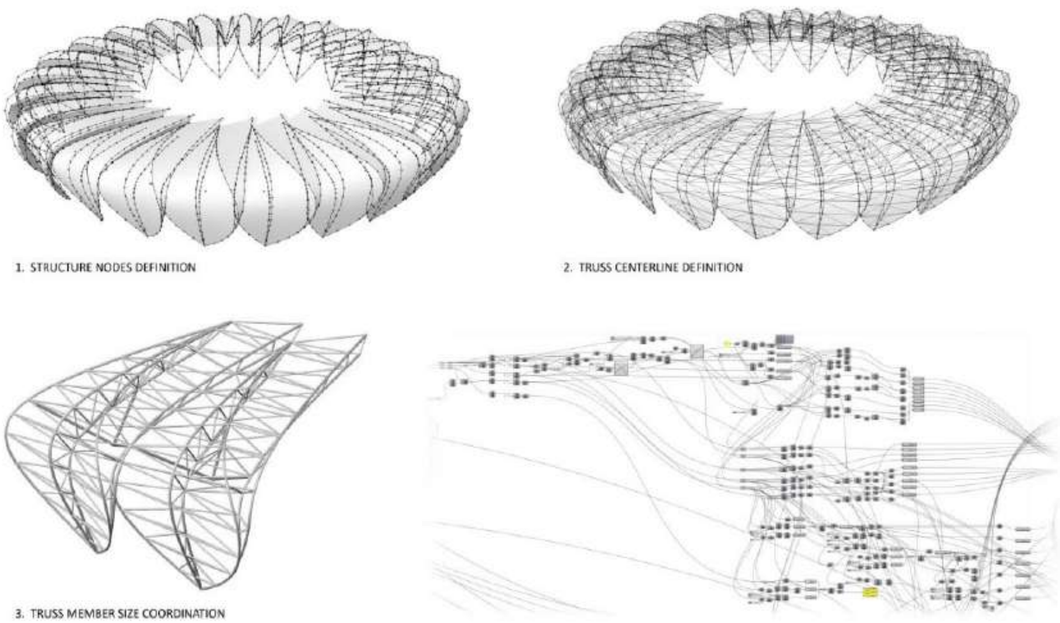


Figure 12 Parametric Structural Design Model by Nathan Miller (Miller, 2013)

7.1.2. Softwares and tools for parametric design

In these last ten years, the growth of solutions that offer to create parametric models using algorithmic rules has grown. Therefore, it should be clarified that although BIM modellers can be considered parametric design software in the broad aspect of the word, we will focus only on those tools that develop the model through algorithmic design.

Although there may be platforms before those mentioned, it will talk about those currently in the market. The most popular algorithmic modelling tool within architecture firms is Grasshopper from McNeel & Associates. Grasshopper was created in 2007 and is found within Rhino, a 3d modelling software (Khabazi, 2012). On the other side, Dynamo from Autodesk, which was created in 2011 by Ian Keogh. That although his leading software is Revit, Dynamo has a connection with other Autodesk software. The other commercial developments are Generative Components from Bentley System, Paramo from ArchiCAD, and Visual Scripting from Allplan.

The main characteristic is that they use programming methods to create the parametric model, mainly visual programming. This type of programming is intended to visually understand the behaviour of the script, defining a logical behaviour using boxes. In this way, it allows it to be accessible to people who do not have a programming background, which fits perfectly with the profiles of architects and engineers. Most of the Algorithm Modeling tools are made up of visual programming.

Visual programming can be done with the function boxes; the interest does not lie in understanding predefined functions; it only needs to use the predefined functions of the boxes to create parametric models and manage the structure information of the model. Which has as main elements that can be called components or nodes; these have a function that requires inputs connected from other boxes by wires. When the operation is done, they return an output, which can be used as an input for a new function. An example of these elements is shown in Figure 13.

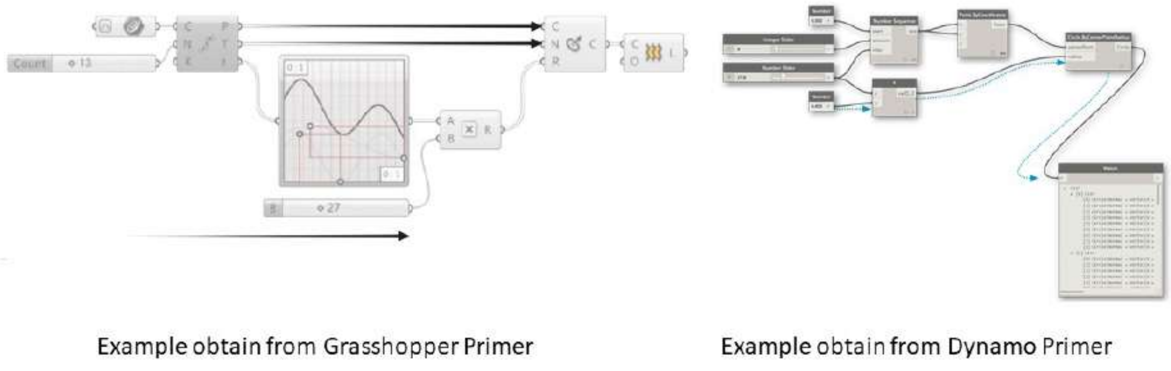


Figure 13 Example of Visual Programming in Algorithm Modelling Tools

These tools allow us to create parametric designs. However, sometimes the search for the optimal design has variables that affect and change, so manual search turns out to be tedious and time-consuming. At this point, the logical progression is to use Generative Design. As a positive point, some of the algorithmic design tools already have generative design engines or packages that allow this to do it.

7.1.3. Generative Design

Within our field, designs require multidimensional variables; there are restrictions on cost, aesthetics, construction, site, and many more. The intention is to fulfil the goals proposed by clients and government requirements where the design is located. While parametric design helps us review multiple options, we have limited time within the design phase, making it impossible to explore all the option space. Traditionally, it can only test and improve a limited number of designs before deciding on a solution. Additionally, the design will be validated through the professional's previous experience, making it possible to have a bias due to the lack of global knowledge in the project.

Fortunately, we can learn quickly with technology, investing more time in the design criteria and less in repetitive tasks and problem-solving. Generative Design integrates Artificial Intelligence in the design process using metaheuristic search algorithms to discover novel and high-performing results through the correct configuration of the proposed algorithm to solve a specific problem (Holland, 1984).

Generative Design seeks to imitate the process of the evolution of nature through its Genetic Algorithm. This approach uses an initial population, which is continuously mutating and evolving to adapt better; in our field, the genes seek to achieve the objective set.

The genetic algorithm was formalized by Holland and De Jong, which involves search optimization methods using pattern strategies like the Darwinian theory of “Natural Selection and Evolution” (Holland, 1984; Johnson and Rahmat-samii, 2009). The optimization method is based on the "selective pressure" of the objective function (Nagy, 2017). Therefore, we have population, chromosomes, parents, children, mutation and new generations within the metaheuristic search for the optimal solution. Figure 14, created by Jacqueline Rohrmann, summarized how the genetic algorithm NSGA II works.

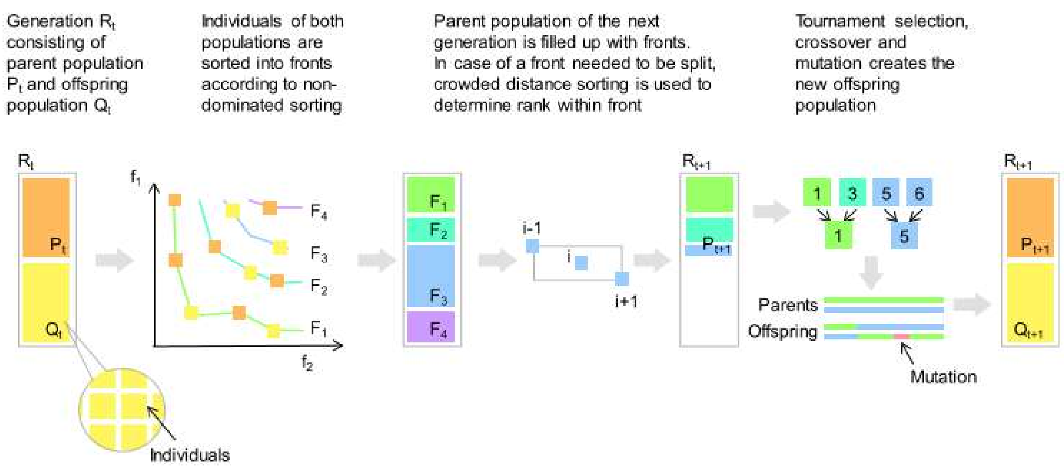


Figure 14 Explanation of how and Genetic Algorithm works (NSGA-II) from (Rohrmann, 2019)

However, the workflow in the search for optimization of the problem comprises three main parts, as shown in Figure 15. First, planning is always the focus for a good result, and, in this case, it is no exception.

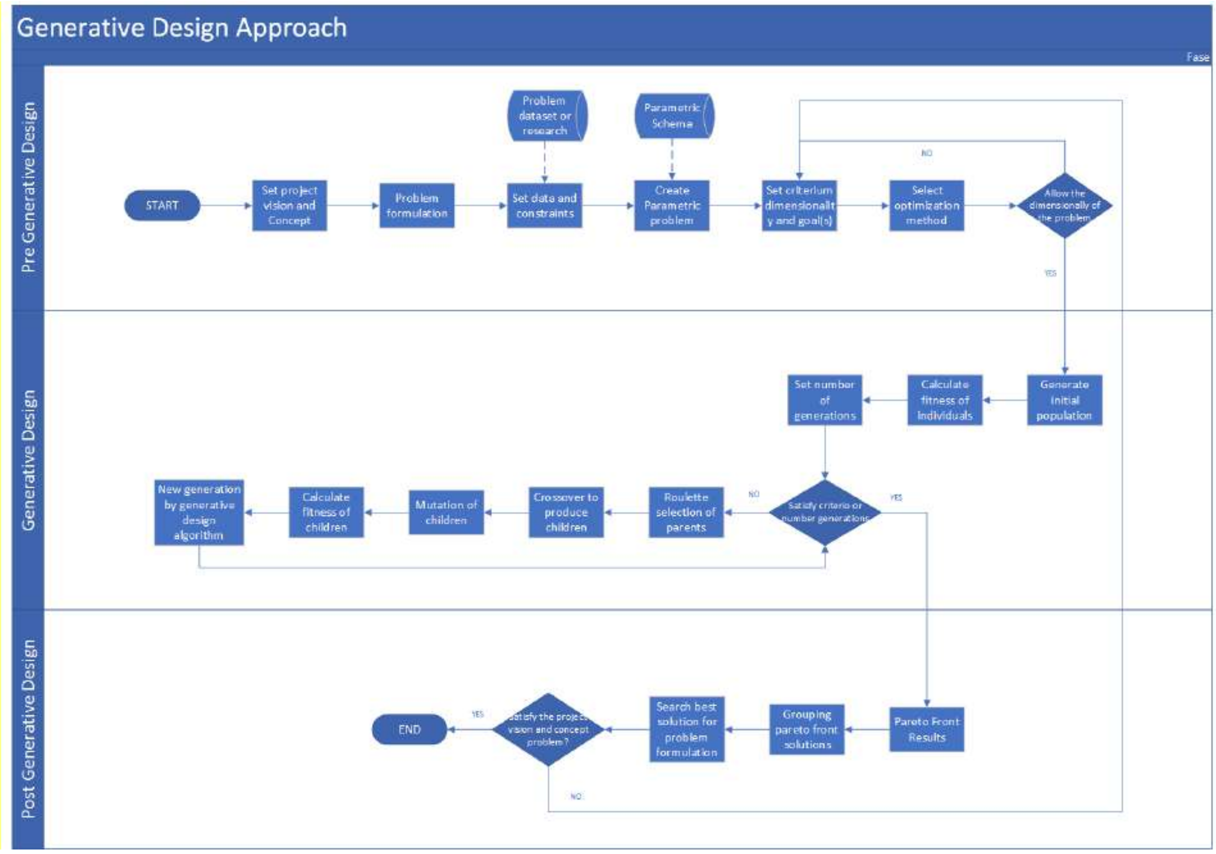


Figure 15 Generative Design Approach proposed by the author

This phase is called Pre-Generative Design, where the foundation for creating the model is laid, and the model's scope is defined. It can obtain information on the generative design and formulate hypotheses about the results. At this point, you choose the level of complexity you want to demand within the study. What are the objectives that help us know that we will be optimizing our model correctly. Some generative design engines such as Galapagos have single criteria, so it is established which calculation engine best suits our needs in this phase. An issue that requires relevance is the configuration of these objectives since to produce better results, they must not be correlated with each other (Rodríguez Hernández, 2019). The goals must compete to find a balance between them, and thus the study produces results with less bias.

Another issue to consider is the computational time used to solve the problem and the constraint of variables. No matter how powerful the computing system is, if this is not taken into consideration, the problem could increase in complexity, thus causing a waste of time and computing resources, which in many cases makes the problem not converge to its best solution.

Therefore, there must be a balance between the number of individuals capable of creating within the problem space so that the calculation engine produces results that can be used.

Within the generative design phase, multiple iterations are carried out that will depend on the search for the engine solution and the complexity of the problem. For simple issues, the generative design engine will return a result. Still, it will return a set of optimal values achieved by the number of generations performed during its execution for most problems.

The evolutionary algorithm used by generative design engines has different methods to rank and select solutions for the new parent population. Among them, the non-elitist method has vector evaluated (VEGA), Multi-objective GA (MOGA) and Niched Pareto GA (NPGA). Among the elitist methods to find solutions exist the Pareto Achieve Evolution Strategy (PAES), Strength Pareto Evolutionary Algorithm (SPEA), Non-dominated Sorting GA (NSGA) and finally, the improvement of the previous one called NSGA II (Coello, 2018).

This thesis decided to use a search engine with NSGA II because it has gained much appreciation and is widely used in optimization problems. Moreover, it has proven superior in various solutions on PAES and SPEA (Yusoff, Ngadiman and Zain, 2011).

NSGA-II mainly uses three properties for search optimization: a simple crowded-comparison operator, a fast, crowded distance estimation procedure, and a fast dominated sorting approach (Yusoff, Ngadiman and Zain, 2011). However, it is understood that everything will depend on the complexity and configuration of the problem to produce good results since there is no magic formula that gives us the best values. For this case, sometimes, due to the limited number of generations or the wrong formulation of the problem, this algorithm will offer solutions that do not meet the objectives initially sought.

Finally, in the part of the post generative design, the selection is represented by the Pareto graph, and within its border, the best solutions found are plotted. Thus, the Pareto frontier is a collection of solutions with overall performance. However, it differs on the importance assigned to each objective that the multi-objective optimization process aims to reach (Moreno-De-Luca, Leonardo, Carrillo Begambre, 2013).

However, the solutions within the Pareto front must be grouped and divided to choose the final solution. This part is the one that requires a more significant criterion of the problem since it is necessary to discard other possible solutions found. Here is where the architect or engineer must evaluate the solution to choose based on their experience and knowledge. The choice is not necessarily the one that has the best values among the whole world of solutions since the complexity of the problem governs the goals set within the study, and other aspects must be considered, such as constructability, aesthetics, among others.

8. PRACTICAL CASE STOŽICE ARENA OPTIMISATION

"You can't connect the dots looking forward; you can only connect them looking backwards. So, you have to trust that the dots will somehow connect in your future." **— Steve Jobs**

8.1. General description

8.1.1. Stožice Arena

The project used as a case study is already built and in operation. Stožice Arena, created by the Sadar + Vuga studio is part of a hybrid project; its implementation results from the public-private partnership between Ljubljana and the development company GREP.

The Stožice Arena, located in Ljubljana, is part of the Stožice Center, Slovenia. The multipurpose pavilion is in the northwestern part of Ljubljana Park; it was inaugurated on August 10, 2010, being built just 14 months after the project's approval. Stožice Arena has a capacity of 12,480 seats for basketball or 14,480 visitors for concerts or other performing arts events. It has four levels with a VIP area, as well as lobbies with lower and upper levels; the primary information of the project is shown in Table 7:

Table 7 Brief of Stožice Arena

Total Cost Estimation	49.195.388 Euros
Client	Grep d.o.o., Ljubljana City Municipality, Delta
Address/Site	Stožice, Ljubljana, Slovenia
Lead Architect	SVA (Sadar+Vuga)
Landscape	AKKA (Ana Kucan, Luka Javornik)
Structural engineer	Atelier One | Elea iC
Consultant	KSS – London
Construction Engineer	Gradis
Sport Arena floors	Two underground levels, ground floor, three levels
Configuration	reinforced concrete with prefab elements, steel roof structure
Roof Cladding	Glass, facade panels
Cinema layout	1.600 m²
Layout class	1.000 m²
Reception	12.400 m²
Banquet	3.500 m²
Surface	146.164 m²
Ceiling height	34 m
Total floor area	35.496 m²

The shape of the shell-shaped roof opens inwards; the ridges continue to the top, where the facade meets the dome; the shell opens towards the perimeter with large crescent-shaped openings facing the Park. A canopy surrounds the room along the entire perimeter, acting as a derivative of the scalloped shell. The living room casing is finished with an exterior cladding that changes colour based on outdoor conditions and viewing distance (Lomholt, 2012).

Figure 16 Stožice Arena, obtain from (*Search Results for "Arena Stozice" – SADAR+VUGA*, 2010; *Center Stožice » Visit Ljubljana*, 2021; *sadar + vuga: sports park stozice*, no date; Lomholt, 2012)

8.1.2. Scope of Stožice Arena optimisation form

Stožice Arena is the case study because of its design and shape complexity and required buildability and constructability processes to optimise construction resources. Therefore, the optimisation process considered creating the initial shape of the Stožice Arena, seeking to optimise constructability processes related to the facade; in turn, multiple structural solutions are shown in the schematic design phase for the solution.

Within the optimisation objectives, a table is shown below that relates the constructability principles obtained by Arash Mohsenijam et., comparing it with the tools and methods with which it is sought to cover the points in this case study.

Table 8 Constructability principles applied in the Case Study

Principle	Description of Constructability	Generative Design Constructability & BIM| Lean Approaches
C1-6	Basic design approaches consider effective construction methods.	Interview with specialists to understand the limitation and constraint of the construction methods and apply in the digital model
C1-8	Advance information technologies are applied throughout the project.	Use Parametric Modelling Software that supports BIM processes, Visual programming, and generative design
C1-14	Simplify and separate building systems and components to facilitate maintenance and future renovations	Setup the configuration like a constraint in the algorithm for creating system or grouping elements
C2-3	Design simplification by designers and design review by qualified construction personnel must be configured to enable efficient construction.	Using BIM Model and the support views for creation of documentation and view perspective to help to understand better the construction systems
C2-4	Design elements are standardised.	Use optimisation methods to reduce the number of different system panels
C2-6	Module/preassembly designs are prepared to facilitate fabrication, transportation, and installation.	Creation of subassembly panelling system similar that was used in Sydney Opera
C2-8	Designs facilitate construction under adverse weather conditions and consider an increase of prefabricated elements.	Establish subassembly panelling system like prefabricated element
C2-14	Optimise dimensions to utilise the entire product/material.	Optimisation of the shape to reduce the material weight
C3-5	Innovative methods for using the available equipment or modification of the available equipment to increase their productivity.	Use Generative Design and BIM and Lean approach to creating multiple designs in a reduced time
C3-6	Use preassembly to increase productivity, reduce the need for scaffolding, or improve the project constructability under adverse weather conditions.	Establish subassembly panelling system like prefabricated element

The goal of the study was not to seek to generate a faithful copy of the infrastructure. Instead, based on the information obtained about the stakeholders involved in the project, restrictions, rules, and variables are defined, resulting in an initial dataset for creating the algorithm used to generate generative designs.

8.1.3. Assumptions for analysis and optimisation development

The project's scope is in the schematic design and only the information necessary to address later phases. That means that within the study, the primary workload focuses on the correct development of the shape, carrying, and checking the elements' stability using gravitational analysis, showing diagrams of the possible solutions without reaching the constructive detail, proposing workflows for later phases of design. With this, it was sought to reduce the time and effort that Lean promotes by not investing in activities that do not add value in the project phase and avoid over-modelling at an early stage.

The design was divided into two parts, mainly due to the shape of the structure and the previous design made. The requirements and costs associated with the change of structure were taken as a reference because, in the seating area, the structure must be concrete due to costs. There is a transition part in the middle connection area between the roof and the facade. The roof is supported by concrete columns, which allows it to be idealised independently (roof and external facade) within the pre-design stage.

Therefore, it was assumed that the roof has rested in the lower zone of the waves. As a result, the loads are transmitted to the concrete columns from the third level to the foundation. As for the study of the roof, it was decided to make two variants.

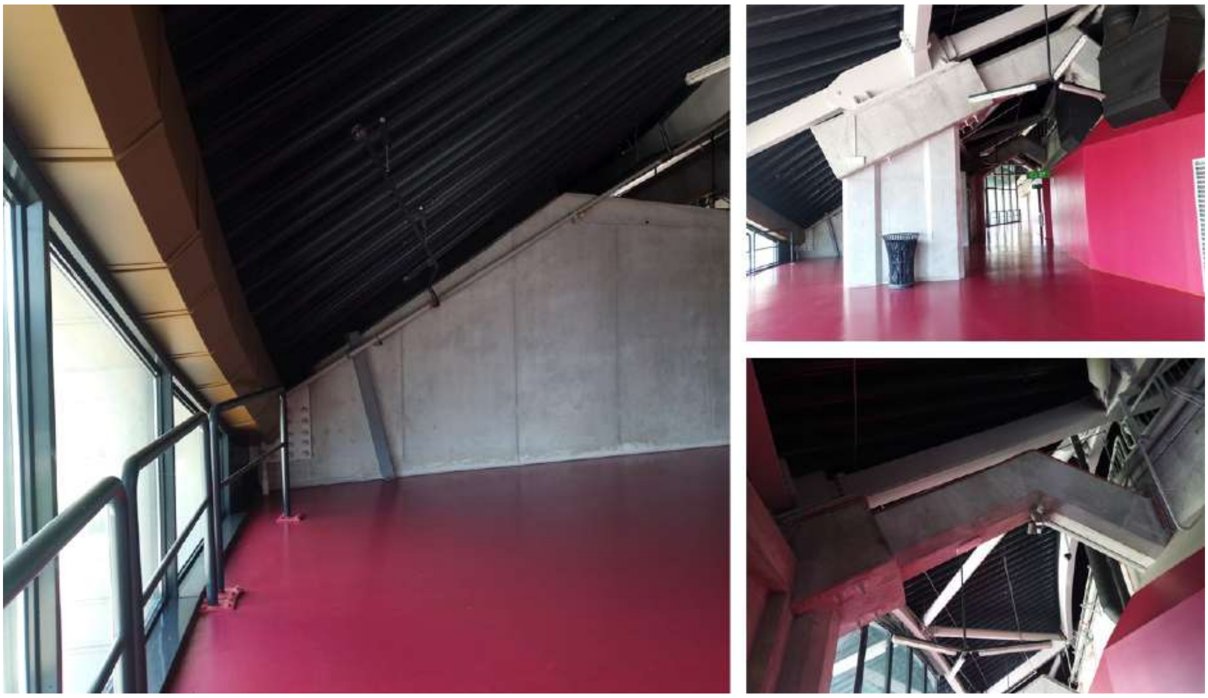


Figure 17 Low wave zones where roof loads are transferred

In the case of the roof, two rationalizations will be made by way of example. In the first, the construction will consist of a metal deck with a concrete compression layer to achieve a self-supporting shell, which allows it to resist its weight and loads—external gravitational factors. For the second example, a steel structure will be created to review the current rationalization vs the proposal with the obtained form, showing the benefits of choosing the optimal form for either of the two constructive solutions.

For the bottom part, the design of the low facade zone was considered a concrete shell capable of support the self-weight and external gravitational loads. Support areas were considered in the lower area of the waves that transfer the load to foundation columns and walls. For the upper area, waves are supported by the columns on the third floor.

Figure 17 shows the stadium areas where they are currently used to transfer loads from the roof structure, which supports the assumption made during the study.

8.1.4. Methods and Materials

For the development of the study, it was decided to use several Lean tools, among them the Deeming Circle, to segment the study phases, having an essential time in planning and searching for information before executing the activities, visual management to manage the development of the study and review the weekly scope, through Kanban.

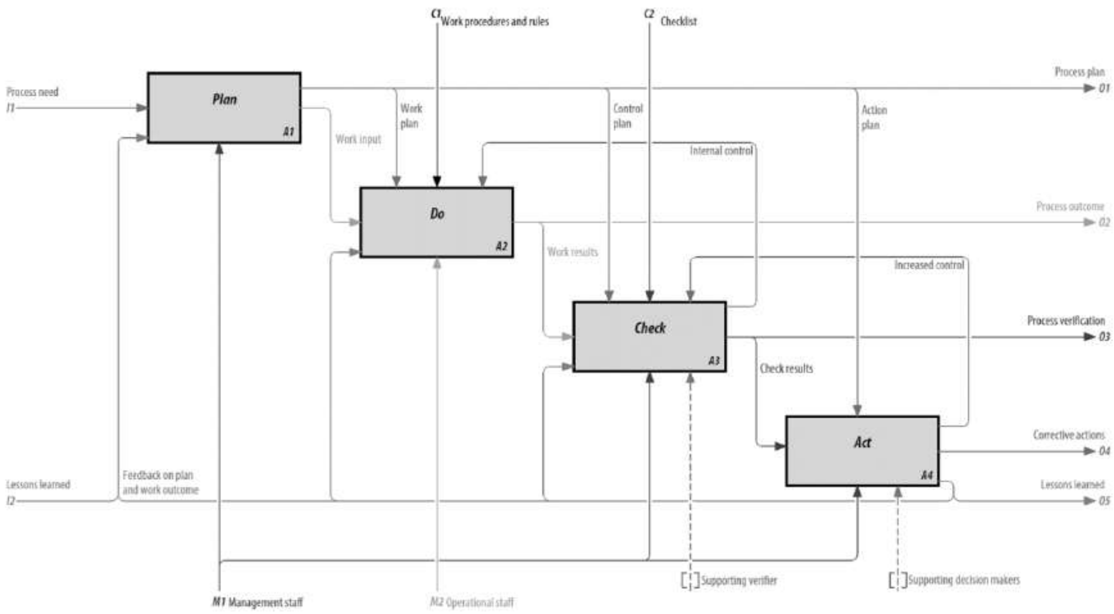


Figure 18 IDEF0 Deming Circle by Tomo Cerovsek

To define the problem, 5 WHY analysis was used to identify the root of the problem, find the key variables and narrow the study. Finally, a master plan and a weekly lookahead were generated using the Last Planner System to have the Job Done.

Figure 19 Web Platform with Weekly Kanban board

To develop the practical case was decided to consider the requirements set for constructability; interviews were planned with the stakeholders who collaborated during the project and collected the knowledge and experience resulting from Stocize Arena. Appendix I shows the list of questions formulated; the critical goal was to understand the needs of each actor to consider during the creation of the study.

Unfortunately, it was impossible to contact the majority due to those involved's limited time and schedule. However, the case study had the support of the Project Manager who participated in the construction and execution, Eng Andrej Lavric, who served as the primary mentor to understand the project and its implications, and one of the principal structural engineers, Eng. Marko Završki.

Dr Tomo Cerovsek was the mentor dedicated to coordinating the scope of the study. On the part of the computational design, we had advice from several people who supported us in seeing the parametric generation from a professional and applied perspective. The most significant contributors in ideas are Lorenzo Comaron specialising in claddings, and Chi-Li Cheng, an architect specialising in computational and experimental design.

In addition to this, extensive searches were carried out in thesis works, articles. Furthermore, several courses were taken that covered similar applications, support and information were obtained in forums about the tools used. The intention of this was to collect the previous experience of the professionals to emulate one of the indispensable requirements of the constructability technique, these being awareness, dialogue, interaction, teamwork and Knowledge-sharing to reduce the bias between the optimisation processes that could have the creator of the optimisation for this study.

Regarding the basic information of the project, searches were carried out on the internet to gather the necessary information (Nagy *et al.*, no date; Holst, Kirkegaard and Christoffersen, 2013; Rebien Olesen, 2018; Rohrmann, 2019; Luka *et al.*, 2021). Additionally, Eng. Andrej Lavric confirmed that the data obtained on the internet were correct and added new information to the existing one.

Visits were made to the project's exterior to admire and understand the apparent structure and its facade, finally, with the support of Eng. Andrej Lavric and at the disposal of the Stocize Arena staff, a guided tour of the interior was developed. Their help allowed us to resolve doubts about the structure's conception and understand the function of the form and the construction system used. During this visit, photographs were taken, and an interview was conducted with Eng. Andrej Lavric serves as support during the development of the study.

Figure 20 Site pictures of Stocize Arena

The previous information and site visits were of great help in selecting tools for the study. An extensive search was carried out on the development and community forum to create the parametric design, generative design and BIM model.

The visual programming tool was chosen to perform the parametric model creation processes. The functionalities for generative design development were limited by two options mainly: Dynamo and Revit vs Grasshopper and Rhinoceros. Because Revit is a software prepared for creating BIM models, Dynamo looks the best way initially. Nevertheless, it was decided to look for other tools because of its initial development within the generative design community and limitations on packages dedicated to geometric manipulation, meshes and pseudo structural analysis. For that, it was decided to use Grasshopper and Rhinoceros 7 as the leading software. Although Grasshopper requires external libraries to enable and improve the workflows for the activities, these packages are described in the specific use sections.

Regarding the verification and structural results checks, it should be mentioned that multiple options were tested before reaching the final software choice, interoperability with SAP2000 required an extra effort, and Sofistik required a steeper learning curve at the beginning of the project same. For this reason, it was decided to use SCIA Engineer as it provides interoperability with Grasshopper through a package, which allowed to reduce rework and maintain precision within the process of creating the analytical calculation model.

Regarding the BIM software for developing the model in schematic design, it was chosen to use Revit due to its excellent support forum, recognition in the market and especially the tools available for interoperability between Grasshopper and Revit.

8.1.5. Breakdown structure of the study goal

To achieve the objectives in Table 8 was decided to generate a breakdown structure of the critical activities that would allow us to show their use within the case study. The IDEF0 in Figure 21 shows the exemplification of the individual objectives made during the study.

Regarding the flow of explanation about the developed subtasks, in this document, they will be approached in the same way as the flow, explaining in each sub-chapters with their intended objectives, the specific tools and the results individually to simplify the global understanding of the optimisation performed. In the end, a summary of the objectives achieved in each of the phases developed is made.

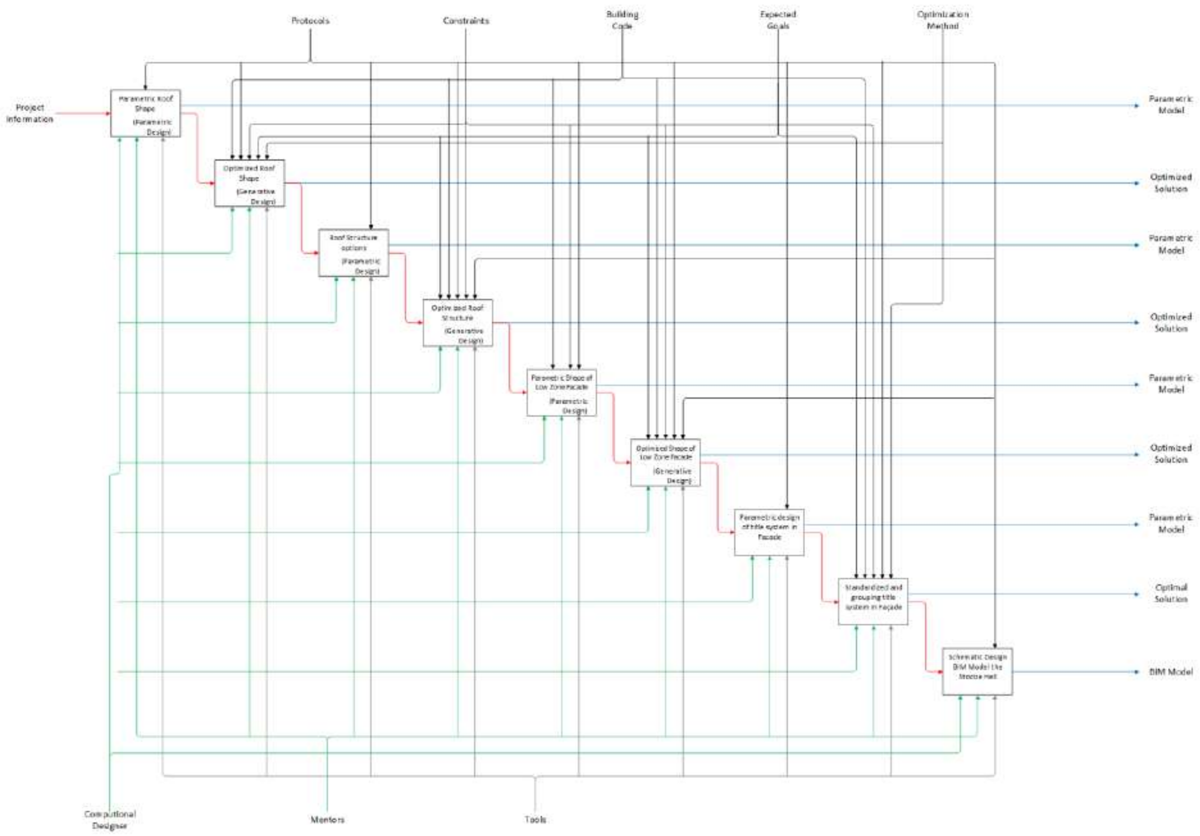


Figure 21 Simplification of inputs, controls and mechanisms for the study through IDEF0

8.2. Roof Shape Parametric Model

During state of the art and information search of the project, base information was found, which served to identify the basic rules established during its design, using reverse engineering to obtain the primitive forms to be used within the creation of the parametric model. The engineering of the process IDEF0 was used; Figure 22 shows the generic flow of the task.

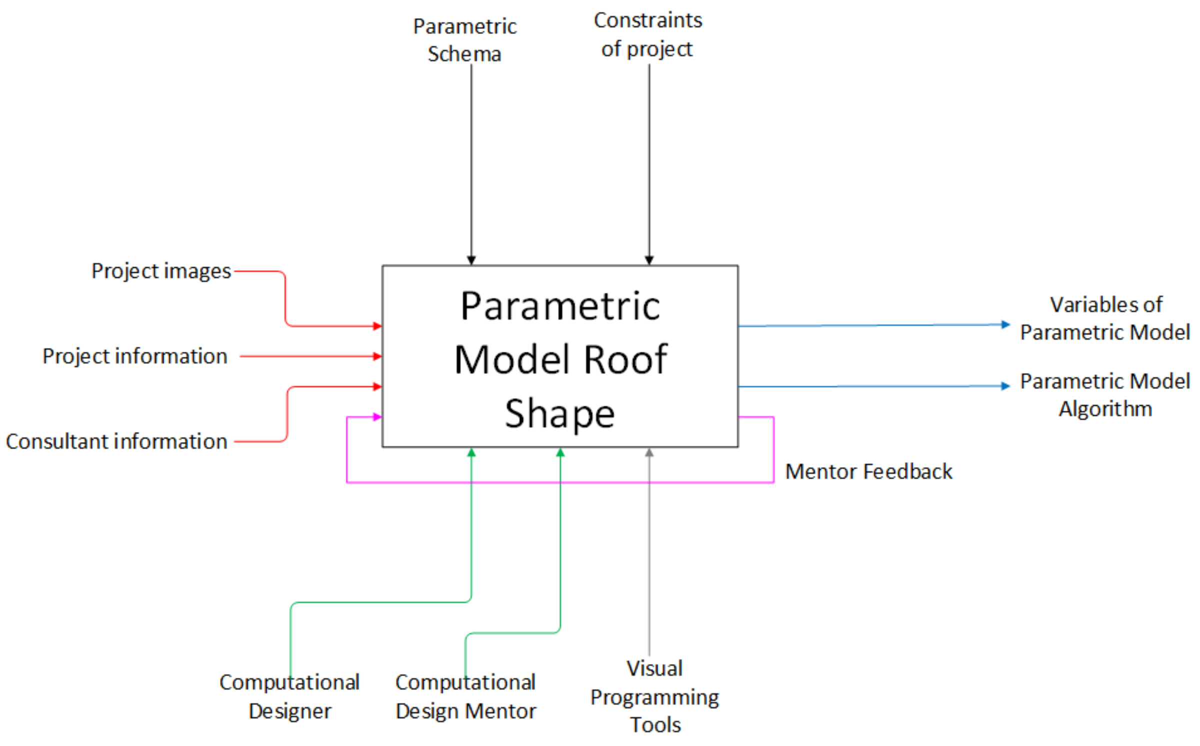


Figure 22 IDEF0 of Parametric Design for Roof Shape

The use of tools and the workflow was carried out using the flow shown in Figure 23.

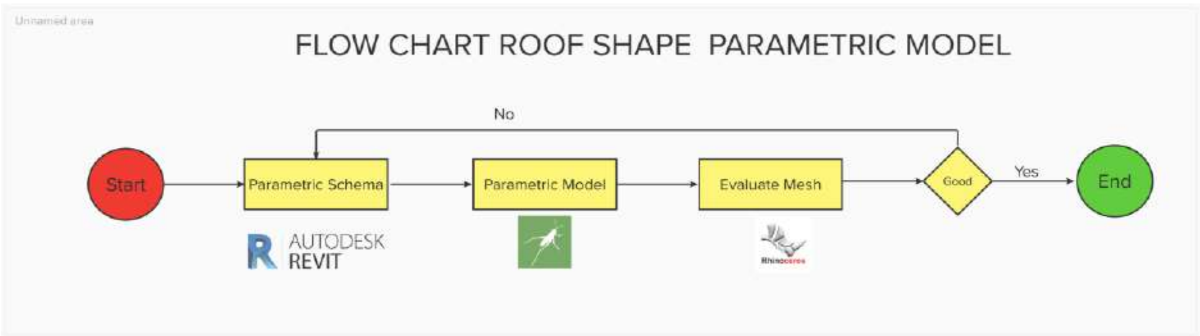


Figure 23 Flowchart Roof Shape Parametric Model

The starting point, in general, was the creation of the parametric schema. Here the idealisation of the primitive forms necessary to achieve the parametrisation was proposed. First, this diagram was subdivided and replicated in Grasshopper. Then, in the parametric schema, the variables that would allow modifying the values were defined. It is worth mentioning that this was created for the complete form, so this phase also applied to developing the lower facade area. Finally, the parametric schema is carried out below in Figure 24; variables' definitions and initial constraints are integrated.

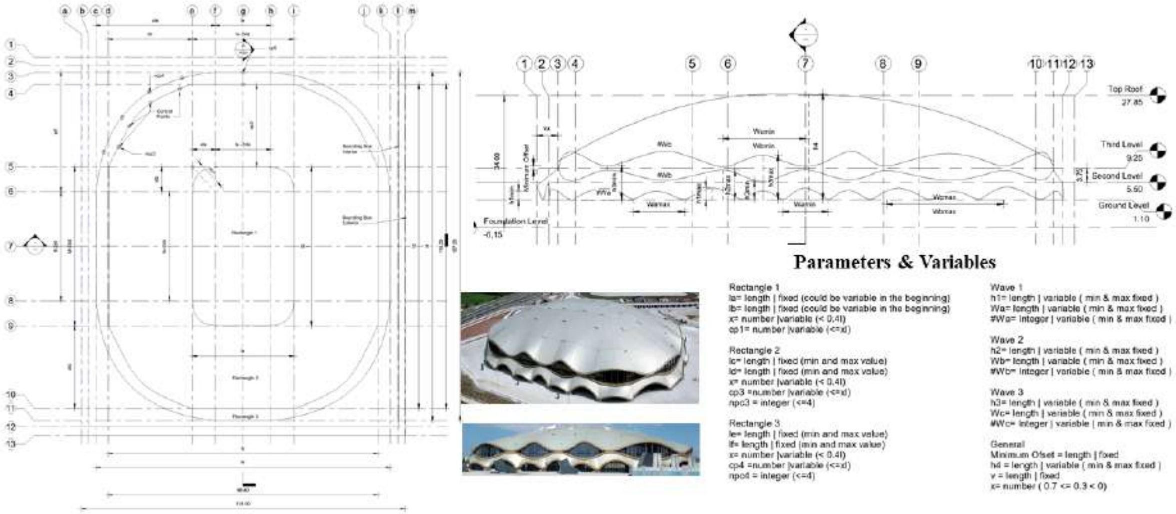


Figure 24 Parametric Schema of roof and facade form

The creation of this script was the most critical since it was an essential part of the whole flow. For this reason, several iterations were carried out before obtaining the result. The code creation had to be as compact as possible to reduce execution time during later phases and be understandable. One problem that Visual Programming has that can be difficult to grow with is spaghetti code's chaos because of its wire connections.

In Grasshopper, there is a way to clean the workflow, so from the beginning, we tried to use good practices and apply them within our workflow.

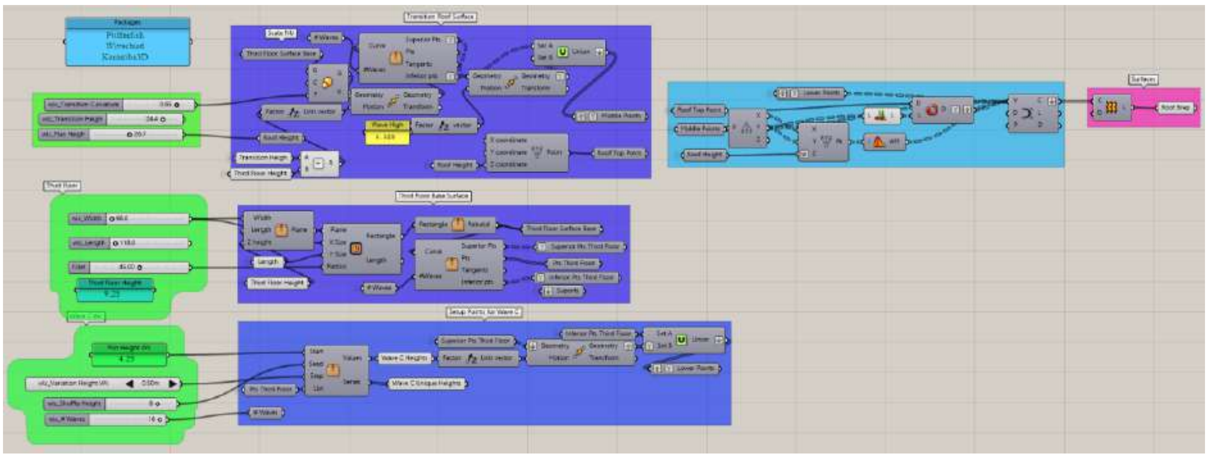


Figure 25 Example of Good practising scripting

Within the workflow, it was indicated that there were multiple iterations at the beginning of creating the parametric model; this is because there are numerous ways to reach the same geometry. However, only a few can be efficient in using the code and functionality for future operations. Therefore, the evaluation form reviewed the triangulation formed by its mesh and compared the most optimal shape.

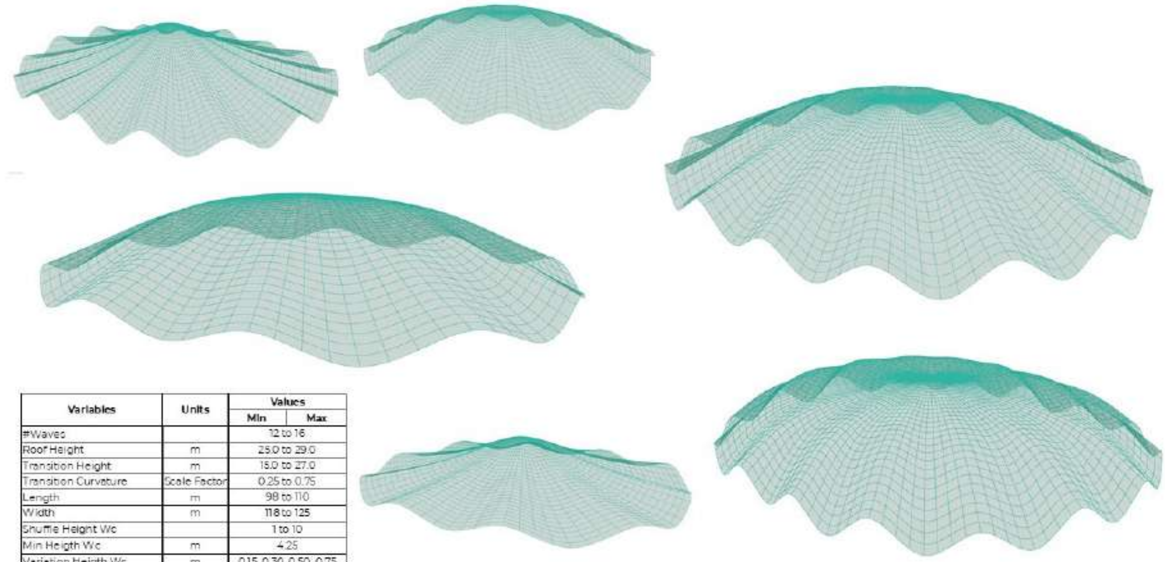
In later phases, we would have to use the code to grow it and integrate it into a flow that would allow a structural pseudo-analysis. Structural analysis software is based on performing mathematical operations using each node created within a mesh or a surface; these operations are based on a matrix method. The problem lies in the fact that when there is no continuity of nodes, the analytical approach grows exponentially to seek to be solved or fails due to the inconsistency of continuity of values.

For this reason, the shape analysis using mesh triangulation was a vital pillar to avoid rework in later phases and thus avoid inconsistencies in analytical calculations.

Figure 26 shows two parametric models; they have the same apparent result in their geometry. However, the results are entirely different when analysing edges on the surface and the triangulation of faces in the mesh.

Figure 26 Comparison between Parametric Models made

The result was the creation of the parametric script that allowed modifying geometric values of the surface. In this phase, the limits of the variables were delimited; this is important because, in generative design phases, it needs to think in: computing time, computer resources available, and logical values in the model to obtain valuable results. At the end of Figure 27 are shown some of the shapes that the script can create.



Variables	Units	Values	
		Min	Max
#Waves		12 to 16	
Roof Height	m	25.0 to 29.0	
Transition Height	m	15.0 to 27.0	
Transition Curvature	Scale Factor	0.25 to 0.75	
Length	m	98 to 110	
Width	m	118 to 125	
Shuffle Height Wc		1 to 10	
Min Heigth Wc	m	4.25	
Variation Heigth Wc	m	0.15, 0.30, 0.50, 0.75	
Third Floor Height	m	9.25	

Figure 27 Parametric Model of the roof

8.3. Generative Design of Roof Shape

The development sought to iteratively generate the creation of different forms and carry out a pseudo structural analysis. To start the engineering of the process, IDEF0 was used; Figure 28 shows the generic flow of the task.

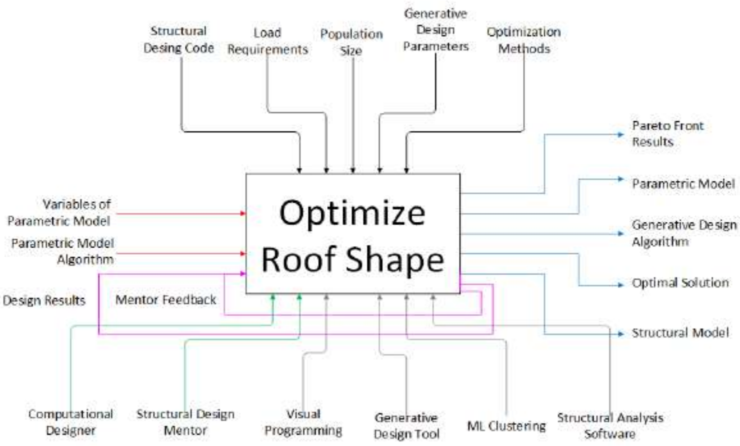


Figure 28 IDEF0 of Generative Design Model for the Roof Shape

The IDEF0 made it possible to identify the mechanisms and controls necessary to carry out the activity. Initially, tests and research were carried out on complementary tools that would allow having the Job Done. Then, after performing several iterations and tests, the specific packages and software shown in Figure 29 were chosen.

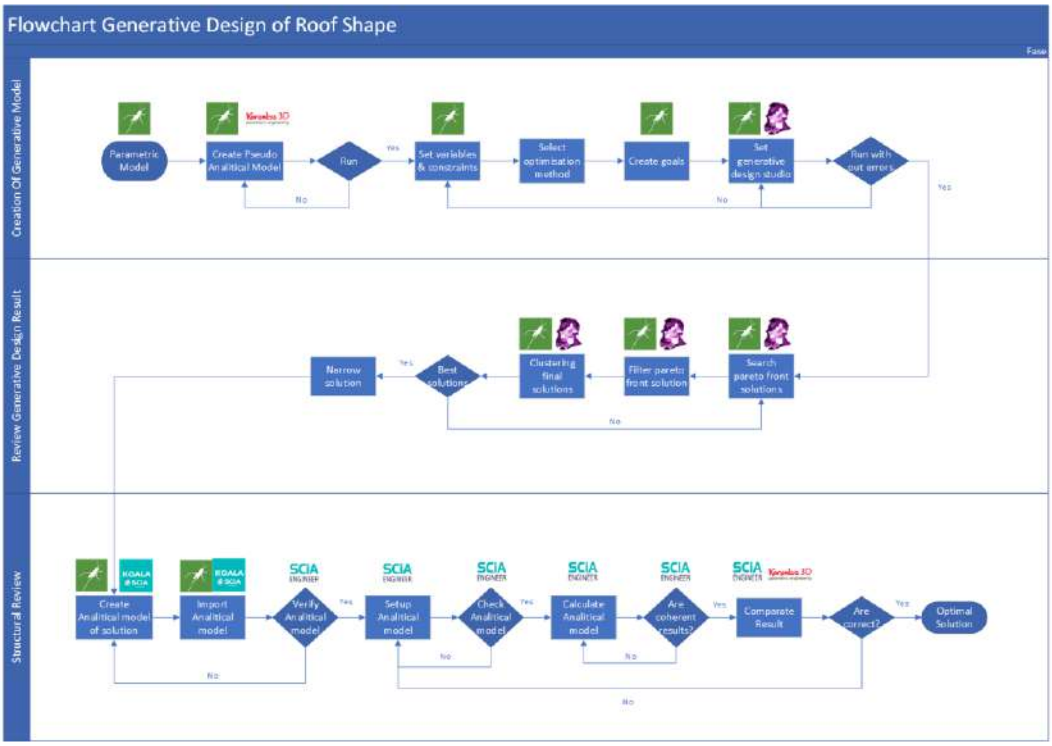


Figure 29 Flowchart of Roof Shape Generative Design

8.3.1. Set up Pseudo Structural Analysis Model

Regarding the structural Pseudo Analysis, research was carried out, which led us to choose Karamba3D as the main engine of solving. This package that can be integrated into Grasshopper allows iterations and returns the results within the tool in real-time. An important point to mention is that this package is very intuitive and works perfectly with Grasshopper. It is also recognised in structural optimisation, used in projects and multiple papers (Preisinger, Hofmann and Bollinger, 2011; Karamba3D, 2018; Hawkins *et al.*, 2019; Zhang *et al.*, 2019; Aksoz and Preisinger, 2020). Karamba3D requires well-defined geometry, so the previous step was crucial to generate the pseudo-analysis model.

In the creation of the model for generative design, multiple iterations were carried out. It was sought to reduce the execution time, simplify nodes to reduce computation in a calculation, review that it would yield coherent values for each creation of the model, reduction of quantity variations by variable, among others.

After that, the research was done for the generative design engine. Grasshopper has multiple engines to do this activity, each with its advantages and disadvantages. From the beginning, the proposed optimisation problem sought to reduce the amount of bias. For this reason, it was decided to seek to perform a multicriteria optimisation.

While a generative design engine can be forced to run multiple criteria within a single value, this can limit understanding of the structure's behaviour. For this reason, an engine was sought that would allow visualising multiple goals. Tests were performed with Galapagos, Octopus and Wallacei to identify the best option for the study.

Wallacei was chosen due to its additional data analytics and Machine Learning functionalities that simplify human interaction, understanding results, and selecting solutions.

8.3.2. Generative Design Setup for the Roof Shape

For the study, it was sought to minimise three goals based on the knowledge of the behaviour of structures. The first point desired the displacement by minimising or eliminating it; thus, the building code for displacements would be fulfilled. However, there would be heavy sections if only that is considered, so the other minimised value was the structure's mass. Therefore, these two criteria effectively counter each other and allow the structure to be optimised.

As an additional goal, it was decided to use the maximum tension of the structure to be minimised. The concrete itself is weak to tension, which means parts of the structure in tension shall increase the costs as more reinforcement is needed. Therefore, it could not be built due to excess stress.

The variables, constraints, and goals in the generative design are shown in Figure 31; on the left side, the graph results are on the right side.

Model Setup

Variables	Units	Values	
		Min	Max
#Waves		10	16
Roof Height	m	25.0	29.0
Transition Height	m	15.0	27.0
Transition Curvature	Scale Factor	0.25	0.75
Length	m	118.0	125.0
Width	m	98.0	110.0
Shuffle Height Wc		1	10
Constraints & Fix Values	**Units**	**Values**	
		Min	**Max**
Wave Heigth(Transition)	m	0.25	
Fillet Curve	m(radius)	45.00	
Min Heigth Wc	m	4.25	
Variation Heigth Wc	m	0.50	
Third Floor Height	m	9.25	
Factor Selfweigth	Scale Factor	1.50	
Thickness	cm	12.00	
Goals	**Units**	**Objectives**	
Max Displacement	cm	Minimize	
Mass	Ton	Minimize	
Max Tension Stress	Mpa	Minimize	

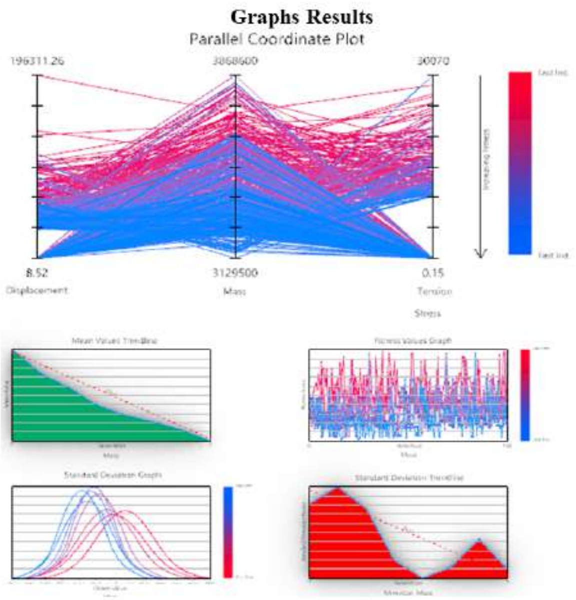


Figure 30 Roof Shape Model Setup

After several iterations, methods were sought to help reduce the creation of false optimal solutions. These results were generated and that, although they allow reaching the optimal solution, they cause noise in the analyses and require many more iterations to reach the optimal result. For that case, penalties were applied increasing values, due to the concept of the problem, are known not to be part of the solution. The penalties involved increase the displacement by 1000 each time the value obtained exceeded the maximum by regulation. In the same way on tension, a penalty was made to those solutions where 10 MPa were exceeded.

As a result, these genes do not pass to the next generation in the first execution, and a faster debugging of unwanted values is obtained. The study settings are shown in Figure 31, along with the filtered results of the study.

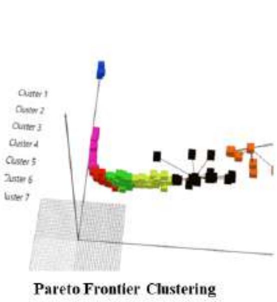
Population	
Generation Size	150
Generation Count	8
Population Size	1200

Algorithm Parameters	
Crossover Probability	0.9
Mutation Probability	1/n
Crossover Distribution Index	35
Mutation Distribution Index	35
RandomSeed	6

Simulation Parameters	
N° of Genes (Variables)	7
N° of Values	422
N° of Fitness Objectives	3
Size of Search Space	1.50E+11

Non-Supervised Machine Learning	
Method (Algorithm)	Kmeans
# Clusters	7

Result and Analytics	
Pareto Front Solutions	70
# Evaluation of Solutions	30
# Filter Solution	4



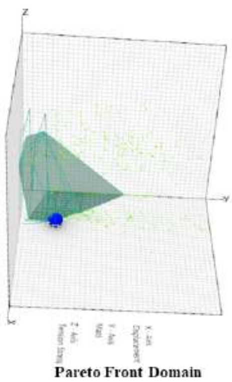


Figure 31 Roof Shape Generative Design Study Setup

Additionally shows that even by reducing and simplifying assumptions the multiple solutions of the problem posed, it was possible to create 150,000,000,000 variants, which would require several weeks to execute each one of them. Finally, Wallacei allows identifying the trend, using data analysis for every new study to know when the goal has achieved its stability. Without this, it will be spending more execution time under consideration, and it would just be a waste of resources.

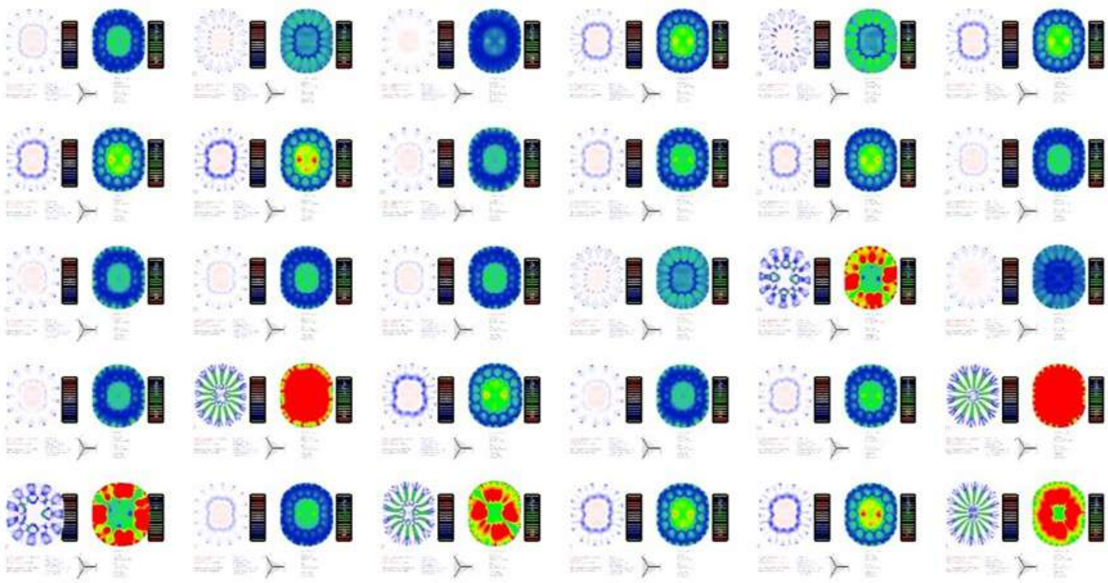


Figure 32 Grid of Pareto Front Solutions of the Roof Shape

Regarding searching for Pareto front solutions, Wallacei Analytics allows doing an intelligent search through all the previous studies, not just the last one.

Hence, the relevance since some optimal values cannot produce offspring in the following generations, and in this way, it is allowing visualise it. In addition, due to the size of the generation of the problem, it was necessary to use the Machine Learning module, which allowed to generate clusters of a selected group of solutions through the K-Means algorithm.

The clustering method allowed cleaning the final results faster and finding the models with more balance consider the three goals.

The main benefit of generative design allowed the generation and visualisation of multiple solutions; in our case, once the values are filtered, we generate our first grid of possible solutions. The main problem in our industry is the lack of time for planning and conception of proposals. As shown in Figure 32, more than 100 proposals can be created with multiple variations, each variation, with the structural implications of its shape. Thus, allowing to have a broader range of solutions and, in turn, understand the consequences of each of them.

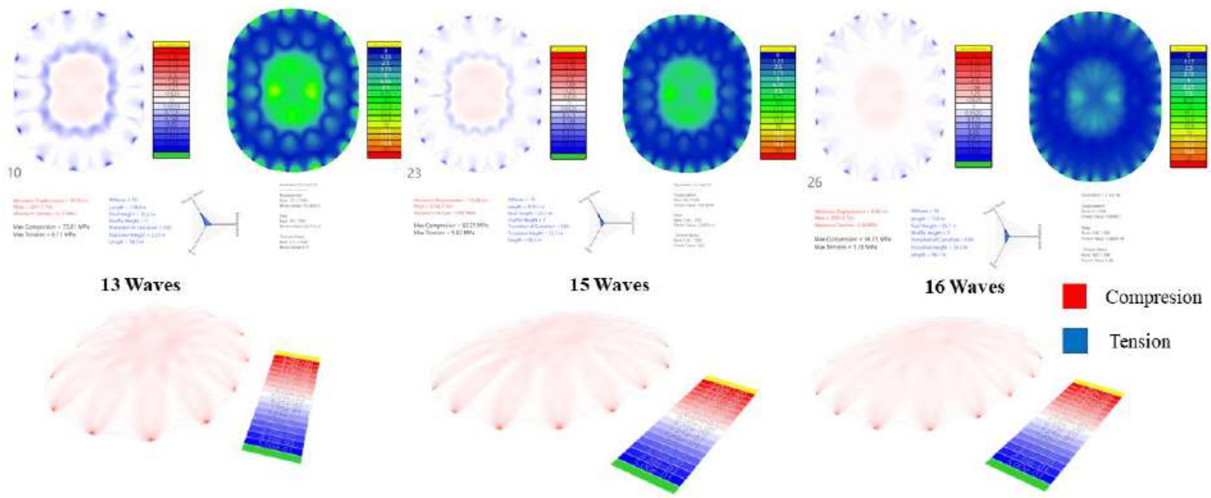


Figure 33 Best solution with different Waves

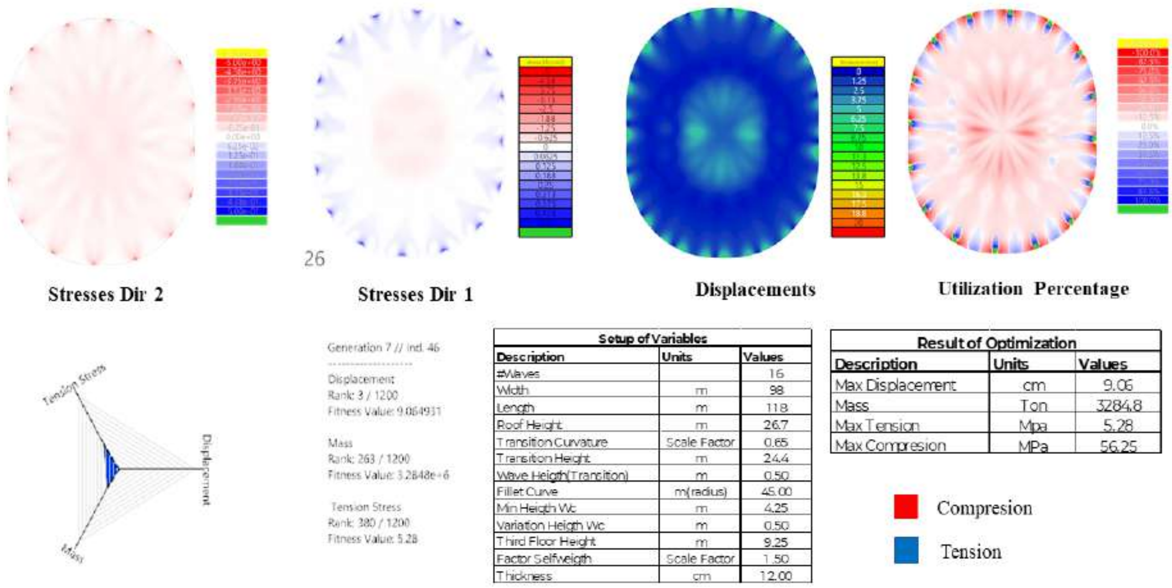
The best solutions found within the study are shown in Figure 33; shells formed with 13, 15 and 16 waves among the optimal shapes. Below are diagrams of the different stresses to which its weight subjects the structure factored in 1.5. This increase was initially that the structure would continue to function well in design phases where the combinations of gravitational loads of the structural code are considered.

As can be seen in both stresses and higher compressions are concentrated in the shell supports, which allows us to consider that if this part is increased in section, it can improve its behaviour and would not affect the general shape of the structure. In addition to this, the maps show that shells work mainly in compression, which is the ideal way to optimise concrete's structural behaviour since it works better in compression.

An important point to highlight is that within the study carried out in which 1200 models were generated, the current shape, which is composed of 12 waves, did not appear among the best results, which implies that from a structural performance vs cost, the current shape was not the best solution.

From its conception of the form, the project would cost more money because the structural behaviour of the current shape would require more material and time in the structural design to solve the project.

After reviewing the three solutions, the roof formed by 16 waves was chosen due to its better structural behaviour vs weight of the structure. In Figure 34, the variables with which this shell is formed are shown. Zones of greater displacement focus on the centre of the structure, showing in Karamba3D an excellent behaviour in terms of displacements in a conceptual design phase.



Setup of Variables		
Description	Units	Values
#Waves		16
Width	m	98
Length	m	118
Roof Height	m	26.7
Transition Curvature	Scale Factor	0.65
Transition Height	m	24.4
Wave Heigth(Transition)	m	0.50
Fillet Curve	m(radius)	45.00
Min Heigth Wc	m	4.25
Variation Heigth Wc	m	0.50
Third Floor Height	m	9.25
Factor Selfweigth	Scale Factor	1.50
Thickness	cm	12.00

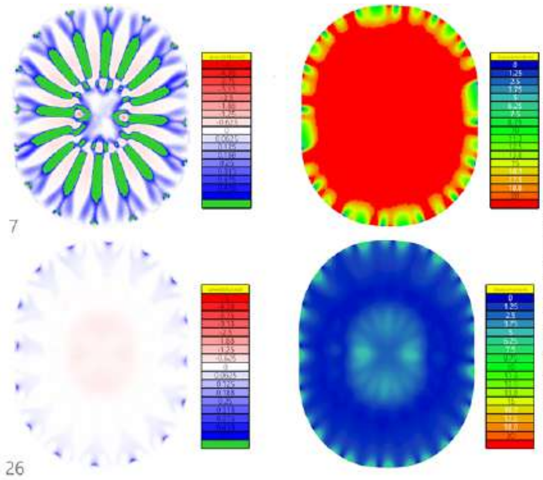
Result of Optimization		
Description	Units	Values
Max Displacement	cm	9.06
Mass	Ton	3284.8
Max Tension	Mpa	5.28
Max Compresion	MPa	56.25

Figure 34 Final Shape Chosen for the study

As a result, after several iterations, it was found that the shell would have a self-supporting behaviour with a thickness of 12 cm, according to the study analysed. The width and length dimensions remained the same as the previous design; the additional change found was that the final development height of the roof decreased 1.10 m in consideration of the currently built one. This height difference can be adjusted by increasing the height of the columns where the roof rests if the intention would be to preserve it.

In Figure 35, optimal and solution results with a similar height to the built design are compared. The figure shows how the variation in height considerably affects the structural behaviour, which causes a displacement that exceeds the maximum allowed by regulation and increases the structure's mass by 65 tons.

Showing how only one variable can influence the structural behaviour, this variable within the design phase can be traditionally iterated few times due to the short design time. So, this is a clear example of how the use of Generative Design allows exploring variables that otherwise only highly experienced Structural Engineers would be able to intuit at the design stage.



Comparison between Designs 16 Waves

Description	Units	Values		Diferences
# Generation		7	16	N/ A
#Waves		16	16	Equals
Length	m	120.6	118	2.6
Roof Height	m	27.9	26.7	1.2
Transition Curvature	Scale Factor	0.41	0.65	-0.2
Transition Height	m	15.1	24.4	-9.3
Length	m	120.6	118	2.6
Displacements	cm	50.54	9.06	41.5
Mass	Ton	3350.7	3284.8	65.9
Max Tension	Mpa	1.37	5.28	-3.9
Max Compresion	MPa	109.66	56.25	53.4

Figure 35 Structural behaviour due to change in development height

8.3.3. Verification of final roof shape chosen in structural design software

The objective of this phase was to verify two crucial points in our study. The first and most important was verifying that the results obtained in the generative design with Karamba3D were coherent and to know the variation between the simplified methods used by Karamba3D vs a software exclusively dedicated to structural analysis and design.

The other important part was to check the interoperability between the parametric design tools and the geometric export to structural design software. This activity is of utmost importance since it allows reducing remodelling, which would require considerable time because it is not a simple way to create within structural design software.

Another point to consider is that human error that may be due to variations between the analytical model and the constructive model is eliminated through correct interoperability. A not correctly idealised form of the existing system can lead to a wrong structural calculation, so this process reduces calculation inconsistencies due to variations in the model.

For this study, as previously mentioned at the beginning of the subchapter, there were several verifications to find the interoperability tool within this flow. Currently, the market has created workarounds to improve interoperability in this phase, so the decision on the choice fell on three main variables.

The first was that the tool was accessible and available for academic projects, ruling out several options since there was no free version. The second was that the interoperability flow required little investment time and a direct flow; this means minimising the use of other additional software due to the time limitation in creating the study. Finally, the third focused on finding a structural design software commercially used in the region. At the same time, initially, the learning curve was not steep.

The last point will facilitate the search for the Structural Engineer mentor, reduce consulting time, and use a flow that can be valid in the current market.

SCIA Engineer was the software chosen because it has a free student license. In addition, its interoperability tool integrates with Grasshopper, its use within the script does not require much time, and finally, it is software used in the European Union in structural engineering projects.

The package dedicated to exporting geometry on Grasshopper to SCIA is called Koala; it requires intermediate Grasshopper knowledge; however, as shown in Figure 36, the configuration of the export flow is relatively straightforward and does not require many components in its creation. Within the export flow, it should be noted that panelling surface's had to be simplified due to the size of the project. The main reason was to reduce the resource overhead required to run and compute the model within SCIA.

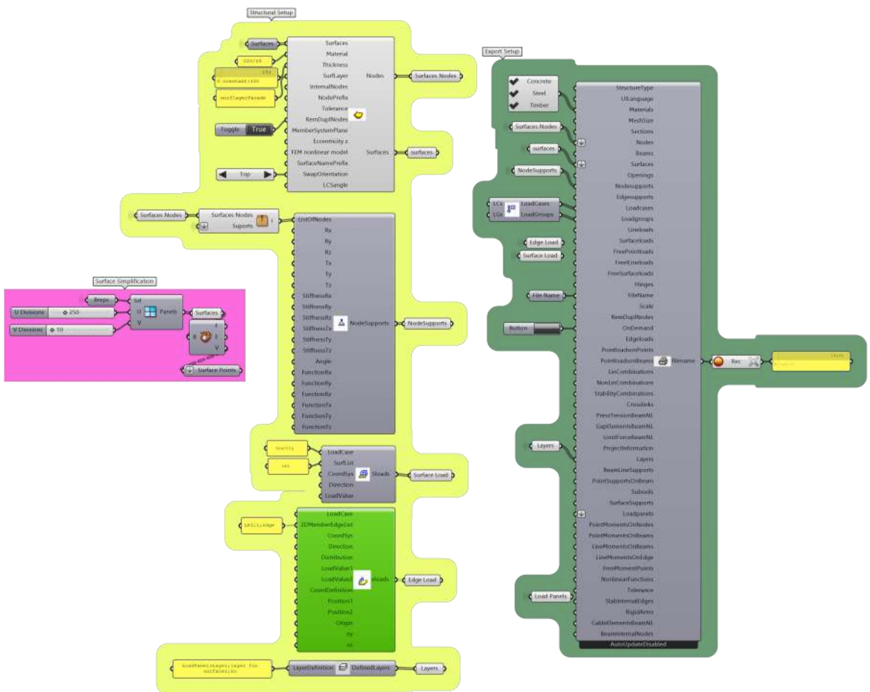


Figure 36 Setup of flow to Export Parametric Model to SCIA using Grasshopper

Remember that the only thing that simplification reduces is the level of resolution of the structural element; this should not compromise the final result, meaning that the simplification should not alter the composition of the shape in such a way that it changes the distribution of forces.

This first revision was decided to use only one combination within Karamba3D, which consisted of 1.5 self-weight regarding the analytical model. Another point in the structural analysis of SCIA vs Karamba3D is that the support system is represented differently. The intention was to simplify the search for the nodes within the mesh and simplify the generative design model.

This simplification was thought to reduce additional computational operations because creating a support per edge would require refining more the mesh. Consequently, adding more unknowns to the matrix method with which calculation operations are solved within Karamba3D.

In the review employing SCIA Engineer, the verification could not be done in the same way, on the one hand, because this method threw instability errors, which made the calculation solution not accurate. Additionally, in SCIA, the aim was to refine the calculation model. On the other hand, as shown in Figure 37, a support can be represented linearly in the current design.

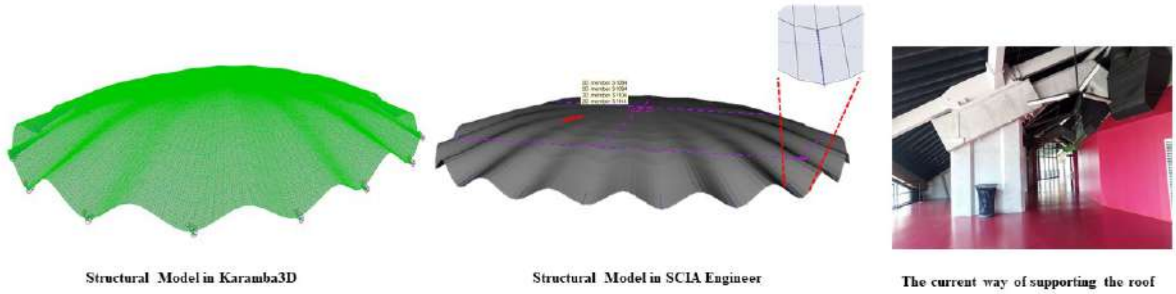


Figure 37 Representation of the analytical models used

The nodal support assumption generates a model with a higher safety factor within Karamba3D, which allows having in SCIA a model with fewer stresses located at a single point. Figure 38 shows the comparison between the displacements obtained in the different tools to verify the results. This image notes that the displacement maps are pretty similar, which tells us that the models agree with their mass distribution and verifies that Karamba3D yields similar values in displacements.

In addition, the stresses in Dir 1 and Dir 2 were revised. As shown in Figure 38, in comparison, the values are close to each other. Thus, the stress maps are equally coincident, with the difference that the SCIA software performs a more detailed meshing and shows the stresses with a better visualization in specific areas, unlike Karamba3D.

As a result of this phase, it was possible to verify the functionality of Karamba3D and the level of precision it has in terms of structural analysis, this being a starting point to ensure its functionality in the following phases. In addition to the functional interoperability that Grasshopper presents with SCIA in the export of the analytical model.

This phase was carried out to show a solution with another construction system. It was also created to obtain the optimal shape of the roof. The roof shape will serve as the basis for comparing and rationalising the design for the steel structural system in the roof and creating restrictions for the lower part of the facade.

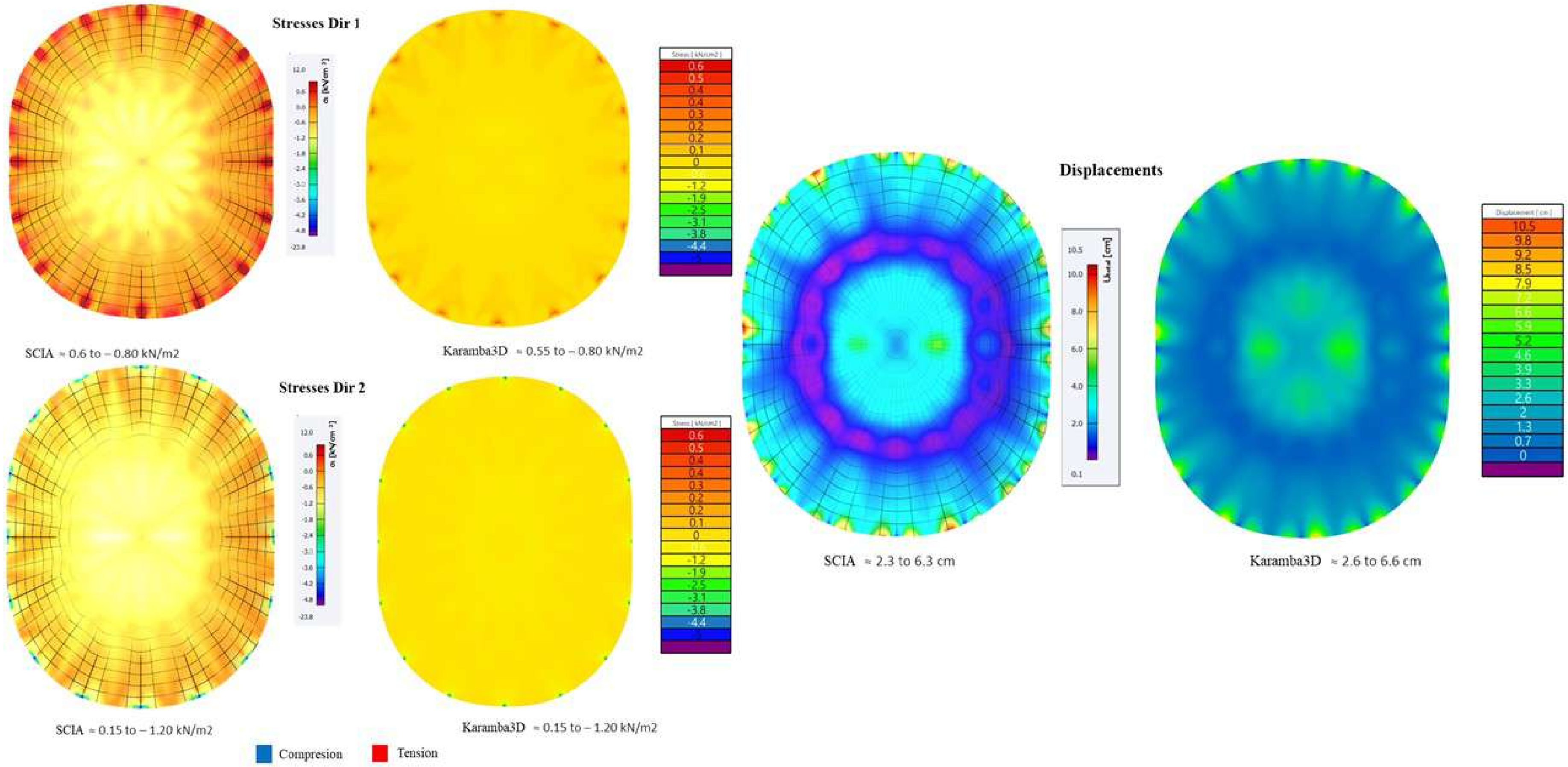


Figure 38 Comparison of displacements

8.4. Parametric Model of Roof Structure

In this phase, it was decided to check the structure of the roof. This part of the case study consists of applying the rationalization of the form in the constructed structural solution, intending to analyze the implications of this with an optimal form. The structural grid will be the proposal taken for the final optimization solution since this is the system currently used. Figure 39 shows the controls and mechanisms used to create the parametric design of the structural grid.

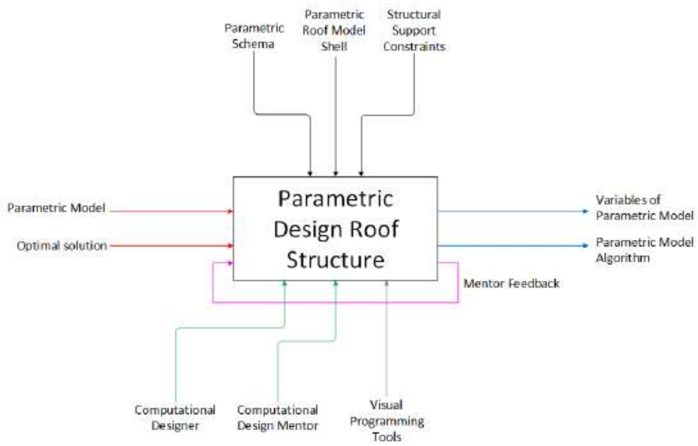


Figure 39 IDEF0 of Parametric Design for the Roof Structure

Within the proposed parametric schema, it was decided to make a substantial change to the original design to check if there was a more efficient way of proposing the structure. Therefore, the proposal is shown below and an image of the current structure on the left side.

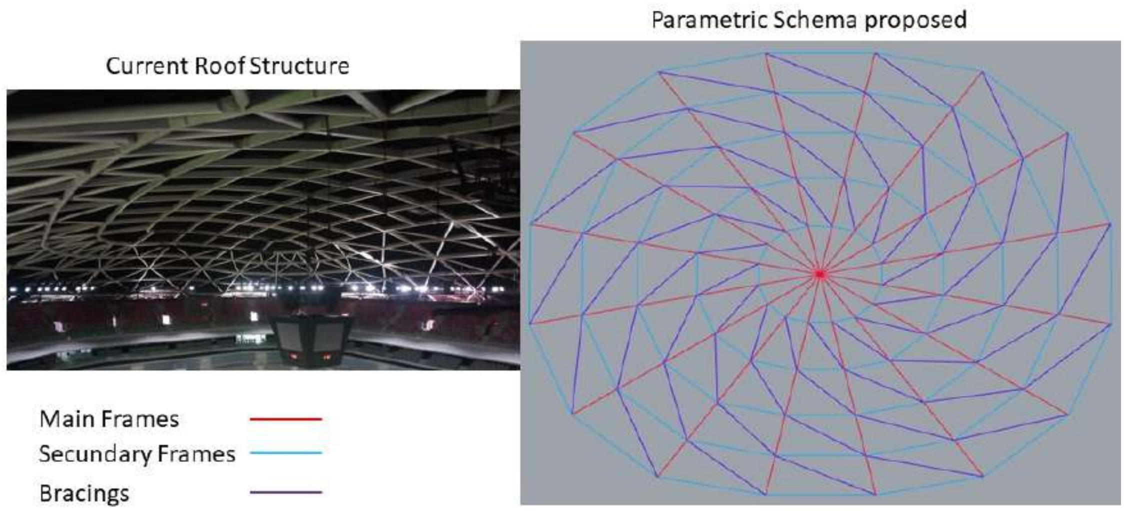


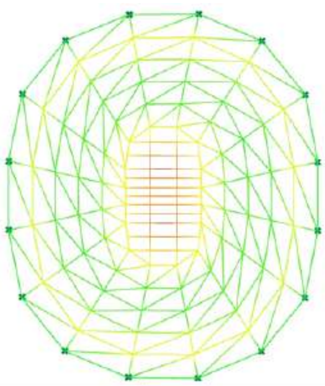
Figure 40 Current roof structure vs Parametric Schema proposed

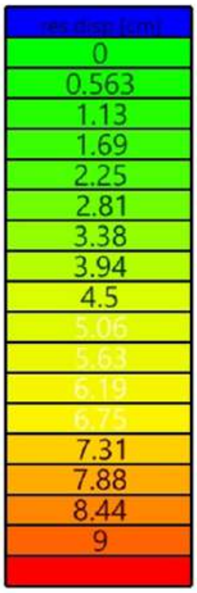
Within this phase, we seek to replicate the structural logic that the Stožice Arena currently has used the efficient form found in the previous phase. For this, the following workflow was defined.

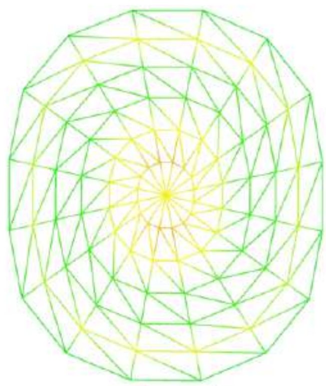
In the first case, it was decided to use the central area to emulate the current construction state. The proposal was developed in a parametric way, taking the number of rings formed to stiffen the main beams as variables. In this study, the profiles in the two proposals were matched.

The creation of parametric design required several iterations and data structuring. Although Grasshopper has packages that facilitate the creation of structural grids, these are limited to simple surfaces. In complex surfaces, the functionality of these packages does not allow to follow the shape of the structure in a precise way. Another point is the curvature of the sections; this is a limitation within the software and structural analysis methods. For this case, geometric operations were performed that consisted of subdividing the beams into small sections so that it was able to follow the structure and reduce the difference that could exist in the oversimplification of the analytical model vs the construction model.

In this comparison, the structure was simplified to reduce the execution time; only one bracing was placed in the solutions. The result obtained is shown in Figure 41, which compares the performance of each of these solutions.







Constraints & Fix Values	Units	Values
		Min
#Waves		16
Ring Division		6
Aditional Rings		1
Main Beam Profile		RHS500x300x16'
Secondary Beam Profile		RHS500x300x12.5'
Bracing Profile		CHS323.9x6'
Self Weight Profiles	Factor	1
Dead Load	kN/m^2	1

Results	Units	Values
		Min
Mass	ton	482.90
Max Displacement	cm	9.20
Average Ratio		12.68%

Like Current Project

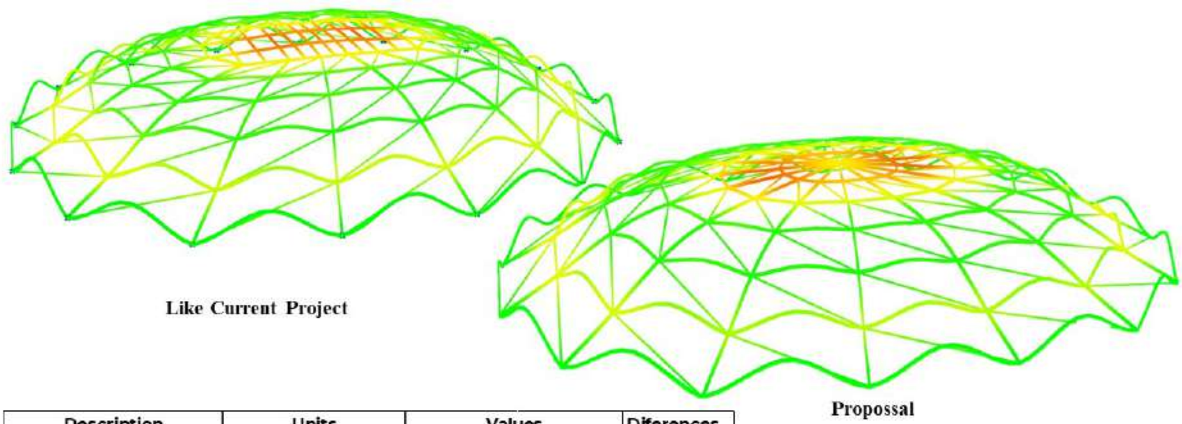
Constraints & Fix Values	Units	Values
		Min
#Waves		16
Ring Division		6
Aditional Rings		0
Main Beam Profile		RHS500x300x16'
Secondary Beam Profile		RHS500x300x12.5'
Bracing Profile		CHS323.9x6'
Self Weight Profiles	Factor	1
Dead Load	kN/m^2	1

Results	Units	Values
		Min
Mass	ton	441.43
Max Displacement	cm	7.55
Average Ratio		12.99%

Propossal

Figure 41 Structural grid proposal

The proposal has better structural performance since using the same profiles has a lower deflection with less material. The difference of this rationalization shows us that it has a saving of 41.5 tons and a deflection of less than 1.7 cm like as shown in Figure 42. Therefore, the proposed solution was chosen for the next optimization step.



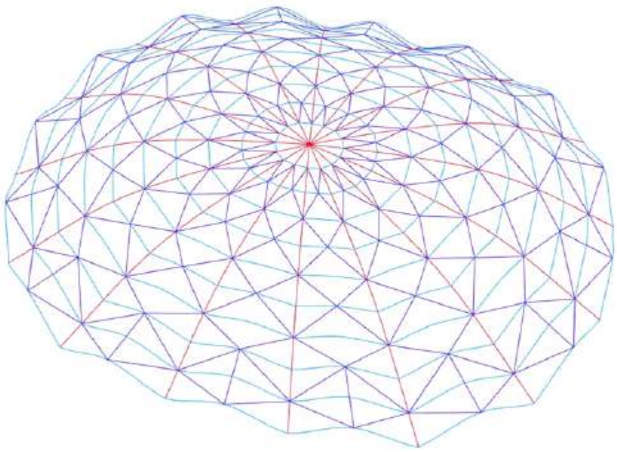
Description	Units	Values		Diferences
#Waves		16	16	Equals
Mass	ton	482.90	441.43	41.5
Max Displacement	cm	9.20	7.55	1.7
Average Ratio		12.68%	12.99%	-0.31%

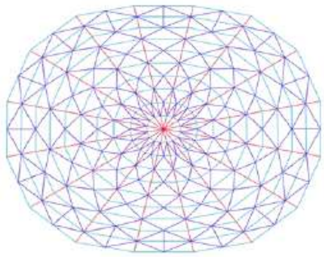
Figure 42 Comparison of structural grid solutions

Finally, the final parametric design was created; this had a higher degree of complexity since the bracings had to be coincident in working to have better structural behaviour. It was sought to emulate a similar bracing solution that the structure has, taking the experience of a good rationalization created by the structural engineer with several years of experience. Something added was to stiffen the beams that had a longer length to the centre, with the intention of this system allows to stiffen the structure and make it work more like a grid system.

One point to mention is that the self-weight of the structure is not factored in. The engineer Marko Završki advised us on the dead load imposed on the structure, for which the uniform distribution was made. The current load of the dead weight is considered 0.74 kN / m^2 plus the point loads imposed by the equipment hanging from the structure.

Variables	Values	
	Min	Max
Ring Division	3	12
Main Frame Profile	352	493
Secondary Frame Profile	352	493
Bracing Profile	80	121





Setup of Variables		
Description	Units	Values
#Waves		16
Width	m	98
Length	m	118
Roof Height	m	26.7
Transition Curvature	Scale Factor	0.65
Transition Height	m	24.4
Wave Heigth(Transition)	m	0.50
Fillet Curve	m (radius)	45.00
Min Heigth Wc	m	4.25
Variation Heigth Wc	m	0.50
Third Floor Height	m	9.25
Factor Selfweigth	Scale Factor	1.00
Uniform Dead Load	kN/m^2	1.00

Figure 43 Roof Parametric Model

Within the conceptual design phase, it was decided to create a uniform load of 1 kN / m^2 to have a safety factor that would allow point loads not to be considered. The main reason lies again in looking ahead and seeing how to optimize the algorithm to reduce execution time.

For example, if each load were placed on specific structure nodes, it would require an additional computation to find the nodes and divide the weight of each node depending on the number of axes and location of the rings. Point loads and a more detailed review could be done in dedicated software like SCIA. The main intention of Generative Design was to find the rationalization of the form.

Therefore, the parametric design shown in Figure 43 was prepared for better execution in the generative design phase. In addition, the variables such as the maximum number of rings and sliders to select within the list of commercial profiles were reduced, removing the smaller profiles that, due to their length, could not be an optimal design solution.

8.5. Generative Design Model of Roof Structure

Once the parametric design was created, the mechanisms and controls necessary to create the generative design study were identified in Figure 44.

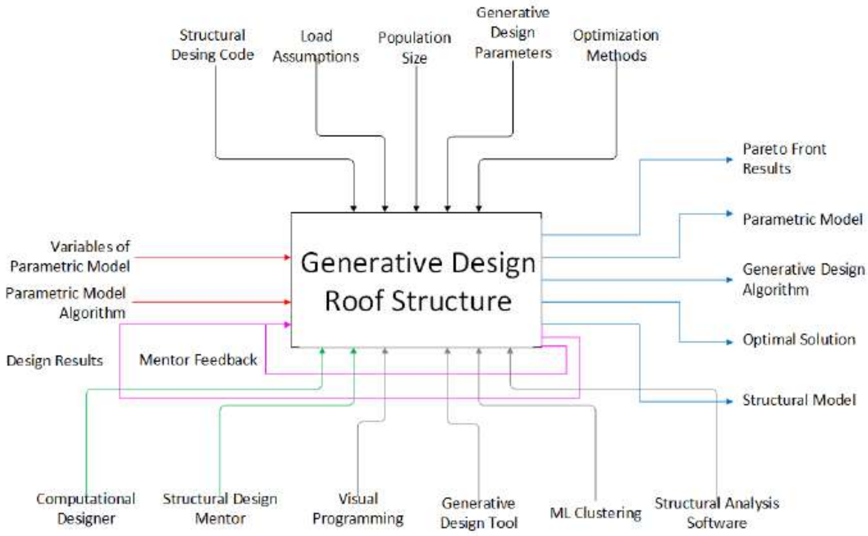


Figure 44 IDEF0 Generative Design of Roof Structure

The variables, constraints, and goals in the generative design are shown in Figure 45; on the left side, the graph results are on the right side. As previously indicated, structural design criteria were used during the parametric design to reduce the number of variables and thus avoid executing non-viable solutions, reducing the computational capacity in coherent operations within Generative Design.

In this case, the multicriteria goals changed due to the problem. In this study, the goals of minimizing global displacement and minimizing the structure's mass were maintained. The change made was to obtain the average of the overall performance ratio of the structure, calling it the percentage of utilization or performance. An optimal structure is capable of having good structural behaviour and works efficiently with the elements.

These elements had a low percentage of structural demand in their weight because they are governed for deflections due to the stadium's length. For this reason, arithmetic operations were performed to invert this relationship, considering the utilization residual rather than the utilization percentage during the generative design.

In this way, minimizing the utilization residue could find a solution that would work more efficiently with the obtained profiles and thus avoid having profiles with a lower utilization percentage. Within the algorithm, arithmetic formulas were applied to penalize the solution if it was less than 10% and greater than 80%.

Model Setup

Variables	Values	
	Min	Max
Ring Division	3	12
Main Frame Profile	352	493
Secondary Frame Profile	352	493
Bracing Profile	80	121

Setup of Variables		
Description	Units	Values
#Waves		16
Width	m	98
Length	m	118
Roof Height	m	26.7
Transition Curvature	Scale Factor	0.65
Transition Height	m	24.4
Wave Heigth(Transition)	m	0.50
Fillet Curve	m (radius)	45.00
Min Heigth Wc	m	4.25
Variation Heigth Wc	m	0.50
Third Floor Height	m	9.25
Factor Selfweigth	Scale Factor	1.00
Uniform Dead Load	kN/m^2	1.00

Graphs Results

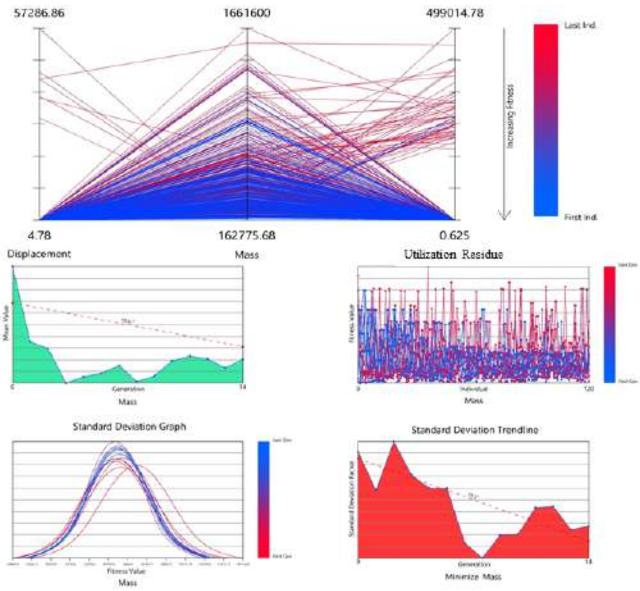


Figure 45 Roof Structure Model Setup

Figure 45 shows how the mass behaviour varied in each study until it reached stabilization. As shown in Figure 46, this generative design study, even with the measures taken, had a reduction of 337 variables, which was reflected in the space of 15,000,000 possible solutions, of which the study covered 1680. In Figure 46, it is shown the grouping carried out to find the best solutions within this study. In this section, several iterations were made to reduce the number of possible solutions, finally being the result of grouping the solutions into 18 clusters. In the end, in Figure 46, the best 36 of the 41 filtered solutions in the study are shown.

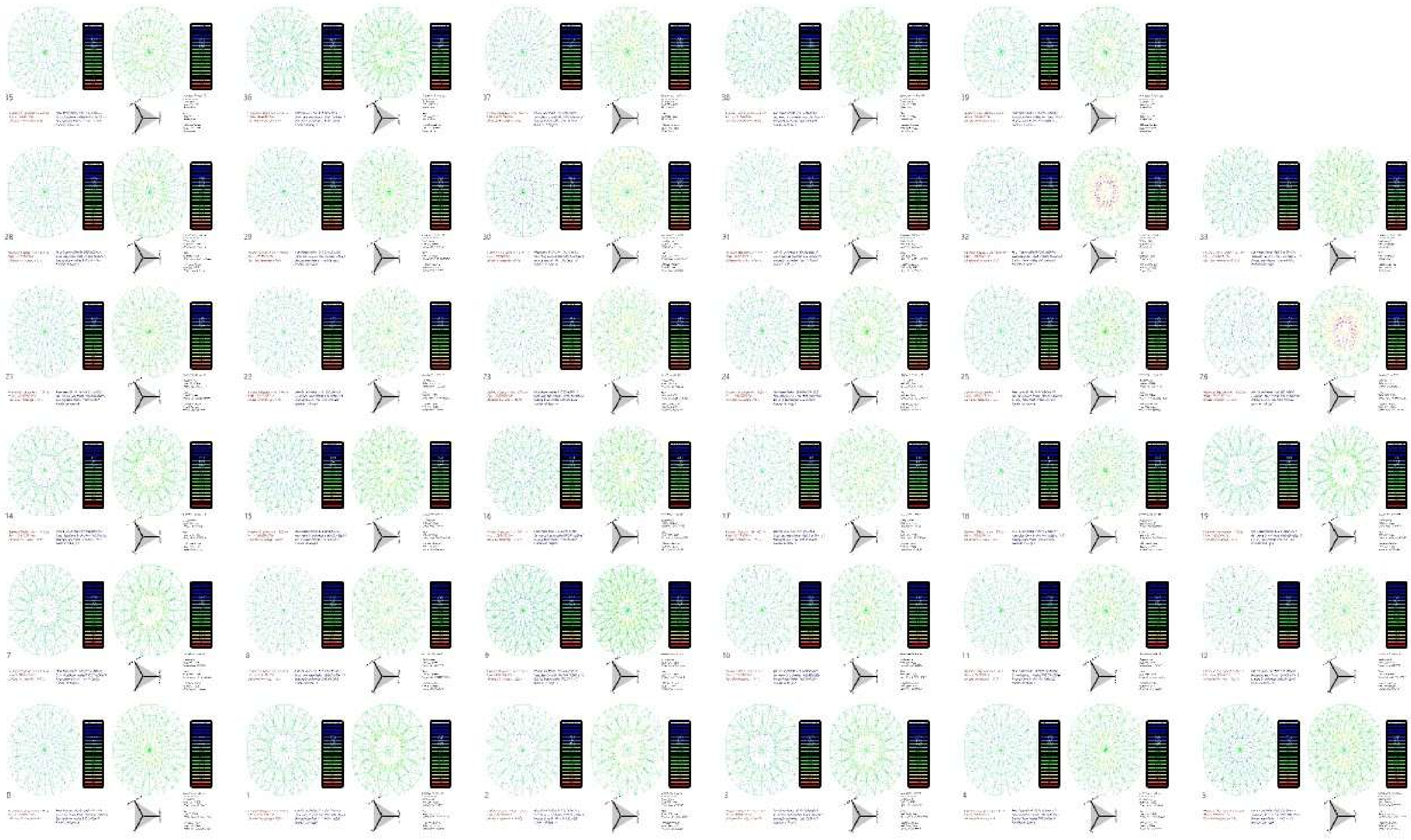


Figure 46 Grid of Pareto Front Solutions of Roof Structure

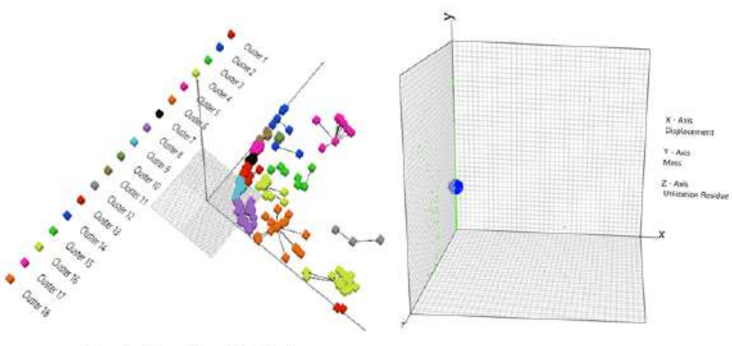
Population	
Generation Size	120
Generation Count	14
Population Size	1680

Algorithm Parameters	
Crossover Probability	0.85
Mutation Probability	1/n
Crossover Distribution Index	25
Mutation Distribution Index	30
Random Seed	8

Simulation Parameters	
N° of Genes (Variables)	4
N° of Values	370
N° of Fitness Objectives	3
Size of Search Space	1.50E+07

Non-Supervised Machine Learning	
Method (Algorithm)	Kmeans
# Clusters	18

Result and Analytics	
Pareto Front Solutions	118
# Evaluation of Solutions	41
# Filter Solution	1



Pareto Frontier Clustering

Figure 47 Roof Structure Generative Design Study Setup

Searching for the best solution was a complex process since some solutions only satisfied one goal. Nevertheless, the importance of the structural criteria and critical thinking led us to take more abstract characteristics to find a solution with better constructability that could be scaled up or improved in later phases. Among the criteria under consideration was ring location for later design phases because the equipment required by the type of use must be hung in the nodes.

Within the analysis by own load, average participation of 18% was found, which means that these profiles have a wide range, which will allow that in later phases where the combinations for last loads are analyzed, fewer changes in profile thickness can be made.

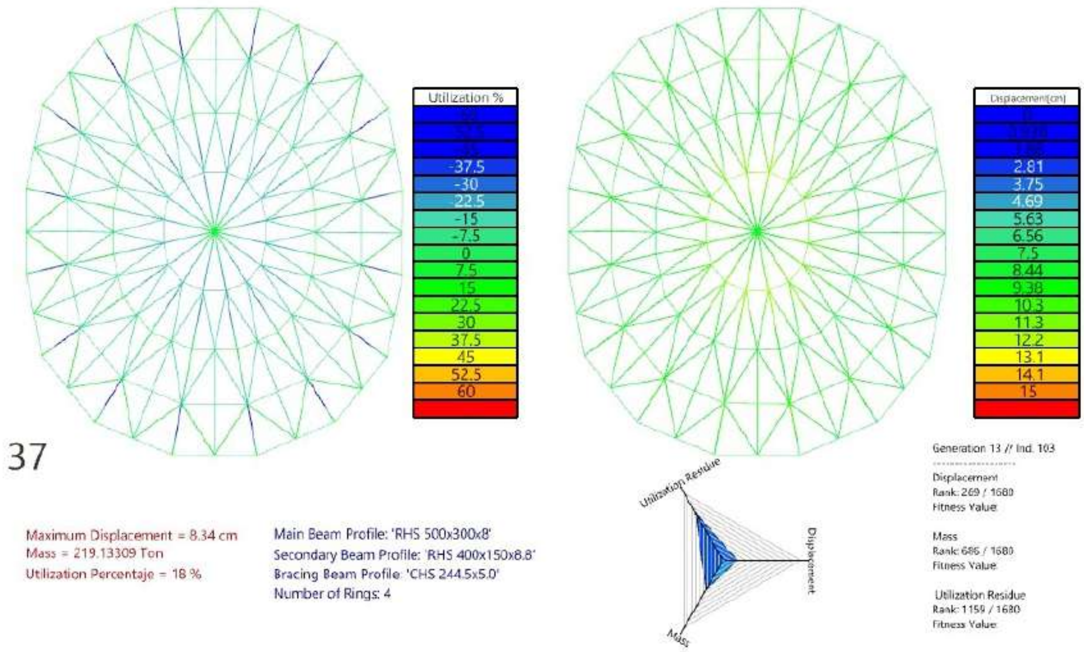


Figure 48 Best solution for Structure Grid

As a result, option number 37 of the filtered elements were chosen, with the main profiles similar to the current construction solution, four rings with a maximum global deflection of 8.34 cm that is admissible and can be reduced with construction processes such as camber in specific elements. Furthermore, within the analysis by self-weigh, average participation of 18% was found, which means that these profiles have a wide range, which will allow that in later phases where the combinations for last loads are analyzed, fewer changes in profile thickness can be made. In the end, as a comparison, we fear that the first test made with the current proposal vs the optimal option has a reduction of 220 tons. The result of this structure will be part of the BIM model for the case study presented.

8.6. Parametric Model of Facade

The planning process was optimized for this next phase because part of its definition was contemplated in 8.2. The engineering of the process IDEF0 was used; Figure 49 shows the generic flow of the task. The main change of the parametric model compared to it is that it requires the optimal geometry as input to make the facade model.

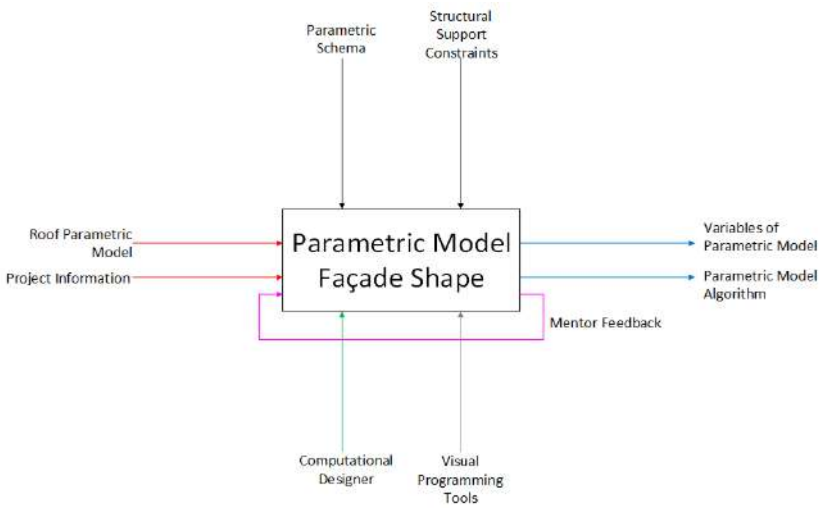
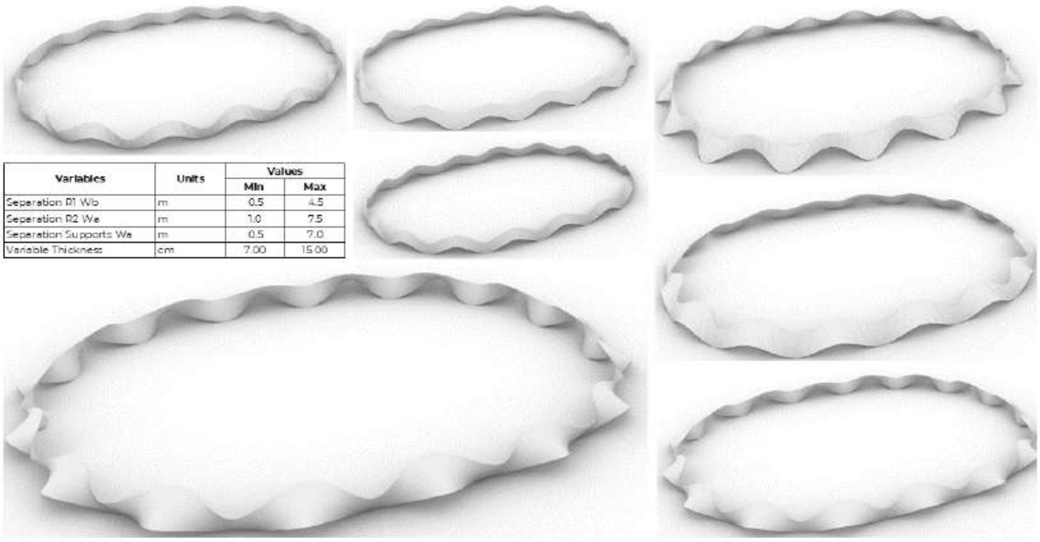


Figure 49 IDEF0 of Parametric Design for the Facade Shape

The parametric schema in Figure 24; is part of all parametric models; for that, it was not necessary to replicate in this task. In addition to this, we require a similar workflow shown in Figure 23.

The result was the creation of the parametric script that allowed modifying the geometric values of the facade. This phase has a more significant element of restrictions because the roof model found the optimal values of the variables, and these in this step are fixed values. Therefore, limits of variables were delimited; the importance was discussed in the previous subchapter. Some of the ways the script can create are shown in Figure 50.



Variables	Units	Values	
		Min	Max
Seperation R1 Wb	m	0.5	4.5
Seperation R2 We	m	1.0	7.5
Seperation Supports Wa	m	0.5	7.0
Variable Thickness	cm	7.00	15.00

Figure 50 Parametric Model of Facade

8.7. Generative Design Model of Facade

Similarly, as previously explained in Chapter 8.3, the goal was to minimize displacements, stresses, and mass to obtain the facade's optimal shape. The basic definition of mechanisms and controls is represented in the IDEF0 shown in Figure 51.

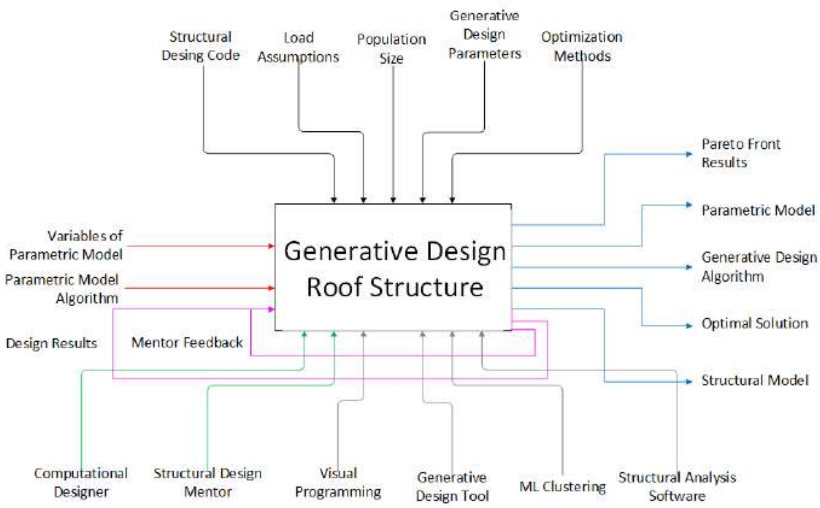


Figure 51 IDEF0 of Generative Design for Facade Shape

The variables, constraints, and goals in the generative design are shown in Figure 31; on the left side, the graph results are on the right side.

Model Setup

Variables	Units	Values	
		Min	Max
Separation RI Wb	m	0	1
Separation R2 Wa	m	1.0	7.5
Separation Supports Wa	m	4.0	10.0
Variable Thickness	cm	7.00	15.00

Constraints & Fix Values	Units	Values	
		Min	Max
#Waves		Fix Value	
Wave Heigth(Transition)	m	0.25	
Roof Height	m	Fix Value	
Transition Height	m	Fix Value	
Transition Curvature	Scale Factor	Fix Value	
Fillet Curve	m(radius)	45.00	
Width	m	Fix Value	
Length	m	Fix Value	
Factor Selfweigth	Scale Factor	1.50	
Thickness	cm	15.00	
Shuffle Height Wc		Fix Value	
Min Heigth Wc	m	4.25	
Variation Heigth Wc	m	0.50	
Third Floor Height	m	9.25	
Second Floor Height	m	5.5	
Min Heigth Wa	m	4.25	
First Floor Height	m	1.1	

Graphs Results

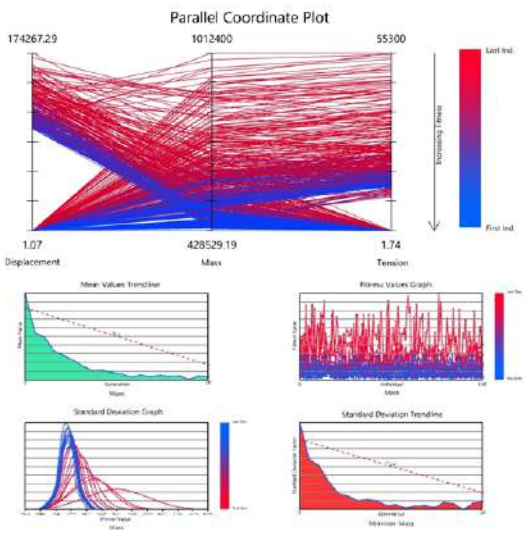


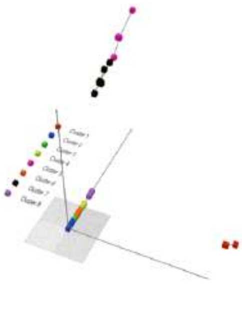
Figure 52 Facade Shape Model Setup

The main difference between the previous approach used in chapter 8.3 was an easy simplification to make the thickness variable on the shell. Where the stresses are high, volume can be concentrated or, in this case, requiring a greater thickness to withstand the structural stresses. Therefore, this leads to material reduction and optimization in areas where stress concentrations are minimal. So for this case, it was decided to create an equation within the algorithm that would use the stress distribution to change the thickness. Finally, a facade with a variable thickness that goes from 7 to 15 cm thick was obtained within this conceptual phase.

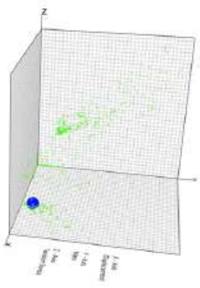
As shown in Figure 53, this generative design study had a considerable reduction in complexity compared to other studies previously carried out. This statement can be check in the size of the search space.

Population	
Generation Size	180
Generation Count	16
Population Size	2880
Algorithm Parameters	
Crossover Probability	0.85
Mutation Probability	1/n
Crossover Distribution Index	30
Mutation Distribution Index	25
Random Seed	2
Simulation Parameters	
N° of Genes (Variables)	3
N° of Values	138
N° of Fitness Objectives	3
Size of Search Space	4.40E+04
Non-Supervised Machine Learning	
Method (Algorithm)	Kmeans
# Clusters	8

Result and Analytics	
Pareto Front Solutions	179
# Evaluation of Solutions	24
# Filter Solution	1



Pareto Frontier Clustering



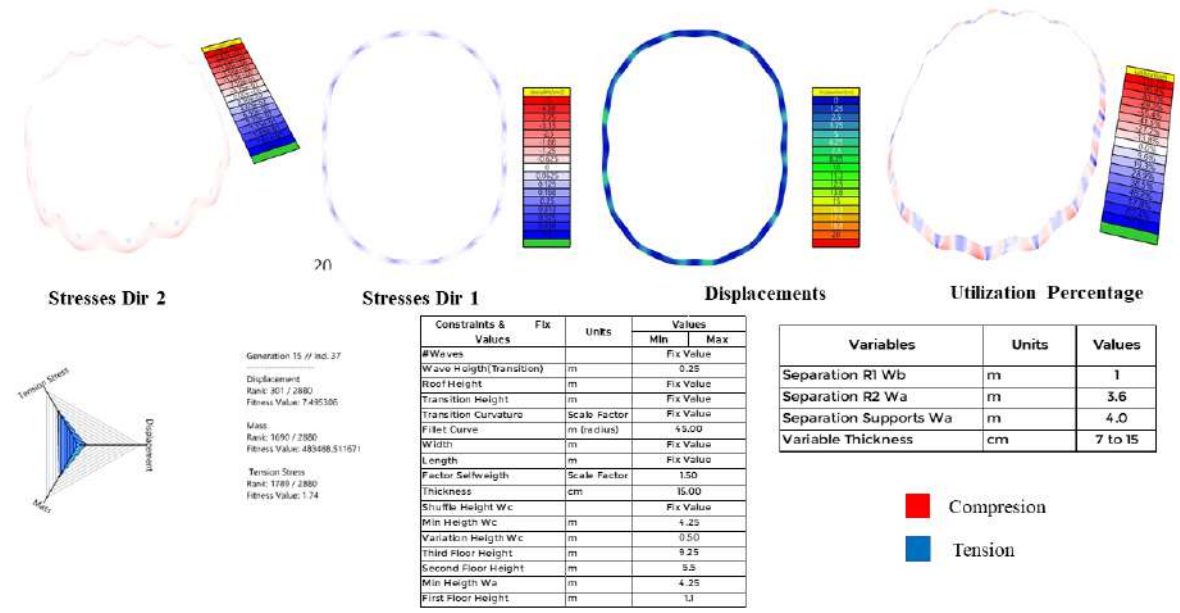
Pareto Front Domain

Figure 53 Facade Shape Generative Design Study Setup

Figure 54, it showed a filter of the best 24 solutions found. Again, several of them were similar; This was because, initially, the minimum spacing that the facade should have been restricted to leave a free zone for circulation, so this variable was practically fixed. Thus, only the calculation engine had to search between two variables to the entire solution space.

Figure 54 Grid of Pareto Front Solutions of the Facade Shape

For this occasion, the optimal solution was found in less computing time and more evident since the problem converged to the global minimum value. In addition, the clustering process used to filter solutions did an efficient job, allowing us to reduce noise among other solutions and easily find the best result.



Constraints & Fix Values	Units	Values	
		Min	Max
#Waves		Fix Value	
Wave Heigth(Transition)	m	0.25	
Roof Height	m	Fix Value	
Transition Height	m	Fix Value	
Transition Curvature	Scale Factor	Fix Value	
Fillet Curve	m (radius)	45.00	
Width	m	Fix Value	
Length	m	Fix Value	
Factor Selfweigth	Scale Factor	1.50	
Thickness	cm	15.00	
Shuffle Height Wc		Fix Value	
Min Heigth Wc	m	4.25	
Variation Heigth Wc	m	0.50	
Third Floor Height	m	9.25	
Second Floor Height	m	5.5	
Min Heigth Wa	m	4.25	
First Floor Height	m	1.1	

Variables	Units	Values
Separation R1 Wb	m	1
Separation R2 Wa	m	3.6
Separation Supports Wa	m	4.0
Variable Thickness	cm	7 to 15

Figure 55 Optimal Solution for the Facade Shape

Inside Figure 55, the final result is shown with its structural behaviour; it has an excellent behaviour since the solicitations are minimal. In addition, the displacement can be decreased in later design phases, adding greater rigidity to the area, increasing its section in the required areas within a more refined analysis.

Finally, the analysis is seen through a change in tonality of grey to black in the areas where a greater concrete thickness is required. The analysis shows that a thicker section is required within the area where it unloads its weight.

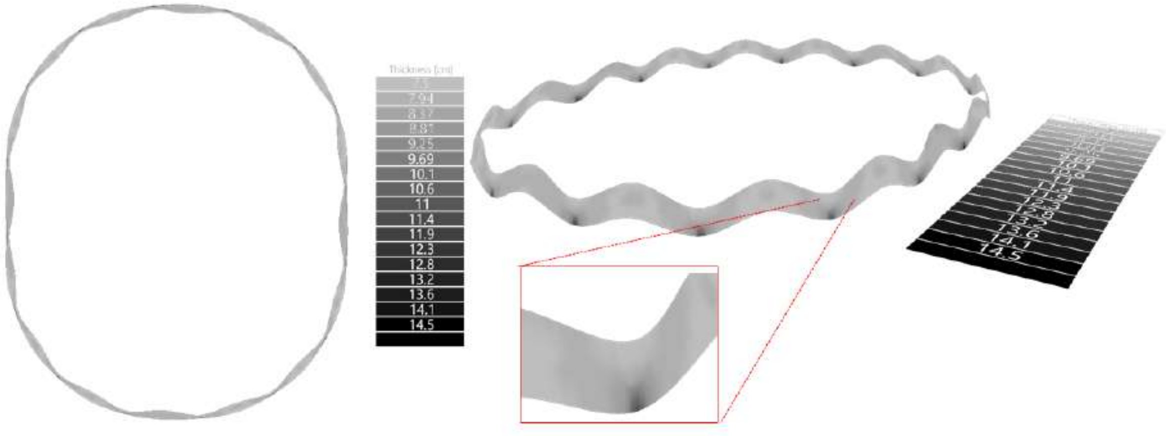


Figure 56 Facade map showing thickness variability zones

8.8. Setup of parametric design of title system in Facade

This phase focuses on preparing the parametric model to reduce the computation and search time to optimise and standardise the elements on the facade. The main objective of this phase was to provide a parametric model that was close to meeting the standard dimensions. The basic definition of mechanisms and controls is represented in the IDEF0 shown in Figure 57.

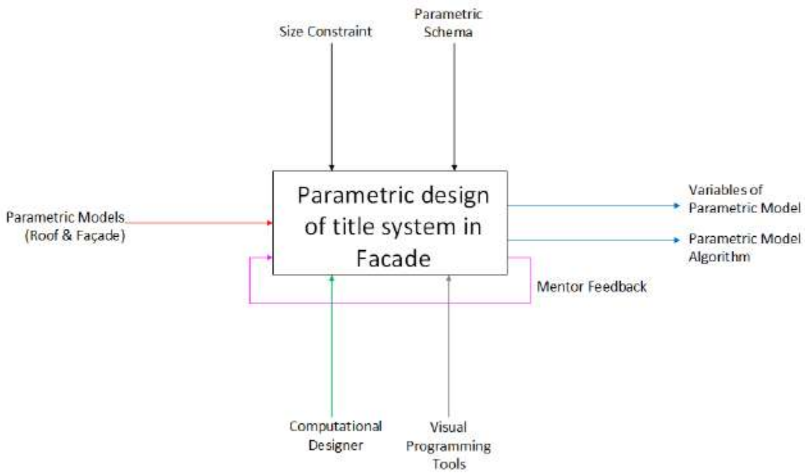
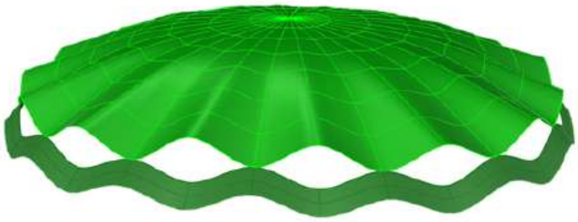


Figure 57 IDEF0 of Parametric Design for Facade Title System

This phase started with the parametric models resulting from the previous phases of the study. Then, it was sought to create parametric designs by separating them on the roof and interior facade to reduce the computation time. As shown in Figure 58, restrictions and objectives were established within it. Then, with the parametric schema, it was sought to obtain clarity when creating the mesh.



Initial Setup of Variables	
Description	**Information**
Area	12967.25 m²
Main Type of Title	Diamonds
Secondary Type of Title	Triangles
Expected length per edge	75 cm
Expected clearance per panel	less than 5 mm

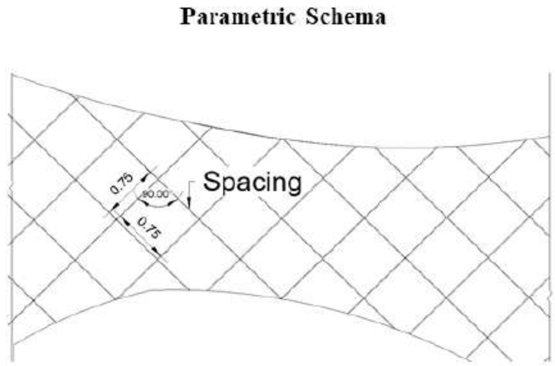


Figure 58 Setup of Parametric Model

Although the generative design could be used, we decided not to use it to find the size of titles in this first phase. Instead, it was decided to choose the set of variables and use mathematical logic to obtain the approximate value by setting the divisions in "U" and "V". Each surface was solved differently. For example, on the roof, the creation was initially using a flat grid with the dimensions of the titles and then projecting it to the surface, doing some geometric subtraction operations only to keep the titles that intersected the surface.

Regarding the facade, the operation was more direct; for this case, a package integrated into Grasshopper was used; this allows panelization in specific ways. Additionally, it is worth mentioning that Lunchbox facilitates geometric operation on simple surfaces but has a drawback with tools made with revolution or a dome shape since the titles created are entirely irregular and decrease in size up to 5 times in the top area.

The result of the geometric design is shown in Figure 59. Due to subsequent considerations, it was configured in a title size of 76 cm in the common areas of the surface.

8.9. Optimisation and Standardisation of title system in Facade

In the optimization phase, the initial configurations of the parametric design were identified, that triangular titles had to be considered in border areas among them.

Although the parametric design sought to restrict the size of the title, it had variations in multiple areas because it is a method based on surface divisions. The surface takes unitary coordinates, which means that the width is equal to 1, and this is divided by similar divisions, thus being irregular where there is a sudden change in curvature.

Therefore, searches were carried out to improve the meshing of the surfaces; for this, the generative design using the genetic algorithm had limitations due to the way of creation, for which it was discarded. Instead, the Physics-Base generative design was employed using the Kangaroo package.

Initial Setup of Variables	
Description	**Information**
Area	12967.25 m²
Main Type of Title	Diamonds
Secondary Type of Title	Triangles
Expected length per edge	75 cm
Expected clearance per panel	less than 5 mm

Tools and Techniques for Optimization	
Description	**Information**
Paneling	By U and V
Initial Method of optimization	Surface Relaxation
Package for Relaxation	Kangaroo
Grouping Similar panels	Machine Learning
Package for Machine Learning	LunchBox ML
Standardization title process	Average geometry

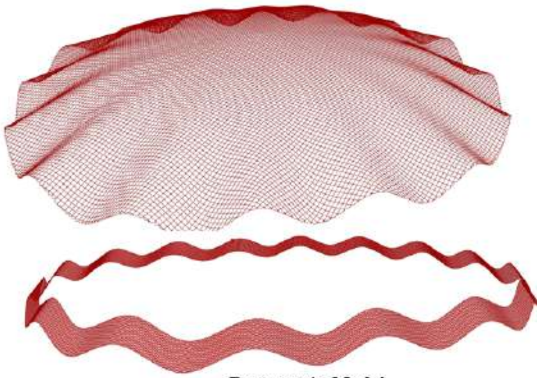


Figure 59 Result of Parametric model and set up for next phase

The Kangaroo package created by Daniel Picker (2010) uses the Particle Spring System (PSS) algorithm. The Physics Base Generative design included the PSS algorithm agreeing on Newtonian dynamics, continuum mechanics, numerical computation, differential geometry, vector calculations, approximation theory, and computer graphic to resolve the geometrical operations (Nealen *et al.*, 2006).

In a simplified way, it is governed by Newton's second law, where the vertices are manipulated accordingly to their position, stiffness, mass and/or speed. For this reason, Kangaroo has multiple components that simulate forces that affect particles or objects. It seeks to find the total force of the vector for each particle by adding different forces that act on it (Piker, 2011).

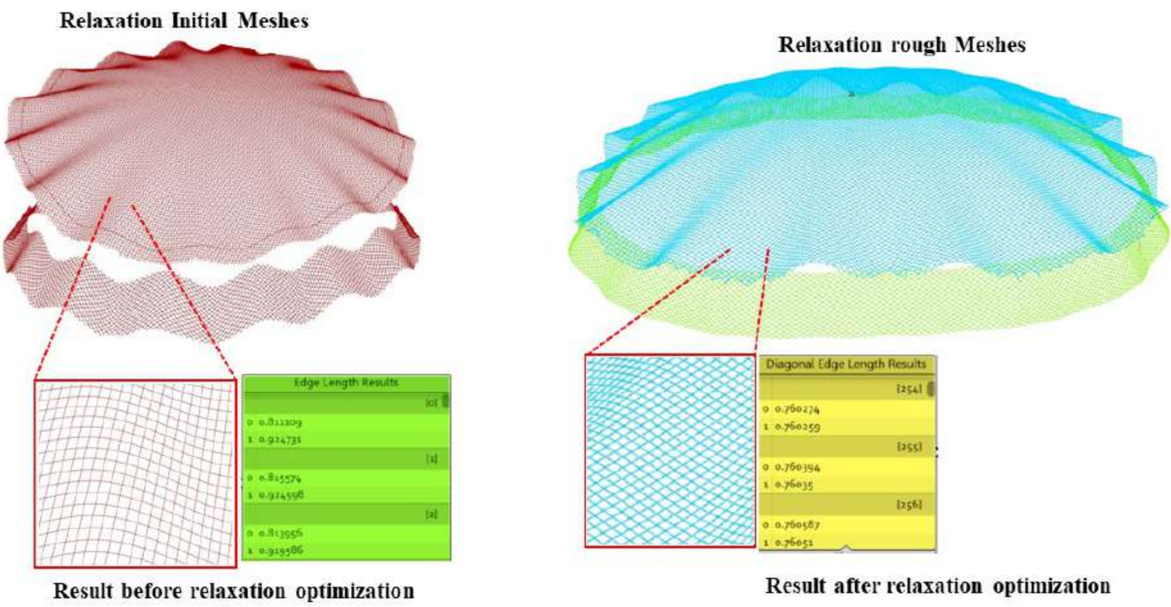


Figure 60 Relaxation results

Due to Kangaroo's working method, the surface had to be converted into the mesh to have access to the vertices and thus apply the forces to reach the goal. Figure 60 shows the two elements (roof and facade) where several iterations were used to define the length that had to reach the edges so that the correct relaxation was allowed.

The initial phase shows that several edges, even though at the beginning, we tried to reach the target value, do not fit with the expected value due to what was previously commented in chapter 1.1

The relaxation method used with Kangaroo acts to use the main mesh and seek to compress or extend the edges to reach the objective set. In this case, the length per edge and keeping the attach to the shape was the main reason for extending the meshing. An additional surface must be given so that, if required, it takes part of the excess surface to rationalize the meshing better.

In Figure 60, the final configurations resulted in discretization and relaxation of the mesh that makes up the titles. As shown in Figure 61, each of the components required different forces to achieve the expected result.

Relaxation Parameters	
Description	Unitary values
Initial U divisions	27
Initial V divisions	580
Collide Strength	600
On Mesh Strength	1500
Length Strength	5
Goal Length Strength	76 cm
Hinge Strength	15
Goal Hinge Strength	90°
Equal Angle Strength	6

Relaxation Parameters	
Description	Unitary values
Initial U divisions	208
Initial V divisions	246
Planarize Strength	200
Smoth Strength	3
Length Strength	100
Plastic Anchor	1
Clap Length Strength	3
Boundary Strength	1000
On Mesh Strength	1000
Min Panel Size	75 cm
Max Panel Size	76 cm

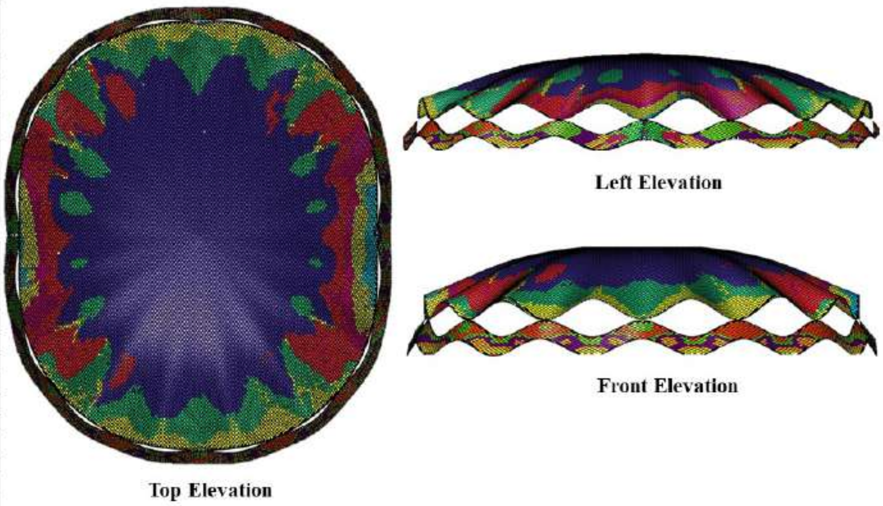


Figure 61 Final Setup of relaxation and Final result of the clustering technique

After this, Unsupervised Machine learning (ML) was used using the Gaussian mixture algorithm. Although other methods perform clustering through ML, it was decided not to use K-Means, because this surface is irregular. It was agreed that the best algorithm to reduce clustering bias due to Gaussian Mixture former performs complex classification (Maklin, 2019) and optimizing the fit between the data and the model (Maugis, Cathy, Celeux and Martin-Magniette, 2009)

For the classification of titles in Stožice Arena, triangular and irregular markers were eliminated from the initial operation to reduce the number of initial groups. In addition, the values sought were normalized. The main objective was to achieve titles grouped into similar elements that allow them to be replaced by a title with the average value of the group. The result of the groups is shown graphically in Figure 62.

Once grouped, the panels were standardized, reducing their variability and creating only standard panels. The geometric mean of the elements within the group was sought to create a single panel.

However, since their geometry changes, the standard panels could overlap, resulting in multiple iterations to find the appropriate groups. In addition to this, the maximum spacing of 5 mm was considered for imperfections in manufacturing or installation.

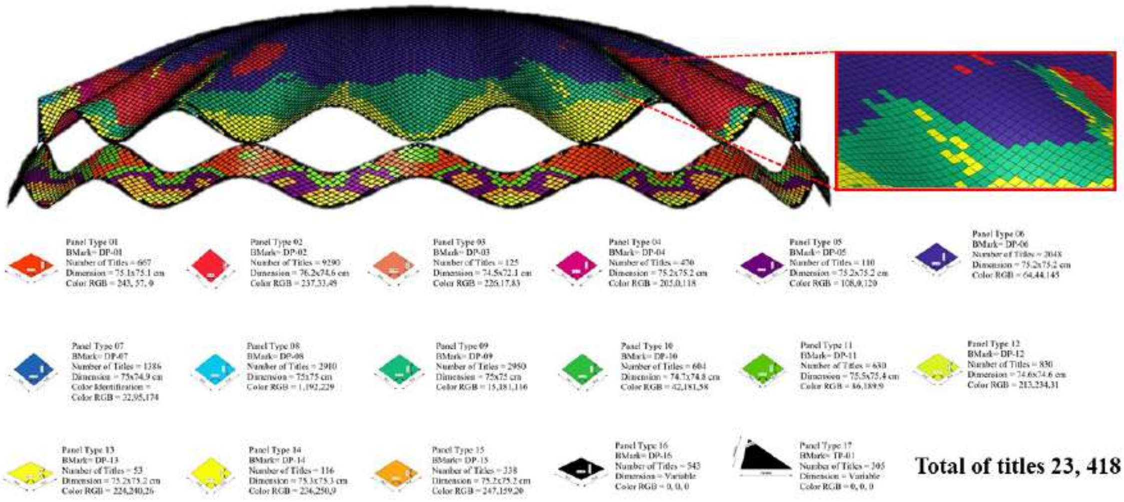


Figure 62 Group of titles found in Stožice Arena

The final result was fifteen standard panels, non-standardized diamond panels, and non-standardized triangular panels. Non-standardized panels can follow the same criteria previously done in another study individually to avoid wasting material.

A point to consider about the activities carried out is that this operation is not magic. Everything has areas for improvement, which require investing extra time in code and separating it from the final result to solve it more precisely. For example, Figure 63 show the errors found in areas where there are irregular diamond panels. These need to be reconstructed to organize their control points correctly for the creation of the titles. In the surface axis facade, an error in titles line insertion was broken within the exchange of the initial panels vs standardized panels.

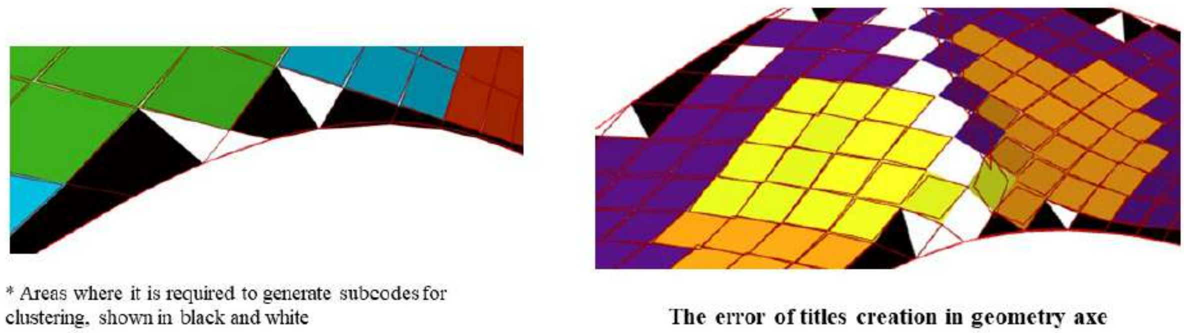


Figure 63 Areas of improvement in the creation of title system

Finally, ML, Generative Design, and Information-fed parametric models are not unique to these previously developed activities.

Using clustering through ML, it is possible to create associated subsystems, seeking to normalize and standardize construction elements, eliminating variability and reworking, serving as tools that achieve the objectives set out in the constructability technique and the Lean philosophy.

Tangible examples within the project could be the placement of formwork, grouping metal deck sheets in the roof area, curtain system, and work fronts by zoning.

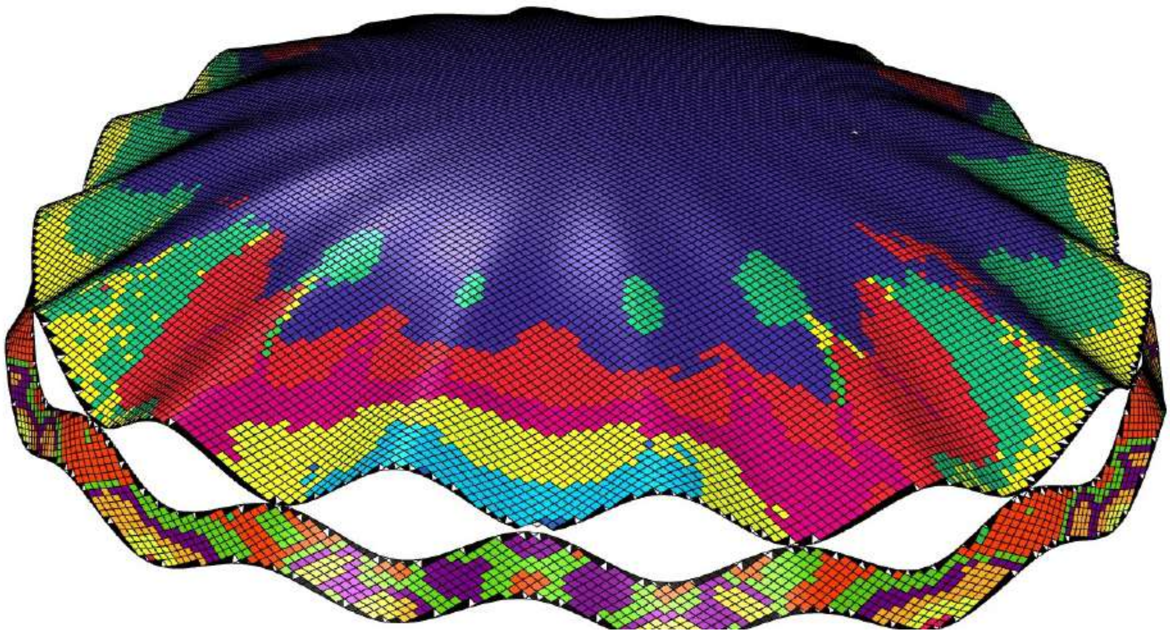


Figure 64 Perspective of Stožice Arena with colour-coding in the title system group

8.10. BIM Model of Stožice Arena in the schematic phase

Finally, once the optimizations have been found, it is time to make the digital model. Therefore, in the IDEF0 shown in Figure 65, the mechanisms and controls necessary for said activity were identified.

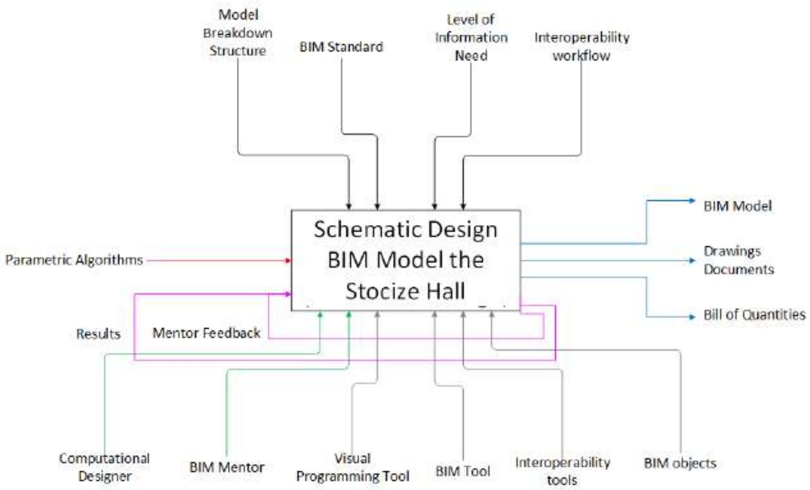


Figure 65 IDEF0 of Stocize Arena BIM Model

8.10.1. Controls and Mechanisms for the creation of the BIM model

As mentioned in chapter 4.2, creating a BIM model requires standards and protocols, so defining them in this phase was essential. The main objective of the model for this case study was the creation of the three-dimensional model, the creation of documentation for the conceptual design phase and obtaining preliminary information on the required quantities of materials. Typically, all this is specified within the BIM Execution Plan (BEP); however, as only a part of the Stožice Arena was developed, it was decided not to reach that level of definition. Furthermore, creating a BEP would further increase the level of complexity and deviate from the study's primary objective, which is to show how generative design helps the tasks related to rationalization.

Considering this, it was decided to take the necessary controls to achieve the previously mentioned objectives. For that motive, the Model Breakdown Structure developed during the study was carried out. The functionality of this lies in standardizing the names of the files for a quick search, obtaining only the elements required for the main activity and finally and most importantly, reducing the computational load for opening and manipulation.

This point is of utmost importance due to the large number of objects required for its creation. Therefore, there must be a balance between the number of sub-models to facilitate the work of the modellers without the need for computer equipment with large computational requirements. This point is part of seeking to implement Lean within a simple process such as defining sub-models. In addition, the creation of the nomenclature has the advantage of allowing the incorporation of new models in later phases, allowing the traceability and development of the project in a more structured way.

Table 9 shows the sub-models created in this study to represent the conceptual phase of the affected elements during this case.

Table 9 Model Break Down Structure of BIM Models

File Name	Description
G5-21-B7-ZZ-XX-G-M3-R21	Documentation and central model
G5-21-B7-CP-XX-A-M3-R21	Curtain Walls
G5-21-B7-SC-LL-S-M3-R21	Facade Concrete
G5-21-B7-SC-RF-S-M3-R21	Roof Concrete
G5-21-B7-SS-RF-S-M3-R21	Roof Steel Structure
G5-21-B7-FT-LL-A-M3-R21	Facade Titles
G5-21-B7-FT-RF-A-M3-R21	Roof Titles
G5-21-B7-FC-LL-A-M3-R21	Facade Curve
G5-21-B7-FC-RF-A-M3-R21	Roof Curve

By themselves, these are only three-dimensional models, which, although they provide a greater understanding of the project, would only serve for renderings or conceptualization. For this reason, it was decided to create BIM objects that would allow the construction elements to be represented graphically. Therefore, the Level of Information Need that should be included for this conceptual phase was defined; it had to be coherent to achieve the objectives set and, in turn, be as Lean as possible. Within Table 10, the Object Break Down Structure is shown to give a clear definition of what BIM objects should contain, considering that this new ISO standard has a definition in geometric qualities, information, and documentation.

Table 10 Level of Information Need in Stožice Arena BIM Model

Geometry							
Element	Detail	Dimentionality	Location	Appearance	Parametric	Accuracy	Reliability
Curtain Walls	Generic	3D	Relative	Schematic	Not request	LOA 20	Preliminary
Mullion	Generic	3D	Relative	Schematic	Not request	LOA 20	Preliminary
Structural Framing	Generic	3D	Relative	Schematic	Not request	LOA 20	Preliminary
Slab	Generic	3D	Relative	Schematic	Not request	LOA 20	Preliminary
Titles	Generic	3D	Relative	Schematic	Not request	LOA 20	Preliminary

Information				
Curtain Walls	Mullion	Structural Framing	Slab	Titles
Uniformat	Uniformat	Uniformat	Uniformat	Uniformat
BMark	BMark	BMark	BMark	BMark
Type	Zone	Type	Zone	IdMark
	Type	Cut Length	Type	Zone
				Type

Documentation	
Curtain Walls	Schematic Design
Mullion	Schematic Design
Structural Framing	Schematic Design
Slab	Schematic Design
Titles	Schematic Design

Regarding the BIM modelling tool, it was decided to use Revit in its 2021 version. This choice was because it is one of the most commercial software in the market, allowing a great support forum and interoperability plug-ins.

The scripts were developed in Grasshopper and Rhinoceros 7, so a way had to be found to interoperate with results and reduce rework. Fortunately, Grasshopper has several developments that make this activity. The study decided to use Rinho Inside Revit for the basic geometric creation, which did not require additional information but only integrated into the object by default.

The author has a broader knowledge of Dynamo. For this reason, he decided to use the Speckle plugin to transfer the information from Grasshopper to Dynamo and create operations to feed the objects that required information, such as the group number and element. Although it is worth mentioning that this operation can be performed in Rinho Inside Revit, the use of Speckle was to reduce the learning time in this subcategory. The final result of the final optimized geometry is shown in Figure 66.

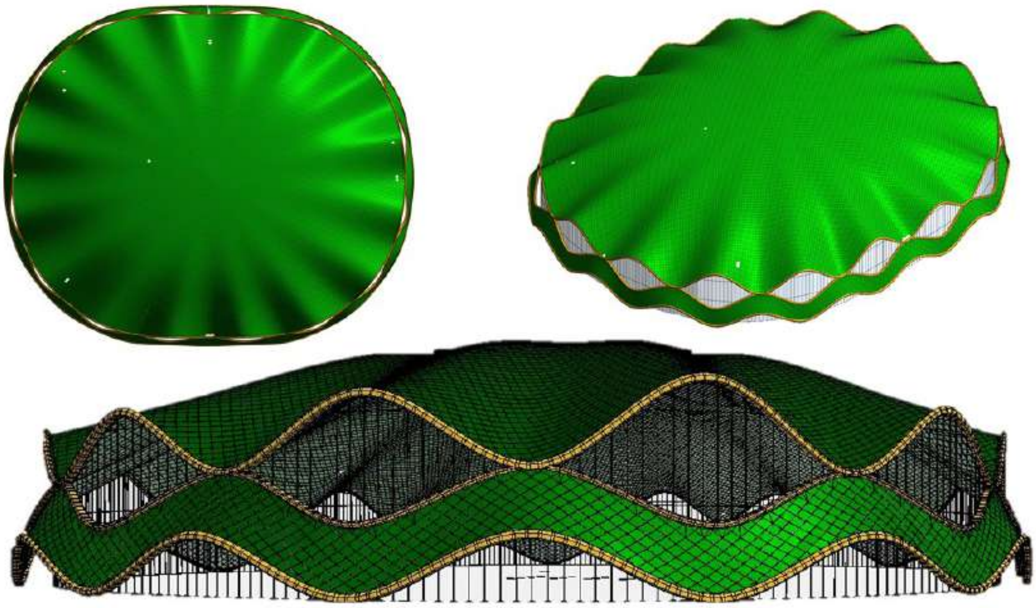


Figure 66 Views of Stožice Arena BIM Model

As indicated, one of the advantages that BIM models have over three-dimensional elements is the possibility of creating support views from the model to be used in the documentation. Annexe 4 shows an example of some sheets taken from the model as proof of its functionality.

In addition, material estimates were made, mainly focused on obtaining the quantities of concrete, the number of fragments that make up the curve of the facade and the number of panels with their respective id. Finally, using BIM models with visual programming tools allows creating information for their manufacture and installation. An example of this is shown in Figure 66.

Finally, it was demonstrated that we could improve processes through technological adoption by establishing an adequate flow with Lean and BIM tools. The sample of this is the BIM model, the result of the optimization and standardization processes, which serves as a basis to be able to host information within the digital model in such a way that it centralizes the activity of graphic representation, information, and documentation of the project for future development phases.

9. DISCUSSION AND GENERAL CONCLUSIONS

The construction sector has mechanisms to improve its productivity. However, it will depend on the vision of governments and private companies to take advantage of these. Currently, the European Union is aware that the industry needs to be digitized, so we hope this continent will lead a digital transformation in our sector in future years.

Most of the problems are due to personalities and lack of empathy with the project's objectives; this causes the individual benefit to always seek instead of the collective one to create the project. Lean seeks to eliminate this vice through its philosophy, making it clear that for a solid team to exist, it must consider the objectives of its members, thus seeking to enhance their skills in favour of their profession and the organization.

BIM is a methodology that unites standardized processes and enables available technology; a clear example is how the Global Economic Forum proposes it as the central point for digital transformation and adopting new technologies in our sector.

Constructability is a technique that is more than 50 years old and that now has tools that both BIM and Lean promote, intending to improve Knowledge Management during the execution of the project. Constructability is based on collaboration, standardization, and repeatability, converging with BIM and Lean.

Adopting technology allows problems such as rationalising design because it separates the competencies between computers and humans, thus having the best of both worlds, precision, and speed of computation in operations vs intrinsic knowledge and creativity. This combination allows us to improve the design rationalization process by planning and searching for the optimal result.

Algorithmic thinking allows us to create generative design models with rules that the computer can compute, allowing us to generate thousands of designs quickly. The use and manipulation of generative designs require a great understanding of the problem and collaborative work in its creation to reduce bias. Multicriteria studies allow generating solutions that consider multiple project variables.

Artificial Intelligence is increasingly democratized within our sector, allowing us to use it through platforms and scripts without the need for an advanced technical level in computer science and programming. For example, this allows us to use Heuristic, Particle System and Clustering algorithms as a support method for the activities required in a project.

Using all these mechanisms and technologies requires a change of mindset, a culture of respect, and innovation to be successfully integrated into an organization.

9.1. Plans for future work

This thesis only showed an introductory part of everything digital transformation brings as a benefit to our profession so that future work will seek to into related topics.

Within the fields to study in more detail within the mentioned topics, the author proposes the following subjects:

- ✓ Non-technical problems within construction: A practical case of Business Reengineering Process.
- ✓ Structural optimization based on design rationalization through Artificial Intelligence.
- ✓ Optimization of constructive rationalization through Last Planner System and Artificial Intelligence.
- ✓ Optimization and standardization of materials within the construction project using Clustering techniques with Machine Learning.
- ✓ Buildability processes implemented as a practical guide for design rationalization.
- ✓ Design based on the simplification of construction elements using Constructability technique and BIM.

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1. LIST OF ACRONYMS AND ABBREVIATIONS

ACRONYM	TERM
3D	Third Dimension
3P	Production-Preparation-Process
5S	Sort, Set, Shine, Standardise, Sustain
AI	Artificial Intelligence
AIA	American Institute of Architects
AIR	Asset Information Requirements
AKKA	Ana Kucan, Luka Javornik
BCF	BIM Collaboration Format
BDAS	Buildable Design Appraisal System
BEP	BIM Execution Plan
BIM	Building Information Model
CAD	Computer-Aided Design
CDE	Common Data Environment
CIC	Computer Integrated Construction
CII	Construction Industry Institute in the USA
CIIA	Construction Industry Institute in Australia
CIRIA	Construction Industry Research Information Association
COBIE	Construction Operations Building Information Exchange
EIR	Exchange Information Requirement
EU	European Union
FIEC	European Construction Industry Federation
GDP	Gross Domestic Product
I.T	Information Technology
IDEF0	Integration Definition for Function Modeling
IFC	Information Exchange Standards Such as Industry Foundation Classes
IPD	Integrated Project Delivery
ISO	International Organization for Standardization
LACCD	Los Angeles Community College District
LCI	Lean Construction Institute
LoA	Level of Acceptance Specification for BIM Reality Capture Simulation
LOD	Level of Development Specification
LPS	Lean Production System
MaRS	Medical and Related Sciences
MEP	Mechanical Electrical and Plumbing
ML	Machine Learning
MOGA	Multi-Objective Genetic Algorithm
MPa	Mega Pascals

NPGA	Niched Pareto Genetic Algorithm
NSGA	Non-dominated Sorting Genetic Algorithm
NSGA II	Non-dominated Sorting Genetic Algorithm II
OCCS	OmniClass Construction Classification System
OIR	Organizational Information Requirement
PAES	Pareto Achive Evolution Strategy
PDCA	Plan-Do-Check-Adjust
PSS	Particle Spring System
SCRUM	Scrum is a process framework used to manage product development and other knowledge work
SISP	Strategies Influencing Suppliers' Performance
SPEA	Strength Pareto Evolutionary Algorithm
SVA	Sadar+Vuga
UK	United Kingdom
USA	United States of America
VEGA	Vector Evaluated Genetic Algorithm
VIP	Very Important Person

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APPENDIX 1: SHAPE OPTIMISATION

I. Question for the Project Manager of the project

1) What were the proposed construction dates, and what was the final project schedule?

2) What were the site limitations that affected the construction process or project design?

3) What were the main changes between the conceptual design and the final shape of the Arena shape?

4) Why was the height of 34 m adopted? Was it a client's requirement due to architecture, structure, or other specific reason, or the initially proposed heights?

5) Was there a minimum or maximum height for the Arena? (Indicate the numbers if you have them)

6) What is the roof system, how is it composed?

7) What was the biggest challenge in the placement and creation of the support structure for the roof?

8) How was the roof installed, construction process (individual panels, prefabricated system, on-site assembly, and so on and so for?

9) How was the facade installed, construction process (individual panels, prefabricated system, on-site assembly, etc?

10) What were the changes within the construction process that most affected the delivery date?

11) How many cranes were used for the project, and how much maximum weight did each one support?

12) How were the cranes were chosen and the location of the same (restriction due to transport of elements, more significant area of influence, restrictions due to other types of things?

13) How many titles does the Arena contain on the facade?

14) How many types of titles were manufactured for the Arena?

15) What percentage of the total cost was used for the creation of the facade and roof?

16) What type of contracting system was used for the project? (Design-Bid-Build, CM at Risk, etc.)

17) How much time was allocated for the design of the project?

18) What tools, methodology, or framework was adopted to coordinate, manage, and control the work?

19) What was the final cost of the project?

II. Question for the Structural Engineer

1) Was there a minimum or maximum height for the Arena? (Indicate the numbers if you have them)

2) What was the restriction between column separation?

3) How is the structure that supports the roof, primary elements, secondary elements, supports or tensioners, columns, piles, and dice composed?

4) How much offset was required in the court and bleachers to place columns?

5) For what actions was the cover of the area design? (Wind, Earthquake, Gravitational, etc.)

6) Why was it decided to use the rectangular metal profiles in the structure?

7) What were the tools for the schematic design of the form (Softwares, mockups, packages, scripts, etc.)?

8) What tools were used for the structural calculation?

9) What tools or methodology was adopted for the creation of the design?

10) What were the dead loads considered for the design, given that should it be designed to be multipurpose?

11) What were the critical loads imposed on the study?

APPENDIX 2: BIM MATURITY ASSESSMENT AND PERCEIVED LEAN IMPROVEMENTS CREATED BY (HAMDI AND LEITE, 2012)

Level n°	Perceived level of maturity	Detail (NBIMS CMM,2007)	Area of improvement	Relationship to Lean		Explanation	Reference
				Involved Lean principle	Lean Construction practice		
9	Limited Knowledge Management	Limited Knowledge Management implies that KM strategies are in place and authorative information is beginning	Having a robust data-rich environment, with virtually all authorative information loaded and linked together	Select an appropriate production control approach	5s Process	Because of the increasing number of people involved in BIM information, there is a need to manage the knowledge acquisition and ensure consistency between plans, specification, models and other supportive documents	Weygant, 2011
10	Supports External Efforts	External information is linked into the model and analysis can be performed on the entire ecosystem of the facility throughout its life	Improving analysis capacities and then decision making effectiveness during the lifecycle	Increase flexibility	Master Schedule	Use and reuse of design models to set up analysis models such as energy, acoustics, wind, thermal, etc. reduce setup time and make it possible to run more varied and more detailed analyses	Sacks et al. 2010
5	Limited Control	Business processes are in place and the organization has begun implementing change management procedures	Achieving an environment in which business processes are routinely supported by integrated change management processes that includes root cause analysis and feedback loops to assess the effectiveness of the change	Standardize Ensure comprehensive requirements capture	PPC for feedback & cause analysis	Having formal processes to changes occurring within the company serves several goals including continuous improvement and variability reduction	Sacks et al. 2010
8	Operations & Sustainment Supported	People's jobs in planning, design, construction, and operations and sustainment are fully supported through BIM in that they do not have to go to other products to accomplish their jobs	Making all facility-related jobs both internal and external to the organization rely solely on the BIM to accomplish their jobs	Cultivate an extended network of partners	Daily Huddle Meetings (in an i-room)	Integration of different companies' logistic and other information systems makes working relationships that extend beyond individual projects worthwhile and desirable	Sacks et al. 2010
8	All BP Collect & Maintain Info	All business processes are designed to collect information as they are performed and all are capable of maintaining information in the BIM	Making all business processes designed to collect and maintain data in real time	Reduce cycle time	5s Process Fail Safe for Quality & Safety	Real time data collection and maintenance is an optimum operation that helps reduce the time for any other risk depending on updated data	
8	Limited Real Time Access From BIM	Information stored in a BIM is available real time and although not from a live feed. Processes are in place to maintain its accuracy	Making information continually updated and available from live feeds to sensor. Responses to questions are immediate, accurate and relational.	Verify and validate	Fail Safe for Quality & Safety	Early detection of actual or potential schedule delay in field construction activities entails project managers to design, implement, and maintain a systematic approach for construction progress monitoring to promptly identify, process and communicate discrepancies between actual and as planned performances	Golparvar- Far et al. 2009
8	Web Enabled Services - Secure	The BIM is web-enabled environment and is considered secure. It is not an SOA	Making BIM a net centric Web environment and served up as a service in a service- oriented architecture with role-based CAC enabled to enter and access information	Design the production system for flow and value	-	Sharing models among all participants of a project team enhances communication at the design phase even without producing drawings, helping ensure that the requirements are understood and transmitted throughout the team and on to builders and suppliers.	Sacks et al. 2010
10	nD - Time & Cost	The drawings stored in the BIM are intelligent and object-based and include time and cost information	Enhancing graphical information that is object- based, parametrically intelligent and that includes information related to time and cost	Use visual management	Increased Visualization	BIM provides the ability to evaluate the impact of design changes on construction in a visual manner that is not possible with traditional 2D drawings. This goes coherently with lean emphasis on visual management	Eastman et al. 2008
9	Integrated into a complete GIS	Information from the BIM is partially recognized by the GIS environment and some metadata is available	Making information from the BIM fully recognized by the GIS environment, including full metadata interaction	Institute continuous improvement	-	With the increasing complexity of projects, such an improvement is for sure beneficial to better control the complexity issues.	-
6	Full Ground Truth - Int And Ext	All internal and external spaces are identified electronically	Calculating all spaces automatically and using metrics to ensure information availability and accuracy	Reduce variability	-	Automated quantity takeoff which is linked to the BIM model is more accurate as there are less chances of human error; hence, it improves flow by reducing variability.	Eastman et al. 2008

APPENDIX 3: COLLAGE OF PHOTOS TAKEN ON THE GUIDED VISIT TO STOŽICE ARENA

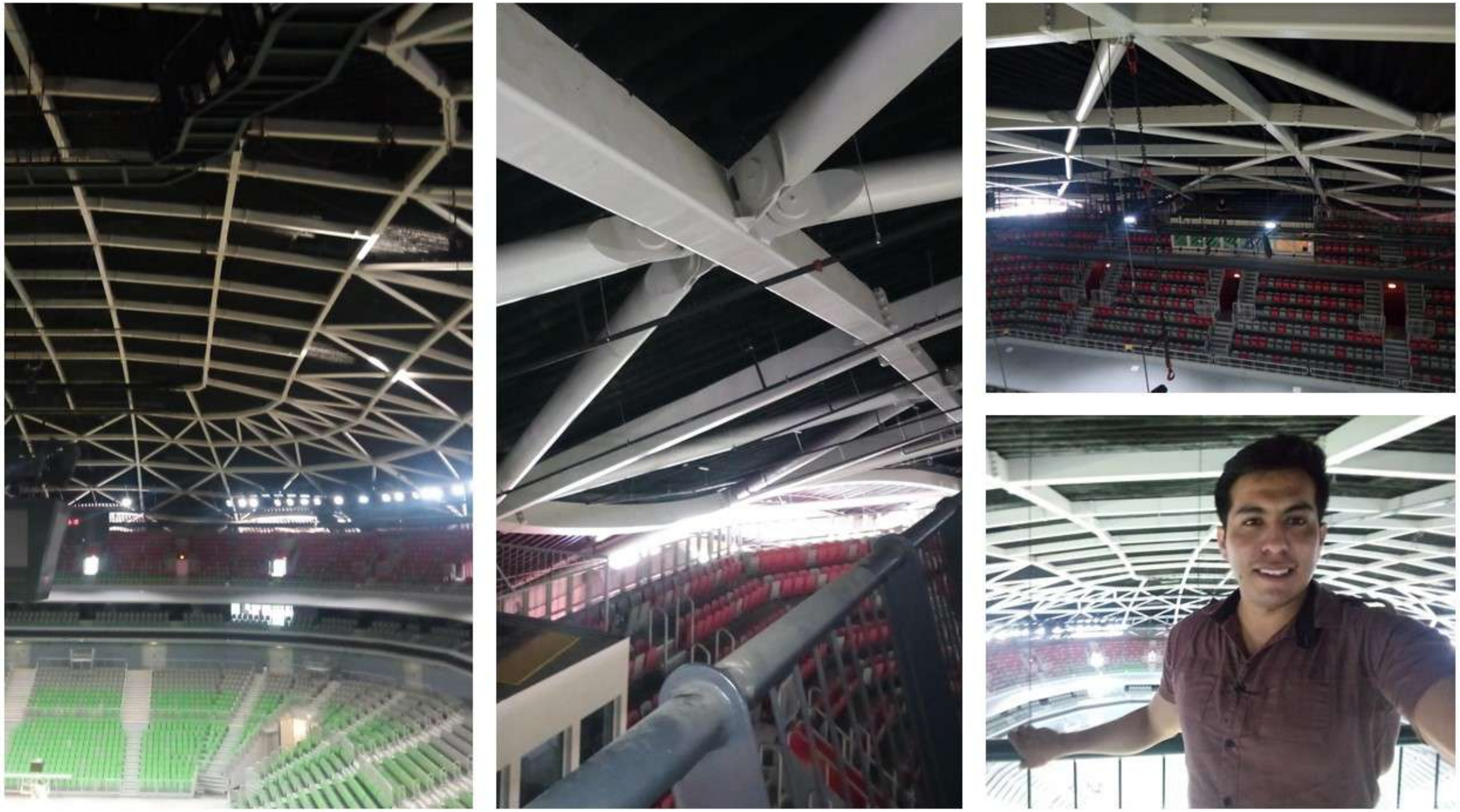


Figure 67 Collage 01 Stožice Arena

Figure 68 Collage 02 Stožice Arena

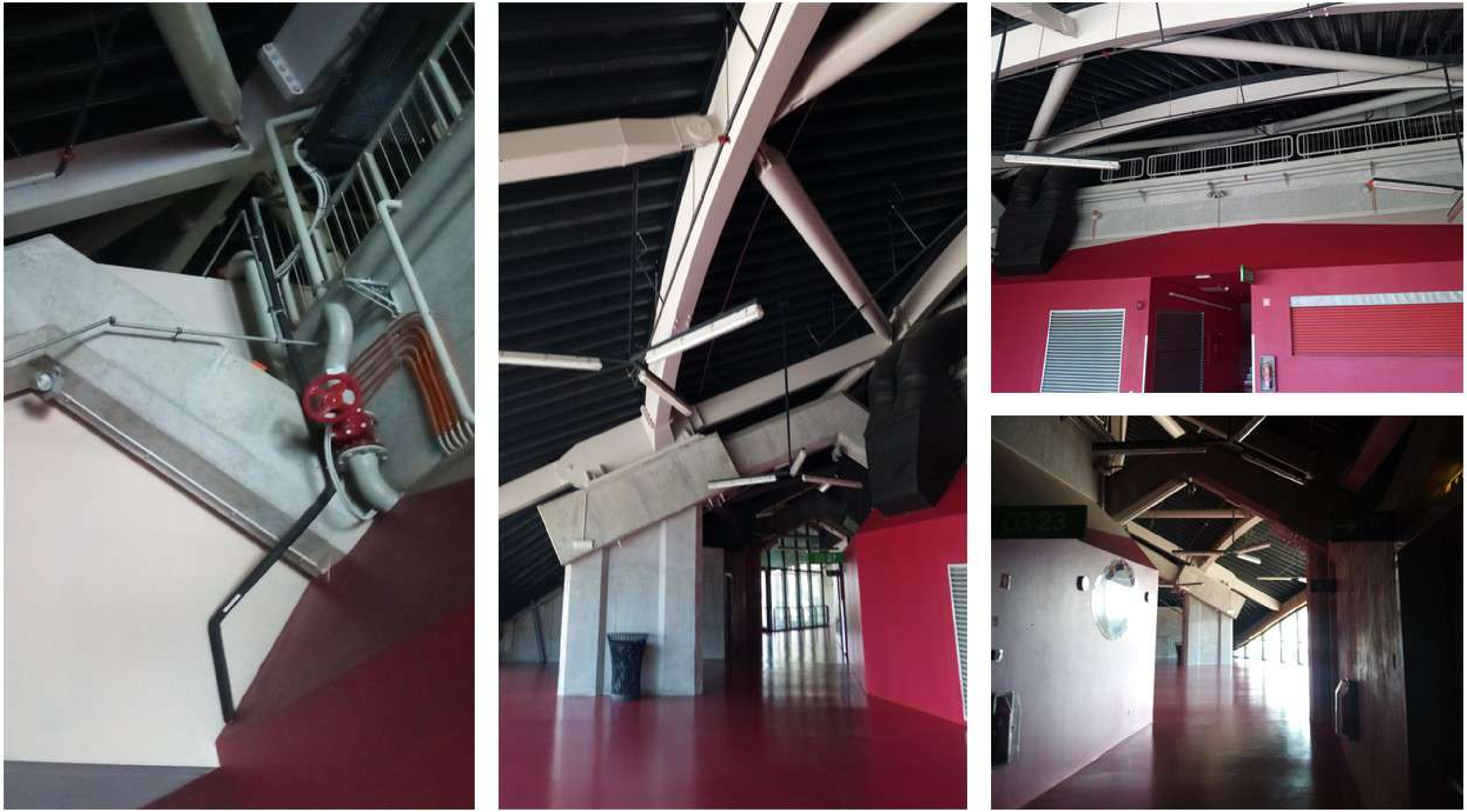


Figure 69 Collage 03 Stožice Arena

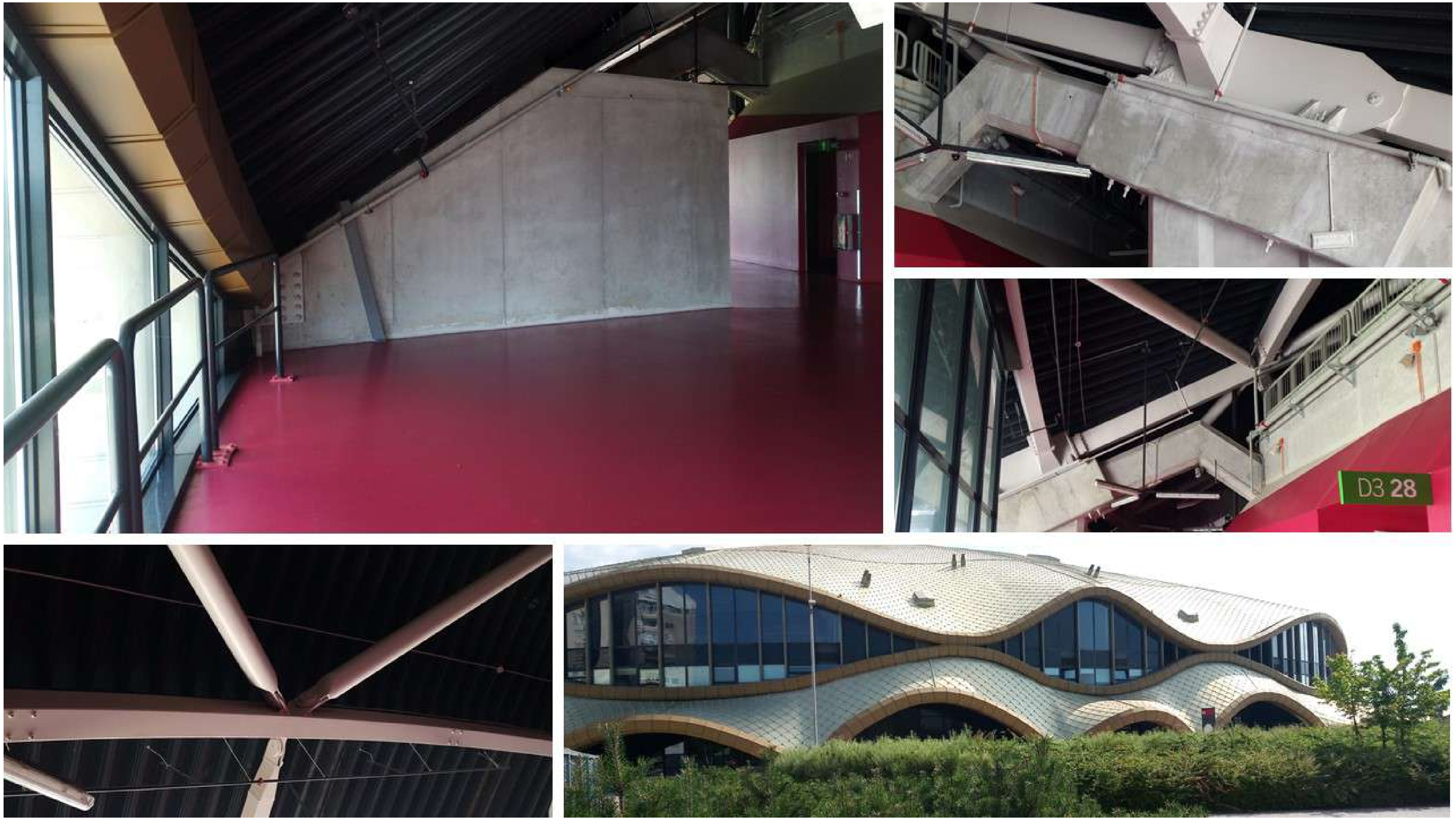
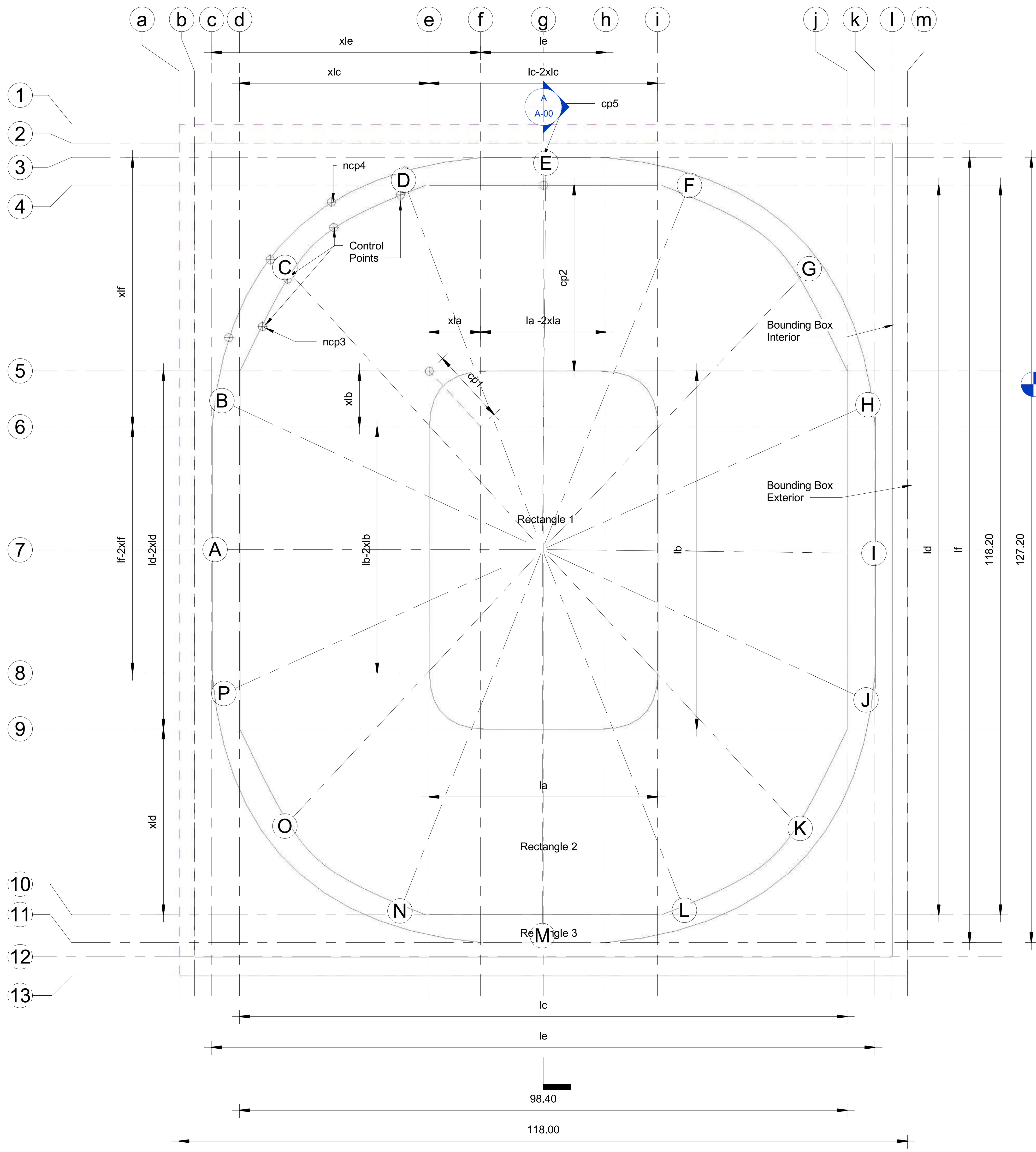


Figure 70 Collage 04 Stožice Arena

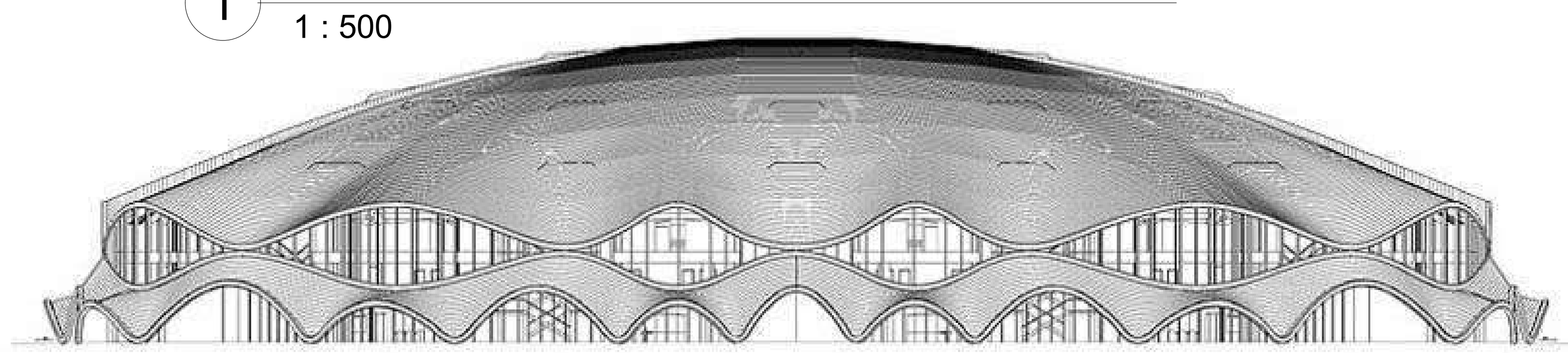
Figure 71 Collage 05 Stožice Arena

Figure 72 Collage 06 Stožice Arena

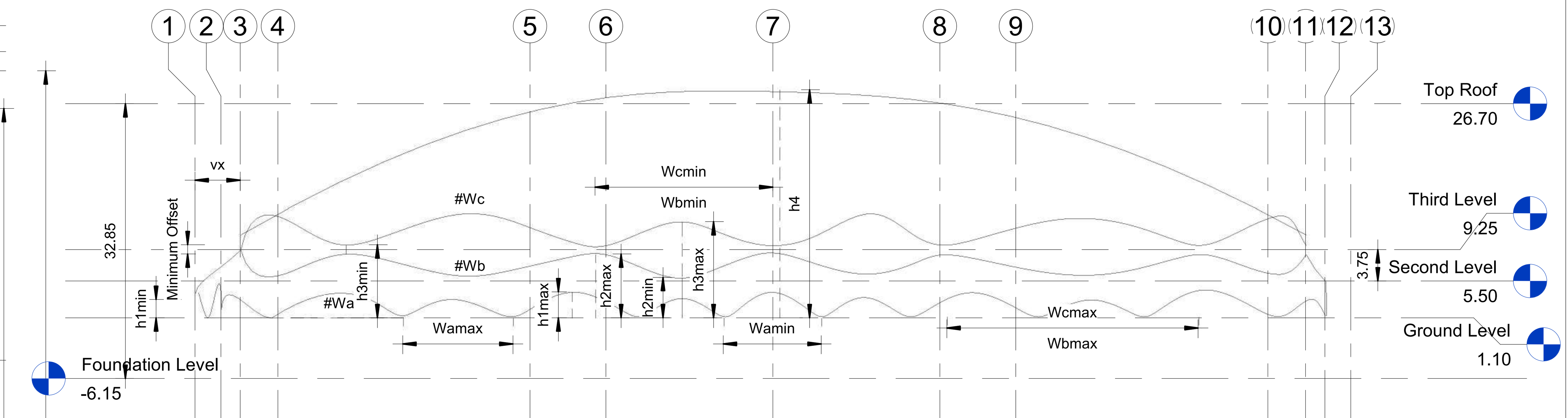
APPENDIX 4: CONCEPTUAL DESIGN SHEETS



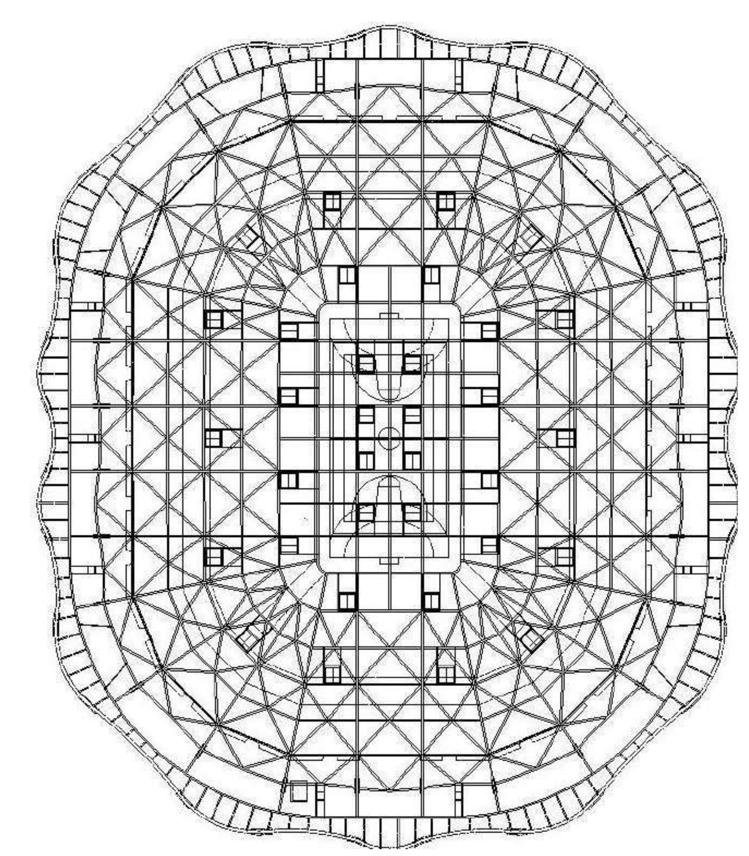
1 FLOOR PLAN PARAMETRIC SCHEMA
1 : 500



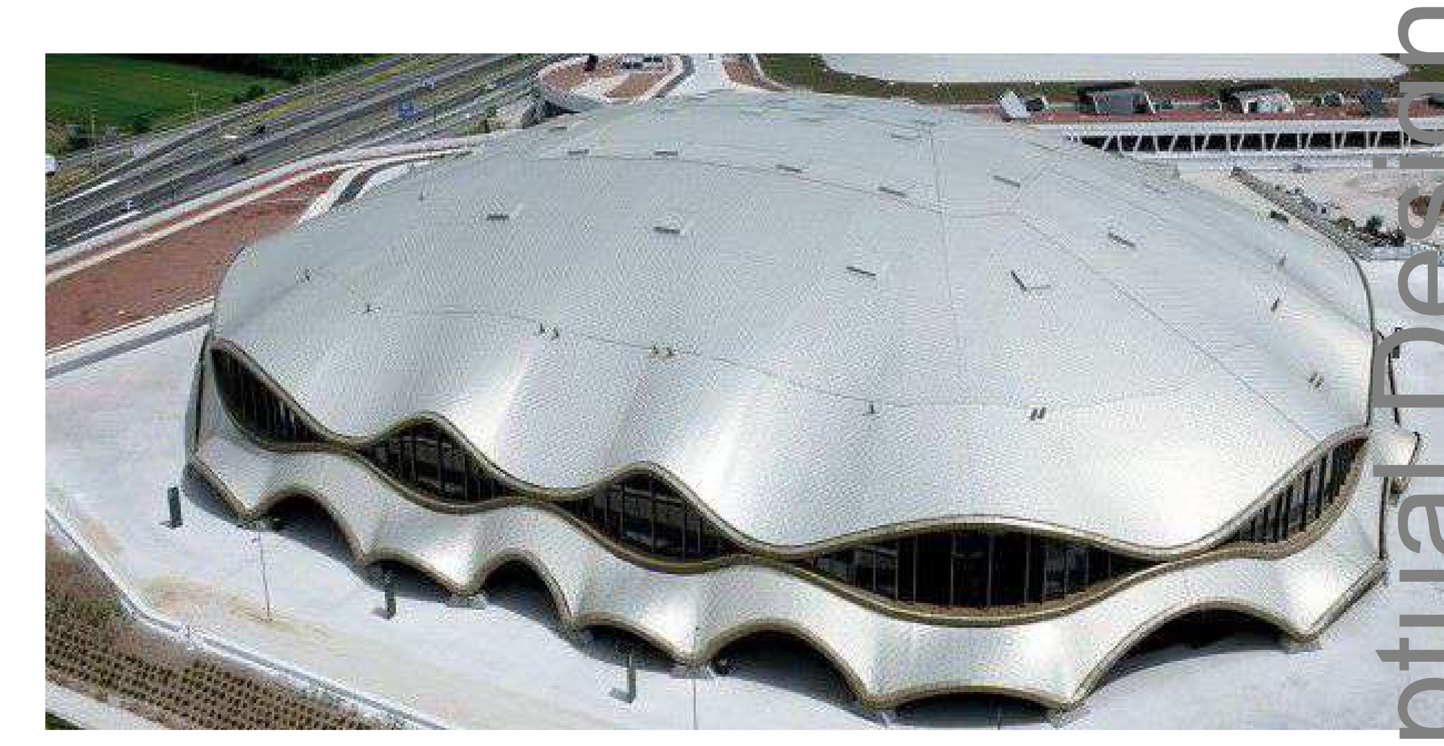
2 PERSPECTIVE OF STOZICE ARENA
1 : 25



A SECTION A PARAMETRIC SCHEMA
1 : 500



3 STRUCTURE
1 : 25



4 PHOTO OF STOZICE ARENA
1 : 25

Conceptual Design

Rectangle 1
la= length | fixed (could be variable in the beginning)
lb= length | fixed (could be variable in the beginning)
x= number |variable (< 0.4l)
cp1= number |variable (<=xl)

Rectangle 2
lc= length | fixed (min and max value)
ld= length | fixed (min and max value)
x= number |variable (< 0.4l)
cp3 =number |variable (<=xl)
npc3 = integer (<=4)

Rectangle 3
le= length | fixed (min and max value)
lf= length | fixed (min and max value)
x= number |variable (< 0.4l)
cp4 =number |variable (<=xl)
npc4 = integer (<=4)

Wave 1
h1= length | variable (min & max fixed)
Wa= length | variable (min & max fixed)
#Wa= Integer | variable (min & max fixed)

Wave 2
h2= length | variable (min & max fixed)
Wb= length | variable (min & max fixed)
#Wb= Integer | variable (min & max fixed)

Wave 3
h3= length | variable (min & max fixed)
Wc= length | variable (min & max fixed)
#Wc= Integer | variable (min & max fixed)

General
Minimum Ofset = length | fixed
h4 = length | variable (min & max fixed)
v = length | fixed
x= number (0.7 <= 0.3 < 0)

5 PARAMETRIC SCHEMA VARIABLES
1 : 25

Project Name

Stozice Arena

SLOVENIA

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DESIGNER
ID LICENCE:
STAMP:
NOTES / SYMBOLS:

SHEET NAME:
PARAMETRIC SCHEMA

SHEET NUMBER:
A-00

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REVISION

APPROVAL DATE:
TOMO CEROVSEK
BIM + A
ANDREJ LAVRIC

IF THIS BAR DOES NOT MEASURE 25mm, ADJUST THE PLOTING SCALE.
SCALE: As indicated

DRAW BY: JLR
DESIGN PHASE:
DESIGN BY: JLR
PROJECT NUMBER: 0001
CHECKED BY: Approver
FILE CAD:
APPROVAL BY: : Owner
REVIEW DATE:

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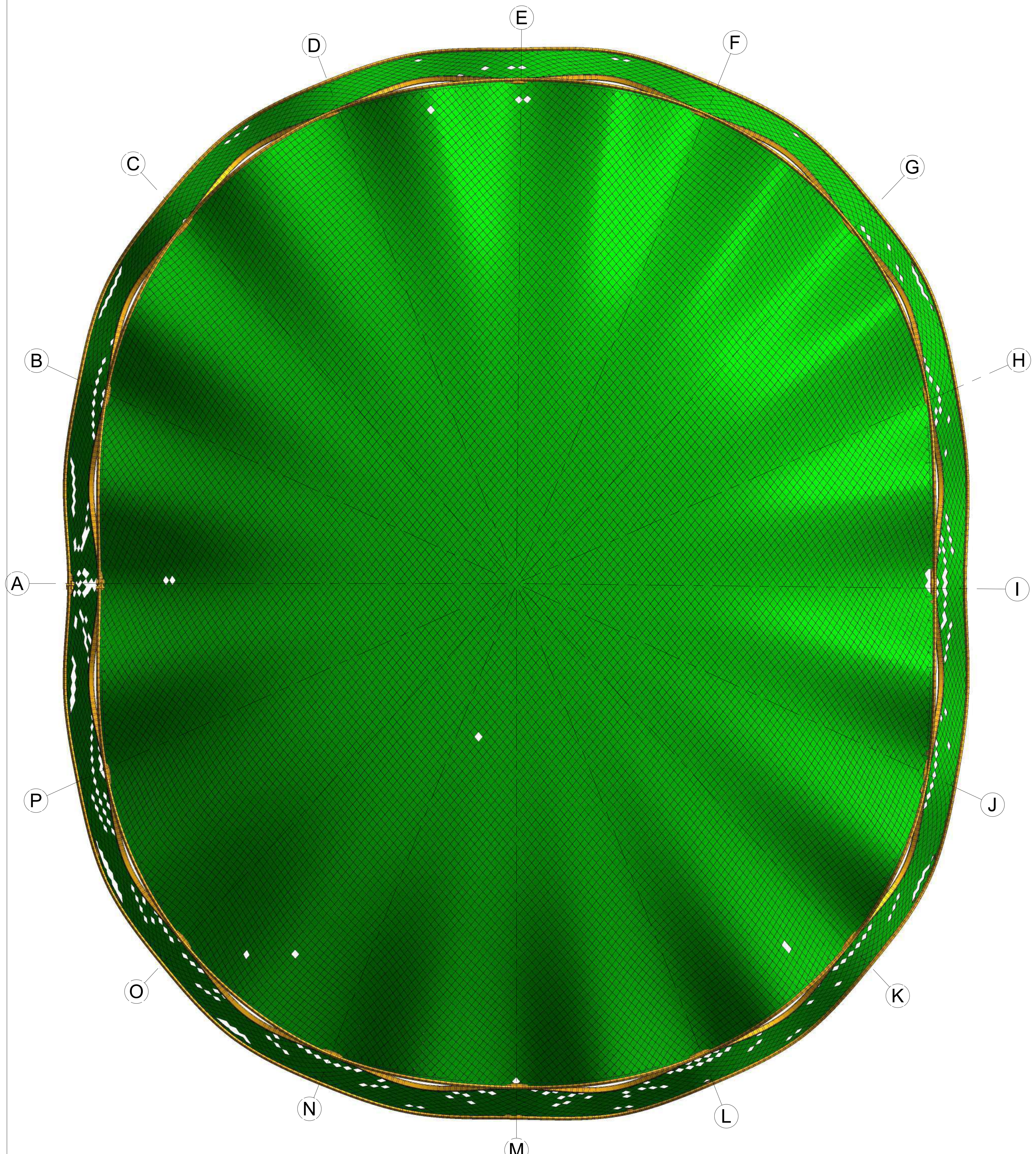
19/09/2021 01:30:26 a. m.



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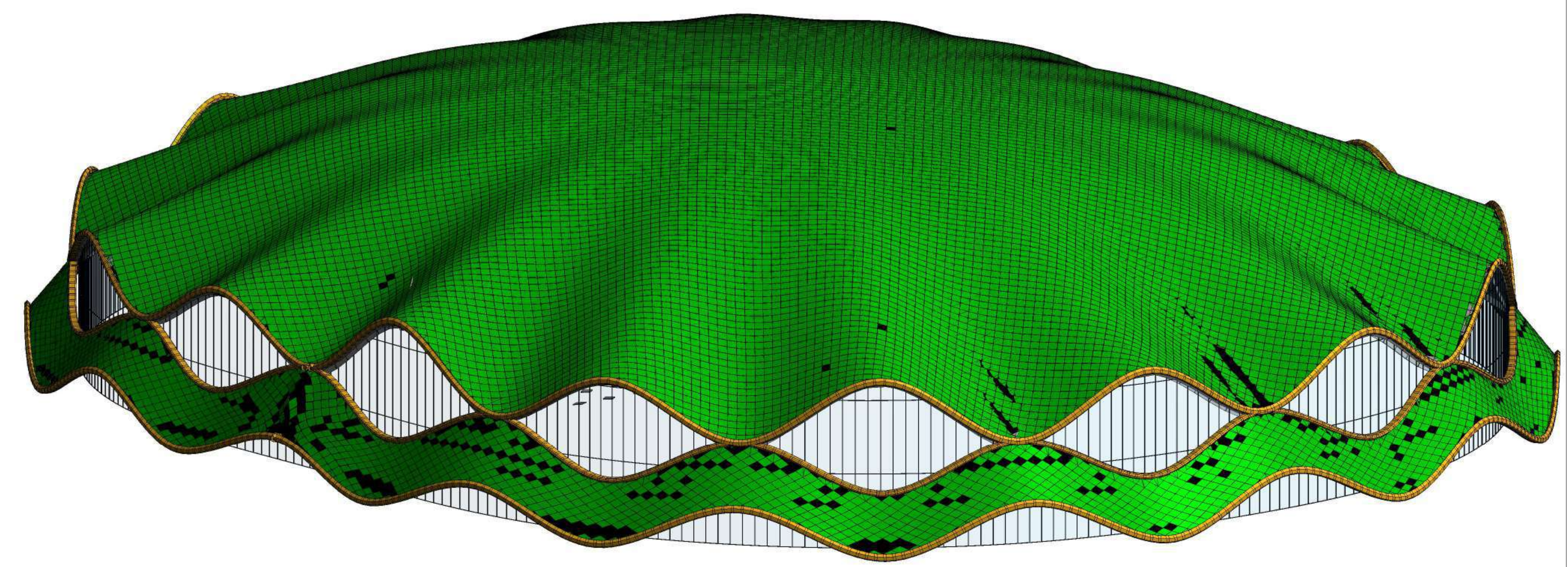
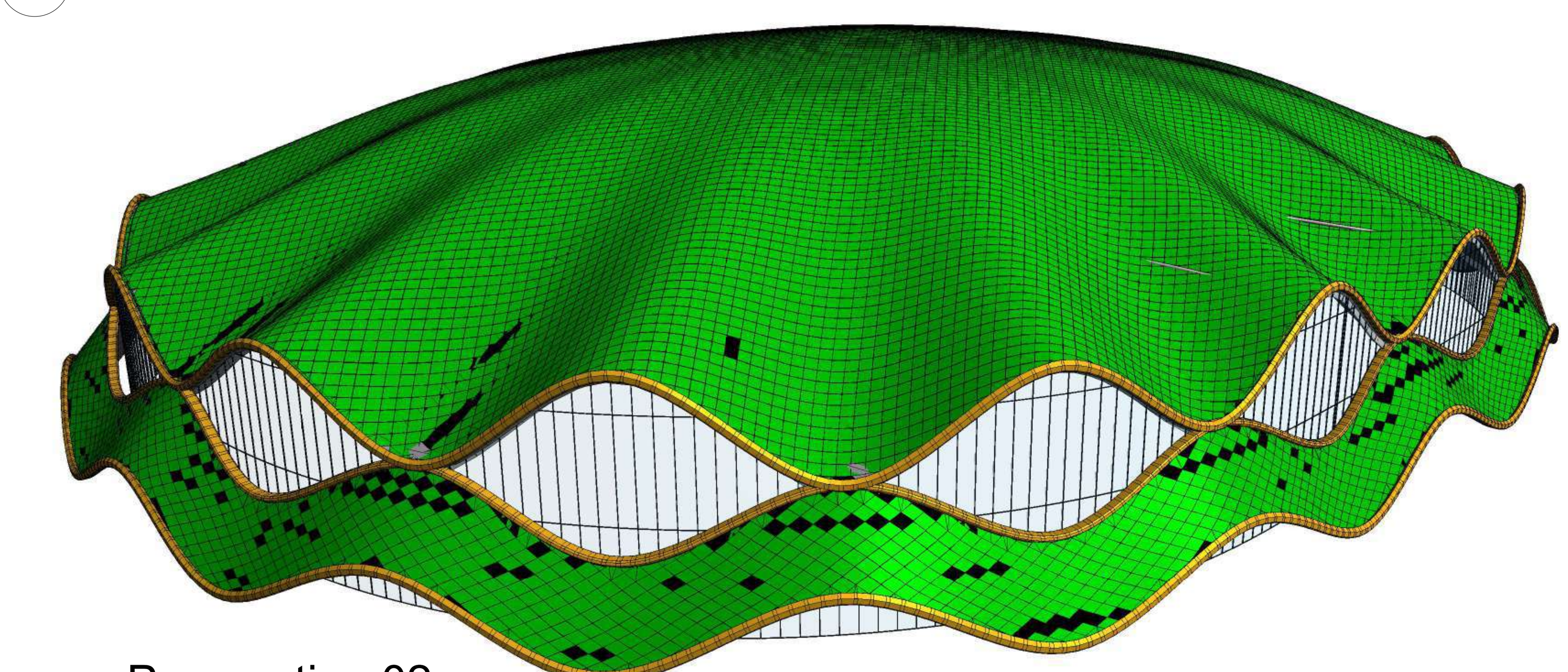
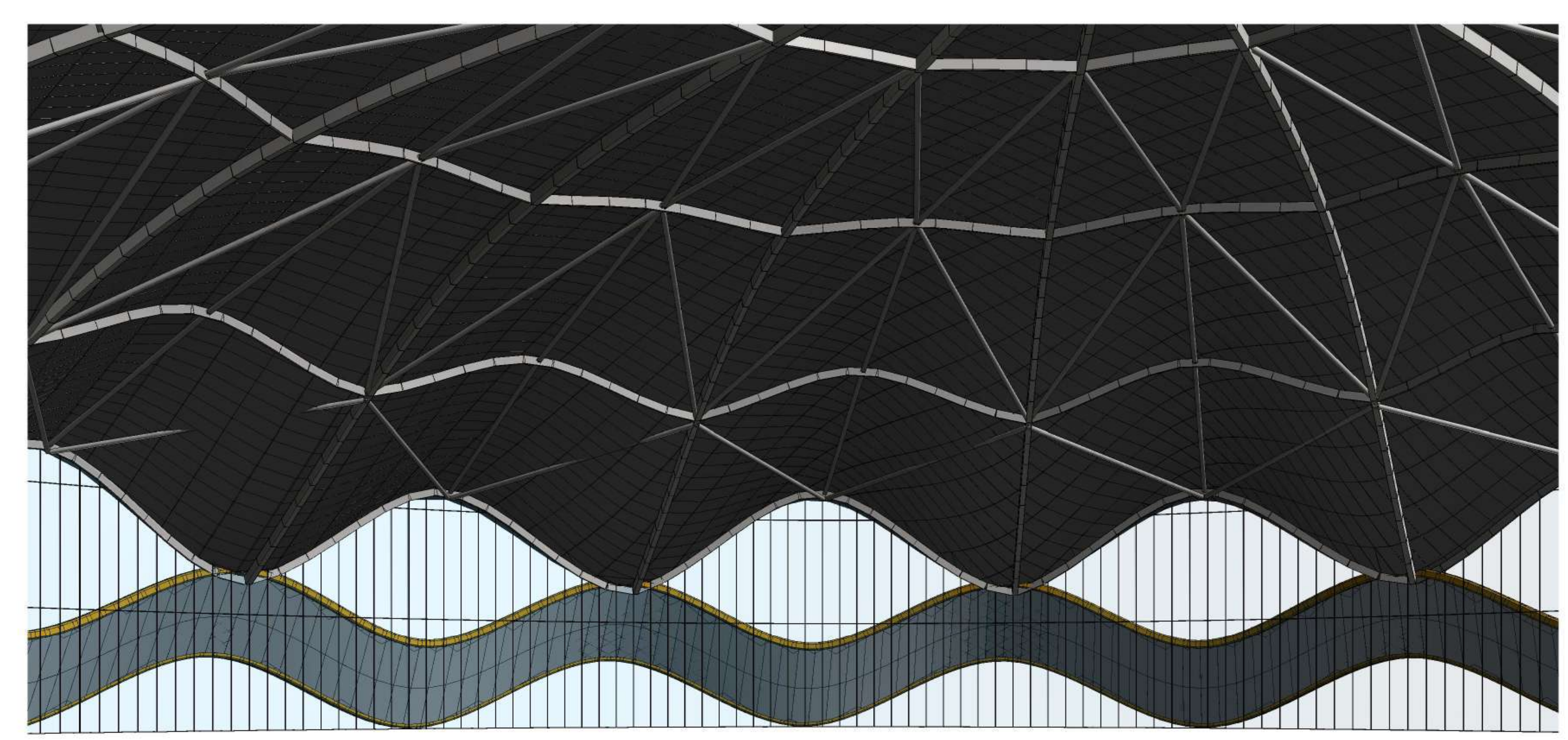
1 : 350



2 Perspective



3 Perspective-02



4 Inside Structure

Conceptual Design

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SHEET NUMBER:
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IF THIS BAR DOES NOT MEASURE 25mm, ADJUST THE PLOTING SCALE.

SCALE: 1 : 350

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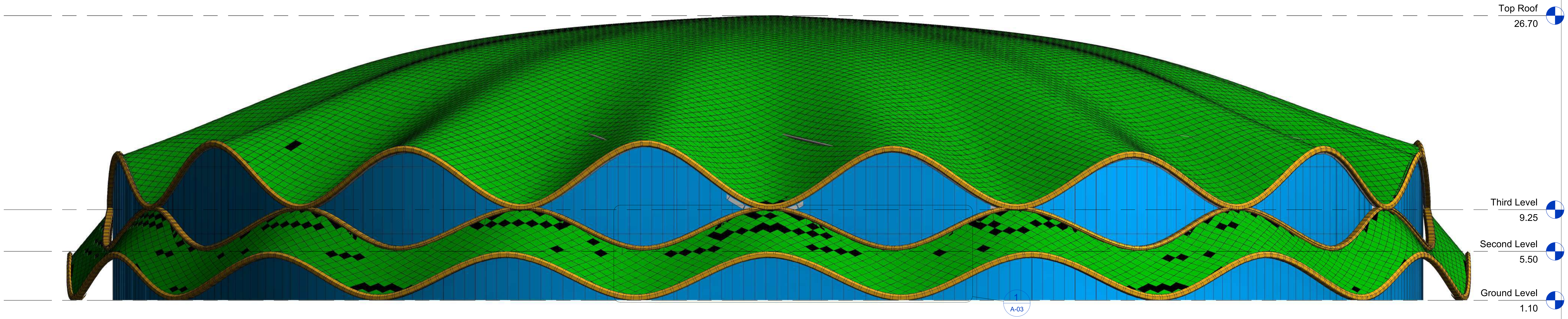
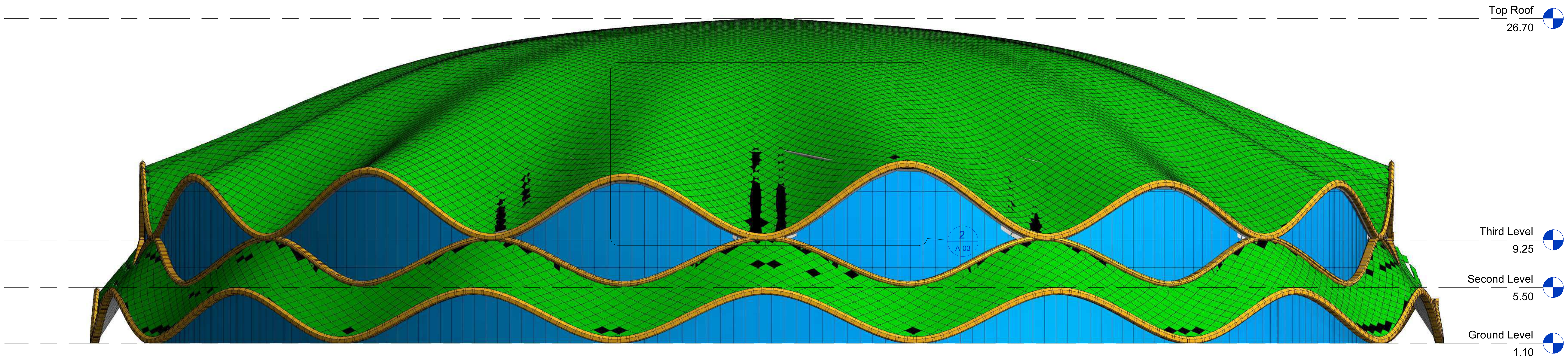
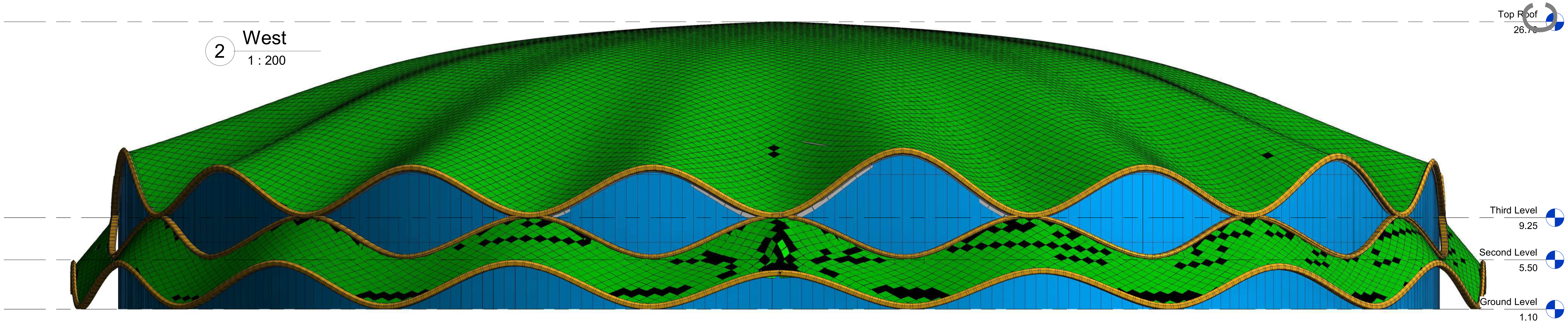
DESIGN PHASE:
DESIGN BY: JLR
PROJECT NUMBER: 0001
CHECKED BY: JLR
FILE CAD:
APPROVAL BY: : Owner
REVIEW DATE:



1 North
1 : 200



2 West
1 : 200



3 South
1 : 200

Conceptual Design

19/09/2021 01:35:45 a. m.

Project Name

Stozice Arena

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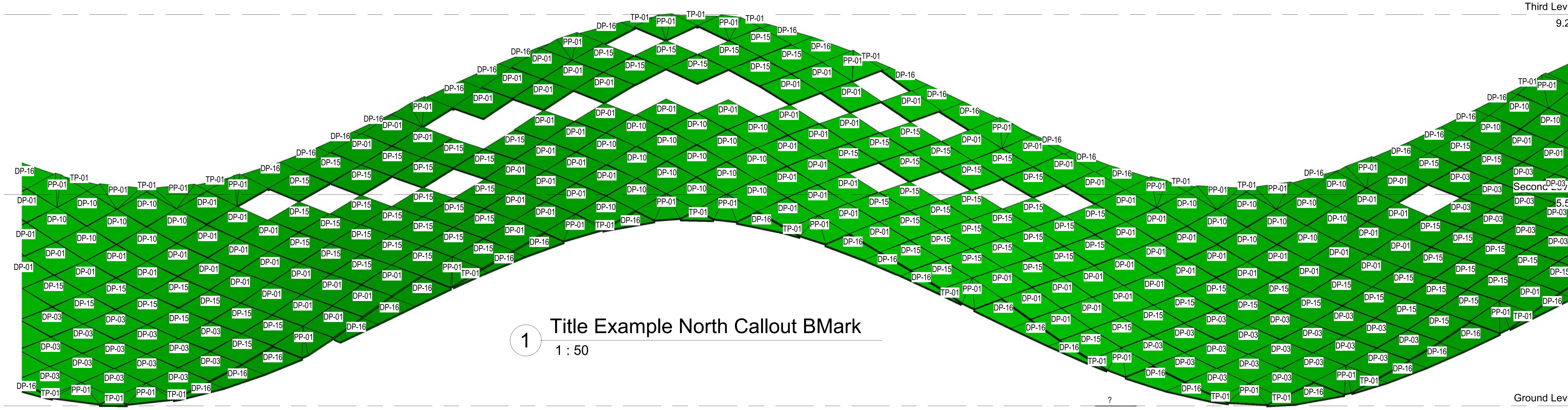
SCALE: 1 : 200

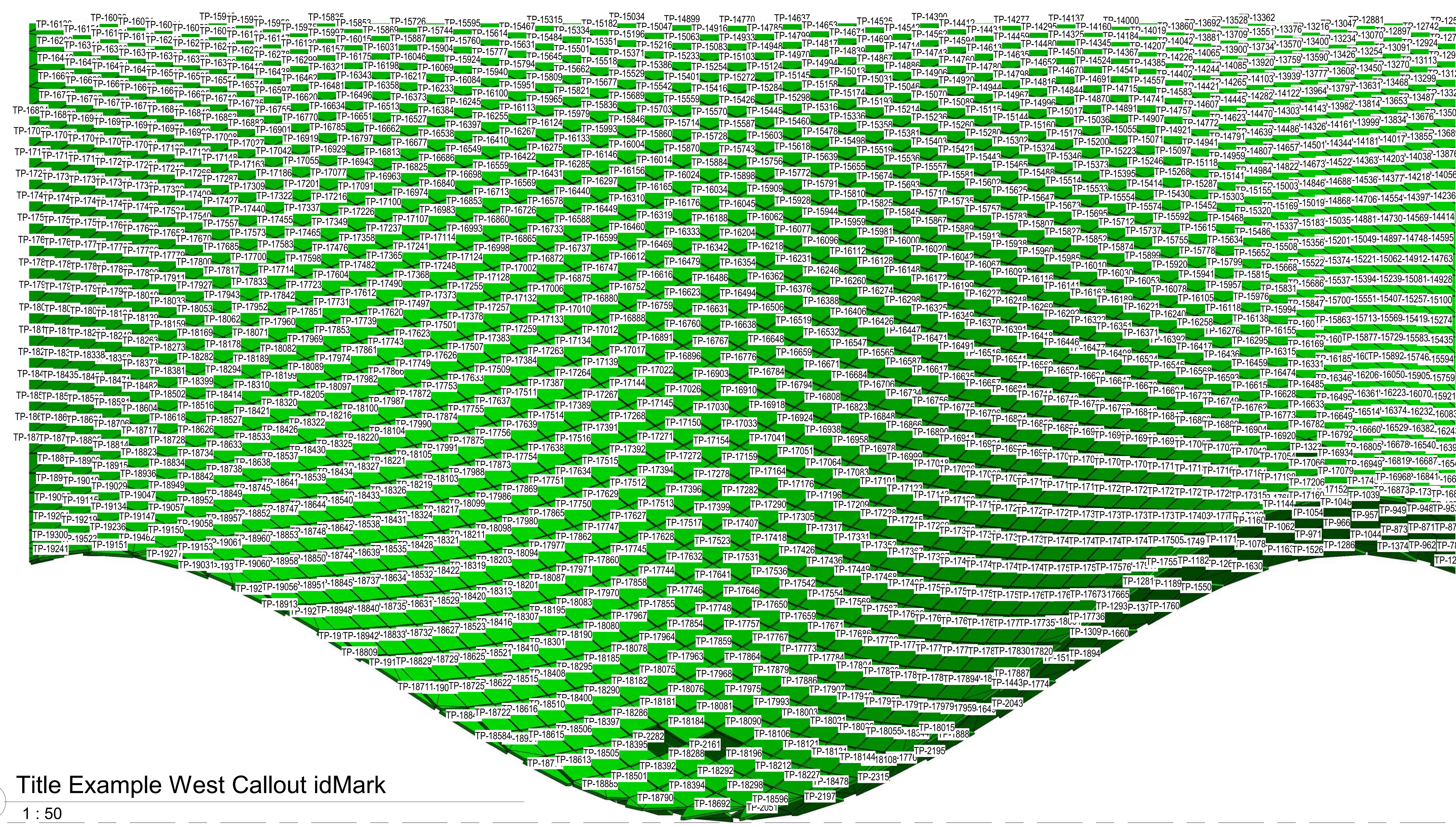
DRAW BY: Author	DESIGN PHASE:
DESIGN BY: Designer	PROJECT NUMBER: 0001
CHECKED BY: Approver	FILE CAD:
APPROVAL BY: : Owner	REVIEW DATE:

19/09/2021 01:36:22 a. m.



1 Title Example North Callout BMark
1 : 50

Type of Titles	
Count	Type
23213	Diamond-Panel
831	Glazed
496	Penta Panel
481	Triangle-Panel
25021	



2 Title Example West Callout idMark
1 : 50

Conceptual Design

Project Name

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DESIGNER

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TITLE SYSTEM

SHEET NUMBER:
A-03

SHEET TO

REVISION

APPROVAL DATE:

TOMO CEROVSEK
BIM + A

ANDREJ LAVRIC

IF THIS BAR DOES NOT MEASURE 25mm, ADJUST THE PLOTING SCALE.

SCALE:
1 : 50

DRAW BY: Author

DESIGN PHASE:

DESIGN BY: Designer

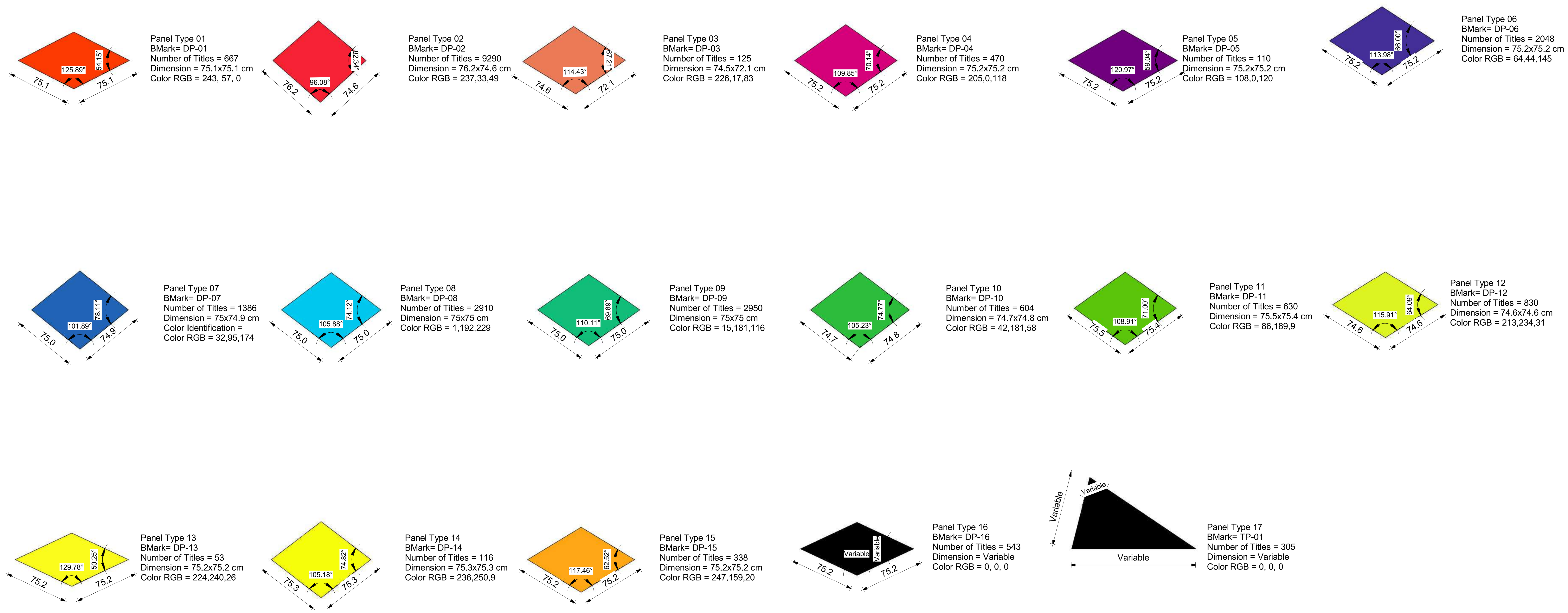
PROJECT NUMBER: 0001

CHECKED BY: Approver

FILE CAD:

APPROVAL BY: : Owner

REVIEW DATE:



1 Type of Titles
1 : 30

Conceptual Design

19/09/2021 01:36:23 a. m.

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IF THIS BAR DOES NOT MEASURE 25mm, ADJUST THE PLOTING SCALE.

SCALE: 1 : 30

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DESIGN BY: Designer | PROJECT NUMBER: 0001
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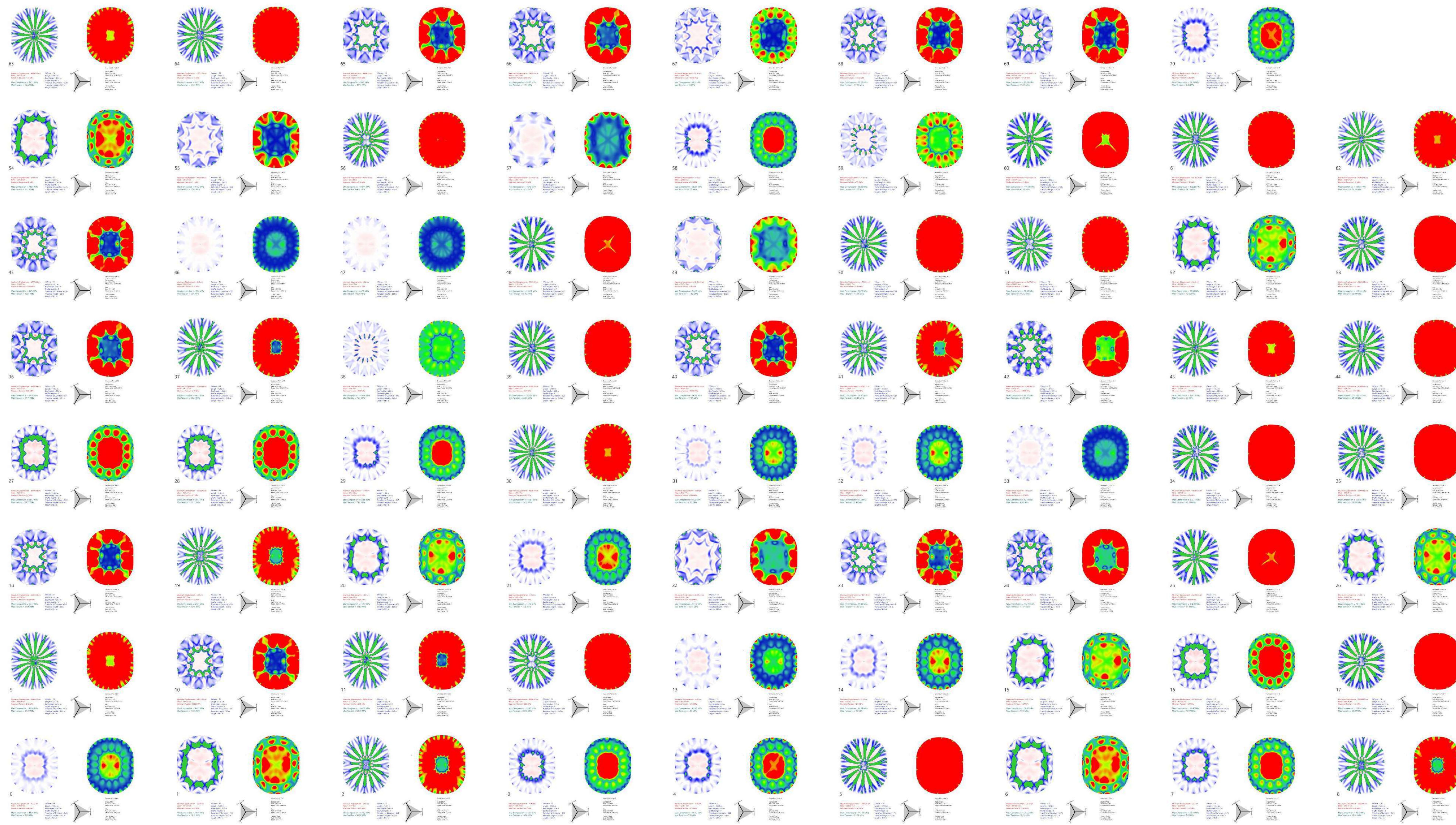
APPROVAL BY: : Owner | REVIEW DATE:



1 Roof Form Pareto Front
1 : 200

Conceptual Design

Project Name
Stozice Arena
SLOVENIA

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FOR:
BIM A+ European Master in Building Information Modelling

DISCIPLINE: ARCHITECTURAL
SIGN: ING. JOSÉ LUIS RODRÍGUEZ HERNÁNDEZ
DESIGNER
ID LICENCE:
STAMP:
NOTES / SYMBOLS:

SHEET NAME:
GENERATIVE DESIGN ROOF FORM PARETO FRONT

SHEET NUMBER:
A-11

SHEET TO
REVISION

APPROVAL DATE:
TOMO CEROVSEK BIM A+
ANDREJ LAVRIC

IF THIS BAR DOES NOT MEASURE 25mm, ADJUST THE PLOTING SCALE.

SCALE:
1 : 200

DRAW BY: Author
DESIGN PHASE:
DESIGN BY: Designer
PROJECT NUMBER: 0001
CHECKED BY: Approver
FILE CAD:
APPROVAL BY: : Owner
REVIEW DATE:

19/09/2021 01:36:24 a. m.

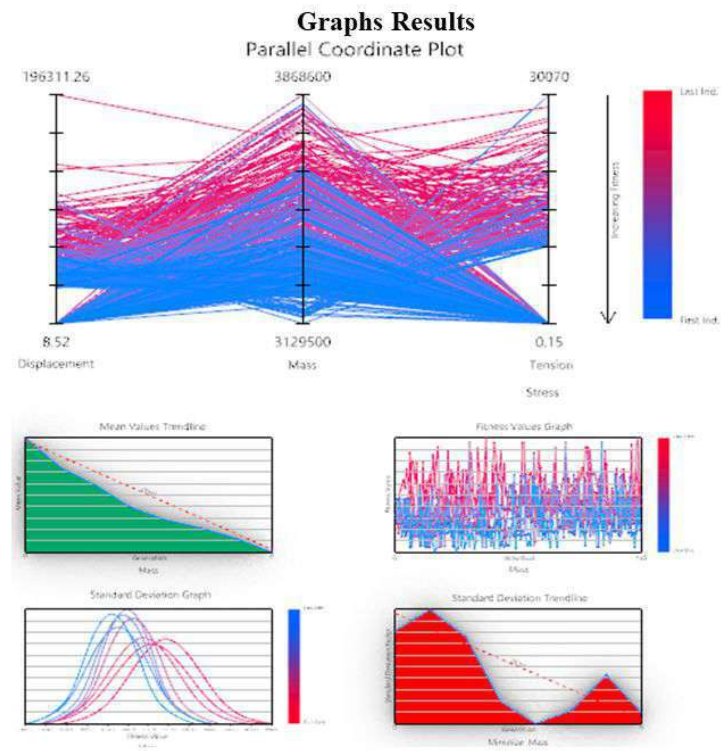
Model Setup

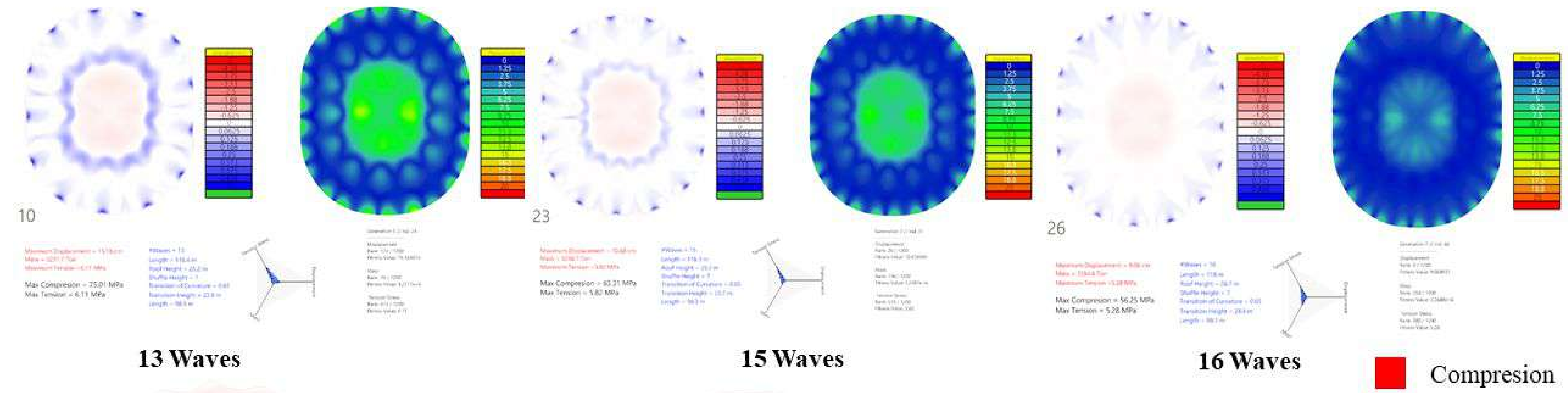
Variables	Units	Values Min	Values Max
#Waves		10	16
Roof Height	m	25.0	29.0
Transition Height	m	15.0	27.0
Transition Curvature	Scale Factor	0.25	0.75
Length	m	118.0	125.0
Width	m	98.0	110.0
Shuffle Height Wc		1	10

Constraints & Fix Values	Units	Values Min	Values Max
Wave Height(Transition)	m	0.25	
Fillet Curve	m(radius)	45.00	
Min Heigth Wc	m	4.25	
Variation Heigth Wc	m	0.50	
Third Floor Height	m	9.25	
Factor Selfweigth	Scale Factor	1.50	
Thickness	cm	12.00	

Goals	Units	Objectives
Max Displacement	cm	Minimize
Mass	Ton	Minimize
Max Tension Stress	Mpa	Minimize

Graphs Results





Compresion

Tension

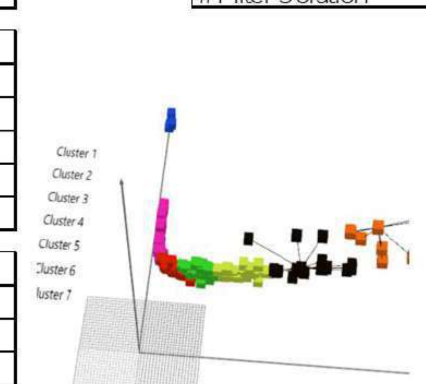
Population	
Generation Size	150
Generation Count	8
Population Size	1200

AlgorithmParameters	
Crossover Probability	0.9
Mutation Probability	1/n
Crossover Distribution Index	35
Mutation Distribution Index	35
RandomSeed	6

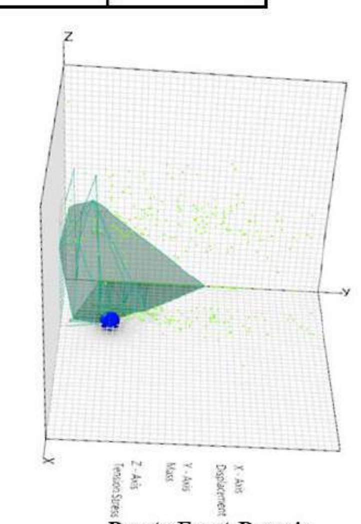
Simulation Parameters	
N° of Genes (Variables)	7
N° of Values	422
N° of Fitness Objectives	3
Size of Search Space	1.50E+11

Non-Supervised Machine Learning	
Method (Algorithm)	Kmeans
#Clusters	7

Result and Analytics	
Pareto Front Solutions	70
# Evaluation of Solutions	30
# Filter Solution	4

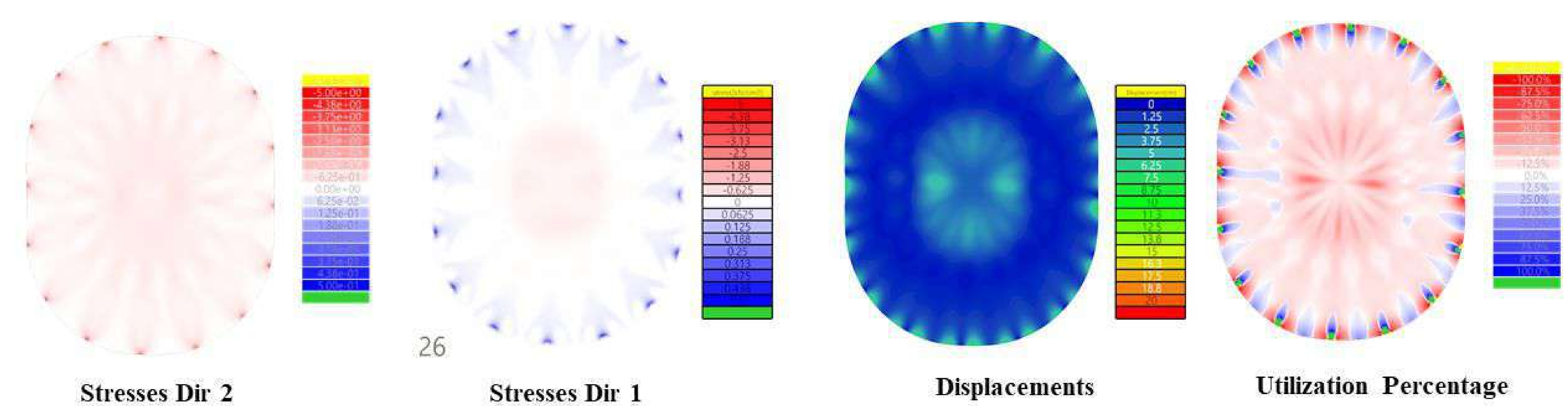


Pareto Frontier Clustering



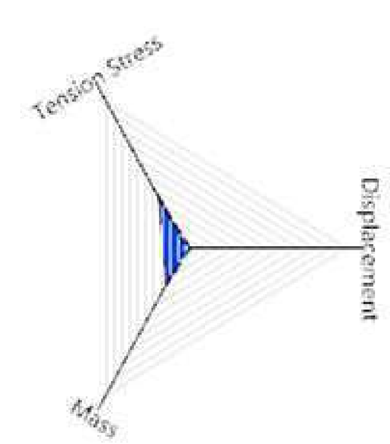
Pareto Front Domain

Conceptual Design



1 Generative Design Roof Form

1 : 200



Generation 7 // Ind. 46

Displacement
Rank: 3 / 1200
Fitness Value: 9.064931

Mass
Rank: 263 / 1200
Fitness Value: 3.2848e+6

Tension Stress
Rank: 380 / 1200
Fitness Value: 5.28

Setup of Variables

Description	Units	Values
#Waves		16
Width	m	98
Length	m	118
Roof Height	m	26.7
Transition Curvature	Scale Factor	0.65
Transition Height	m	24.4
Wave Heigth(Transition)	m	0.50
Fillet Curve	m(radius)	45.00
Min Heigth Wc	m	4.25
Variation Heigth Wc	m	0.50
Third Floor Height	m	9.25
Factor Selfweigth	Scale Factor	1.50
Thickness	cm	12.00

Result of Optimization

Description	Units	Values
Max Displacement	cm	9.06
Mass	Ton	3284.8
Max Tension	Mpa	5.28
Max Compresion	MPa	56.25

Compresion

Tension

Project Name

Stozice Arena

SLOVENIA

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SIGN: ING. JOSÉ LUIS RODRÍGUEZ HERNÁNDEZ

DESIGNER

ID LICENCE:

STAMP:

NOTES / SYMBOLS:

SHEET NAME:
GENERATIVE DESIGN ROOF FORM

SHEET NUMBER: A-12

SHEET TO | **REVISION**

APPROVAL DATE:

TOMO CEROVSEK BIM + A | ANDREJ LAVRIC

IF THIS BAR DOES NOT MEASURE 25mm, ADJUST THE PLOTING SCALE.

SCALE: 1 : 200

DRAW BY: Author | DESIGN PHASE:
DESIGN BY: Designer | PROJECT NUMBER: 0001
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APPROVAL BY: : Owner | REVIEW DATE:

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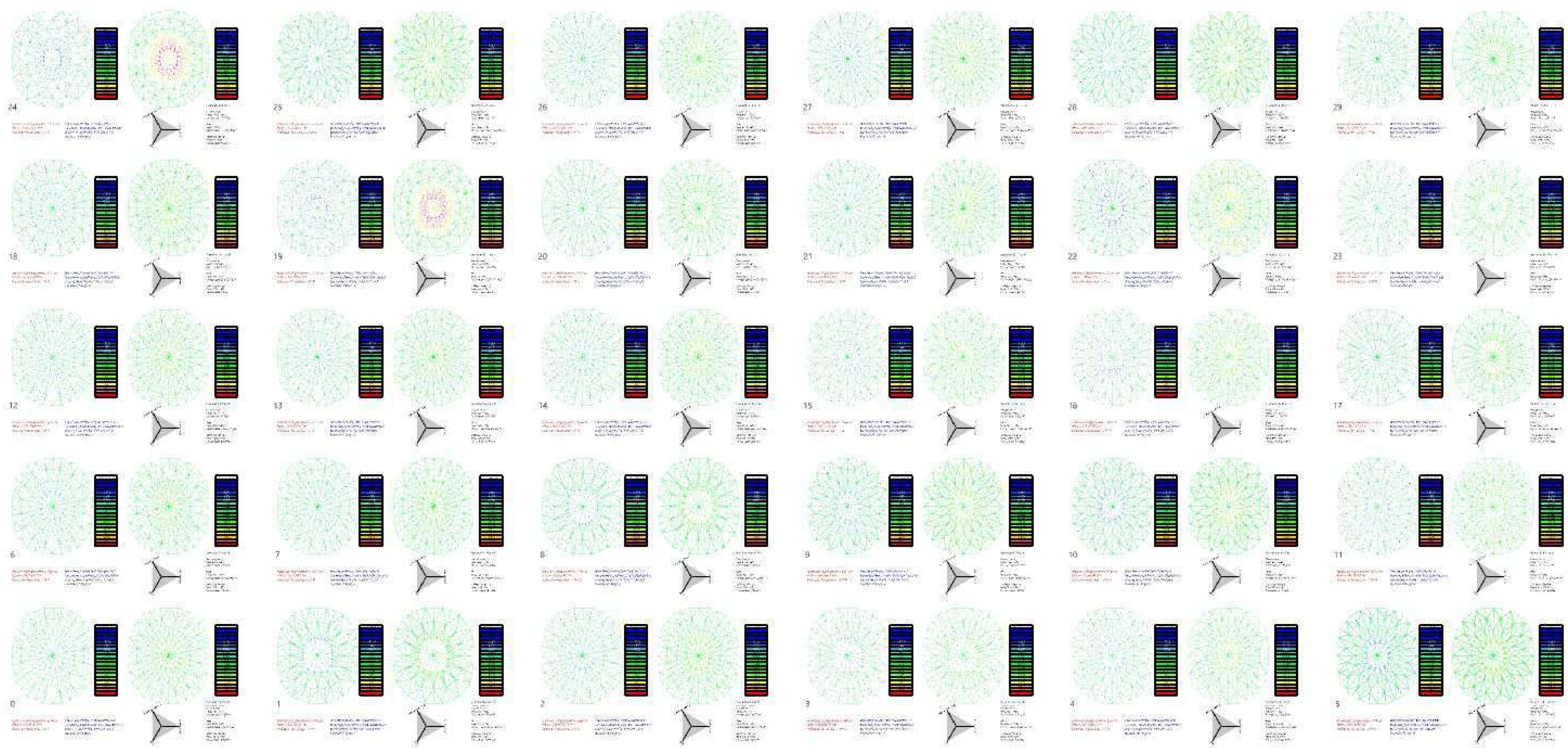

Conceptual Design

1 Generative Design Roof Structure Pareto Front
1 : 200

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Project Name

Stozice Arena

SLOVENIA

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DESIGNER

ID LICENCE:

STAMP:

NOTES / SYMBOLS:

SHEET NAME:
GENERATIVE DESIGN ROOF STRUCTURE PARETO FRONT

SHEET NUMBER:
A-13

SHEET TO

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ANDREJ LAVRIC

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SCALE: 1 : 200

DRAW BY: Author

DESIGN PHASE:

DESIGN BY: Designer

PROJECT NUMBER: 0001

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FILE CAD:

APPROVAL BY: Owner

REVIEW DATE:

Project Name

Stozice Arena

SLOVENIA

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STAMP:

NOTES / SYMBOLS:

SHEET NAME: COMPARISON ROOF STRUCTURE

SHEET NUMBER: A-13a

SHEET TO

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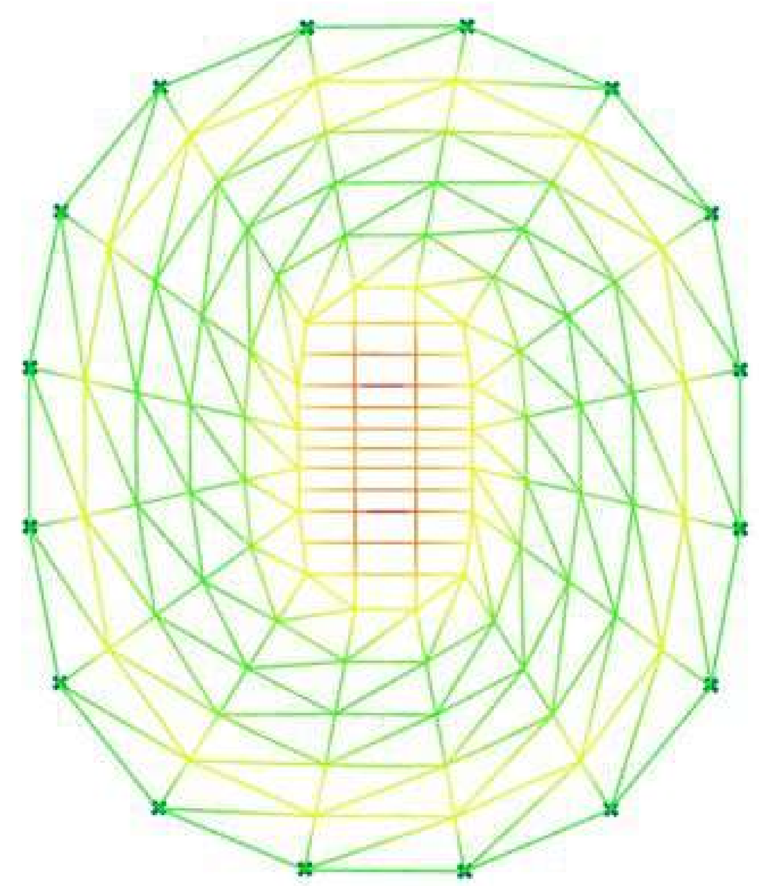
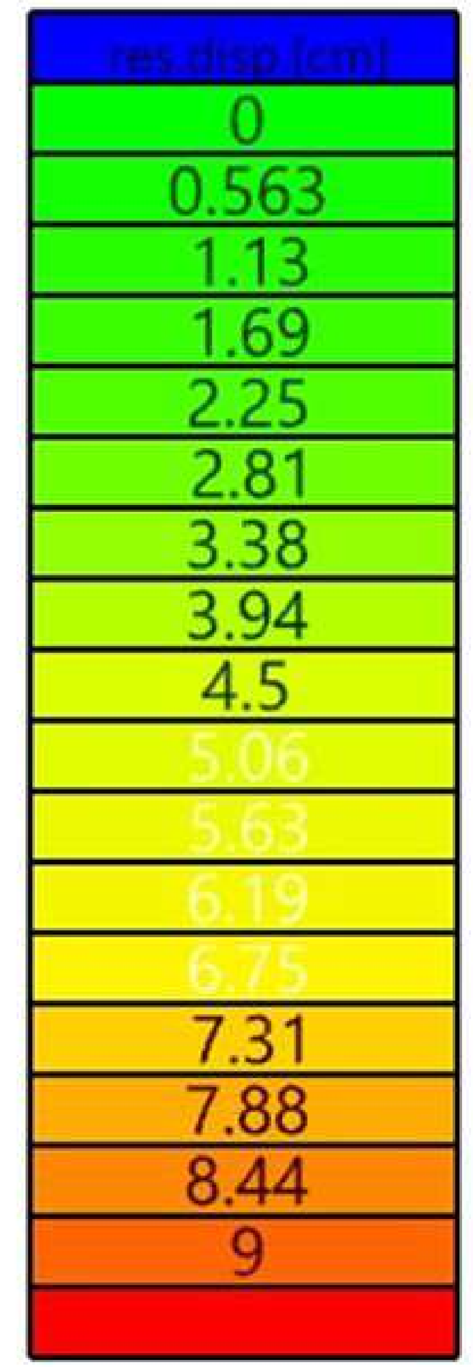
Conceptual Design

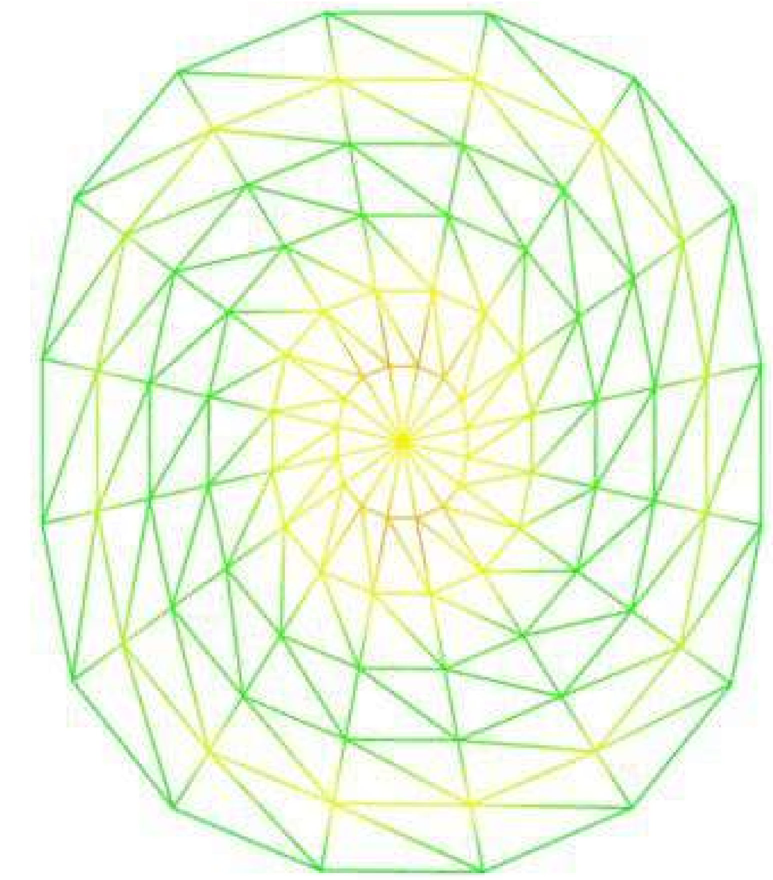


Constraints & Values	Fix Units	Values Min
#Waves		16
Ring Division		6
Aditional Rings		1
Main Beam Profile		RHS500x300x16'
Secondary Beam Profile		RHS500x300x12.5'
Bracing Profile		CHS323.9x6'
Self Weight Profiles	Factor	1
Dead Load	kN/m^2	1

Results	Units	Values Min
Mass	ton	482.90
Max Displacement	cm	9.20
Average Ratio		12.68%

Like Current Project

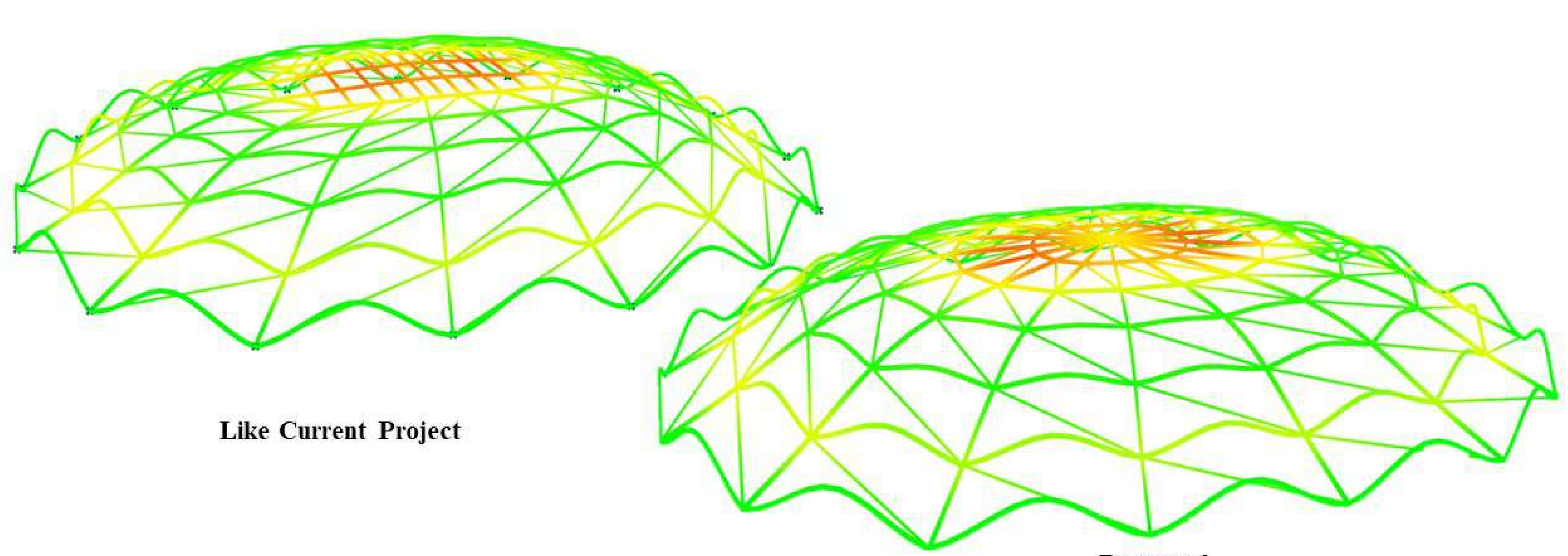




Constraints & Values	Fix Units	Values Min
#Waves		16
Ring Division		6
Aditional Rings		0
Main Beam Profile		RHS500x300x16'
Secondary Beam Profile		RHS500x300x12.5'
Bracing Profile		CHS323.9x6'
Self Weight Profiles	Factor	1
Dead Load	kN/m^2	1

Results	Units	Values Min
Mass	ton	441.43
Max Displacement	cm	7.55
Average Ratio		12.99%

Propossal

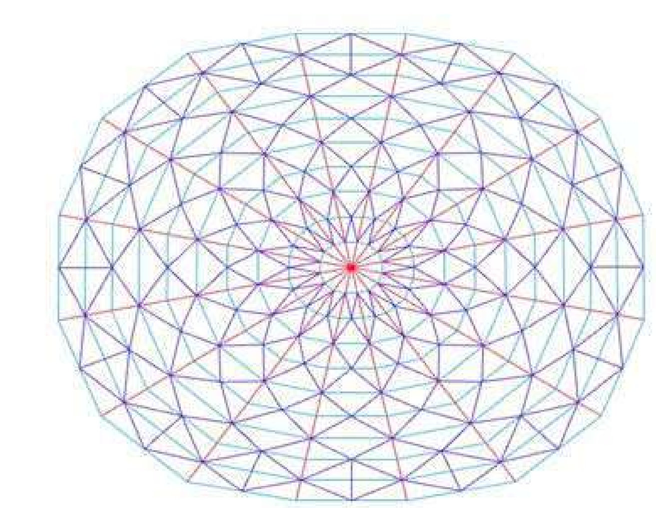


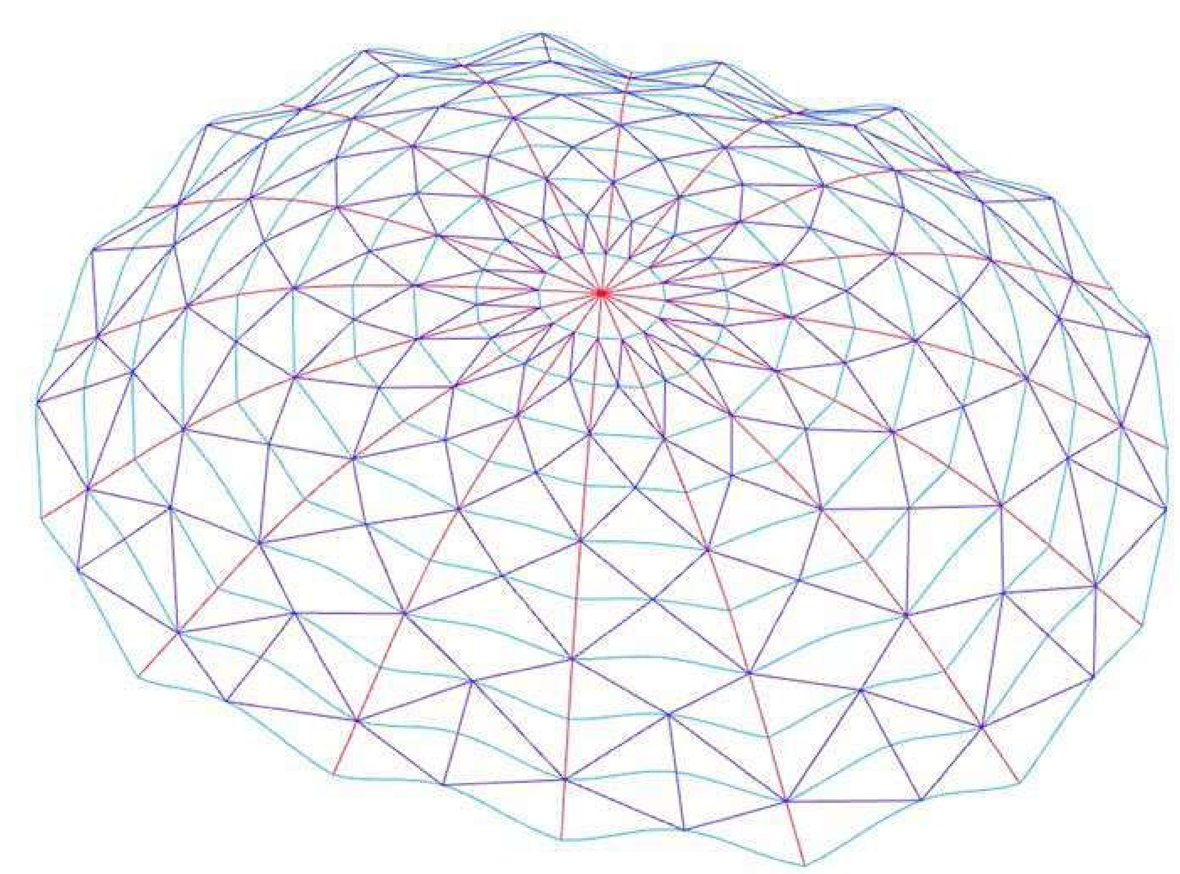
Like Current Project

Propossal

Description	Units	Values		Diferences
#Waves		16	16	Equals
Mass	ton	482.90	441.43	41.5
Max Displacement	cm	9.20	7.55	1.7
Average Ratio		12.68%	12.99%	-0.31%

Variables	Values Min	Values Max
Ring Division	3	12
Main Frame Profile	352	493
Secondary Frame Profile	352	493
Bracing Profile	80	121



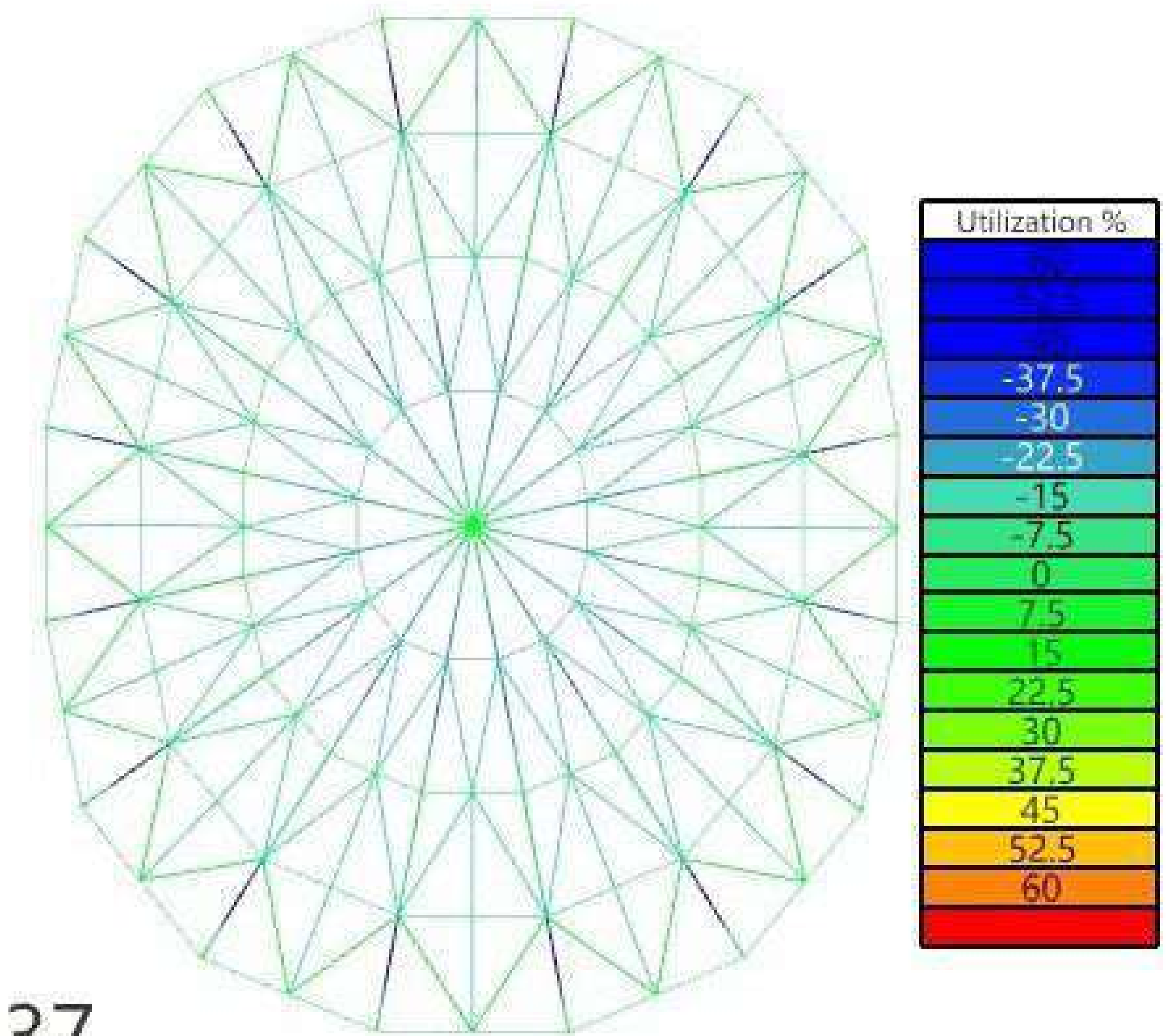


Setup of Variables

Description	Units	Values
#Waves		16
Width	m	98
Length	m	118
Roof Height	m	26.7
Transition Curvature	Scale Factor	0.65
Transition Height	m	24.4
Wave Heigth(Transition)	m	0.50
Fillet Curve	m (radius)	45.00
Min Heigth Wc	m	4.25
Variation Heigth Wc	m	0.50
Third Floor Height	m	9.25
Factor Selfweigth	Scale Factor	1.00
Uniform Dead Load	kN/m^2	1.00

1 Comparison Roof Structure & Parametric Model

1 : 200



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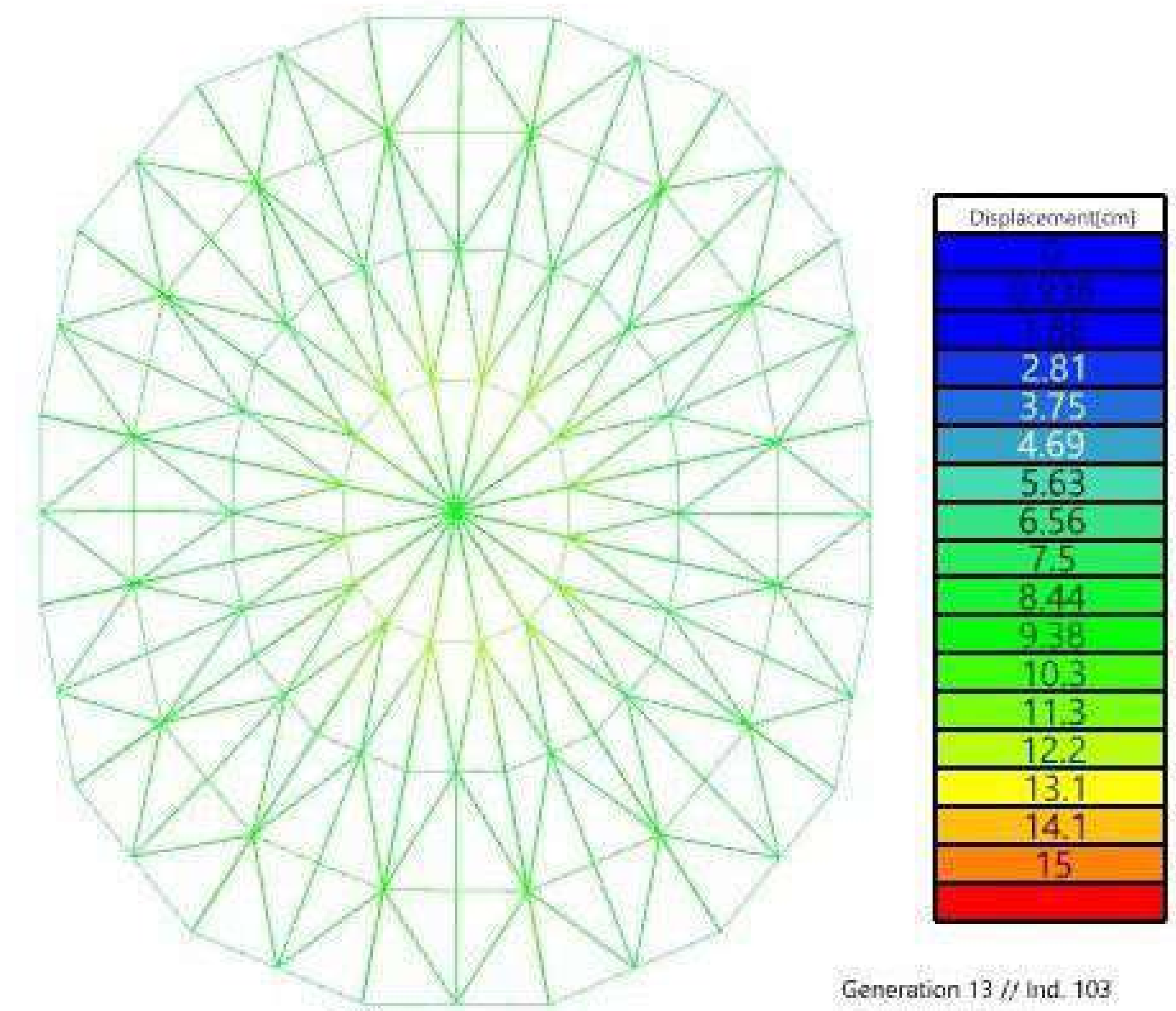
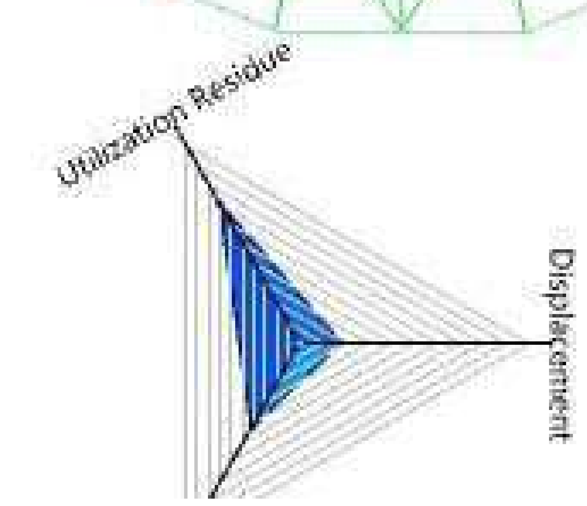


Maximum Displacement = 8.34 cm
Mass = 219.13309 Ton
Utilization Percentaje = 18 %

Main Beam Profile: 'RHS 500x300x8'
Secondary Beam Profile: 'RHS 400x150x8.8'
Bracing Beam Profile: 'CHS 244.5x5.0'
Number of Rings: 4



Generation 13 // Ind. 103

Displacement
Rank: 269 / 1680
Fitness Value:

Mass
Rank: 686 / 1680
Fitness Value:

Utilization Residue
Rank: 1159 / 1680

Conceptual Design

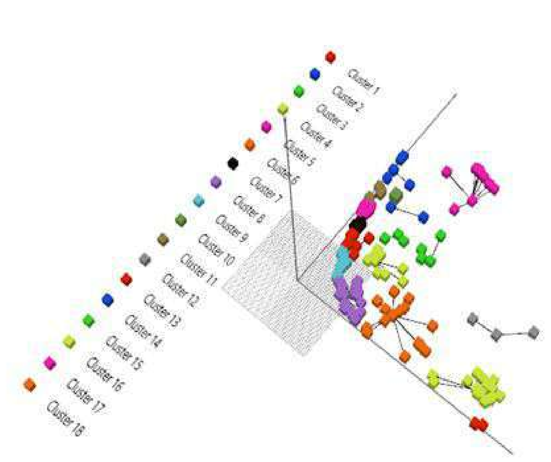
Population	
Generation Size	120
Generation Count	14
Population Size	1680

Algorithm Parameters	
Crossover Probability	0.85
Mutation Probability	1/n
Crossover Distribution Index	25
Mutation Distribution Index	30
Random Seed	8

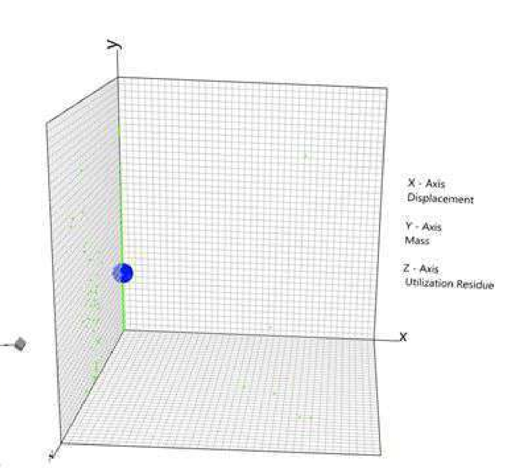
Simulation Parameters	
N° of Genes (Variables)	4
N° of Values	370
N° of Fitness Objectives	3
Size of Search Space	1.50E+07

Non-Supervised Machine Learning	
Method (Algorithm)	Kmeans
# Clusters	18

Result and Analytics	
Pareto Front Solutions	118
# Evaluation of Solutions	41
# Filter Solution	1



Pareto Frontier Clustering



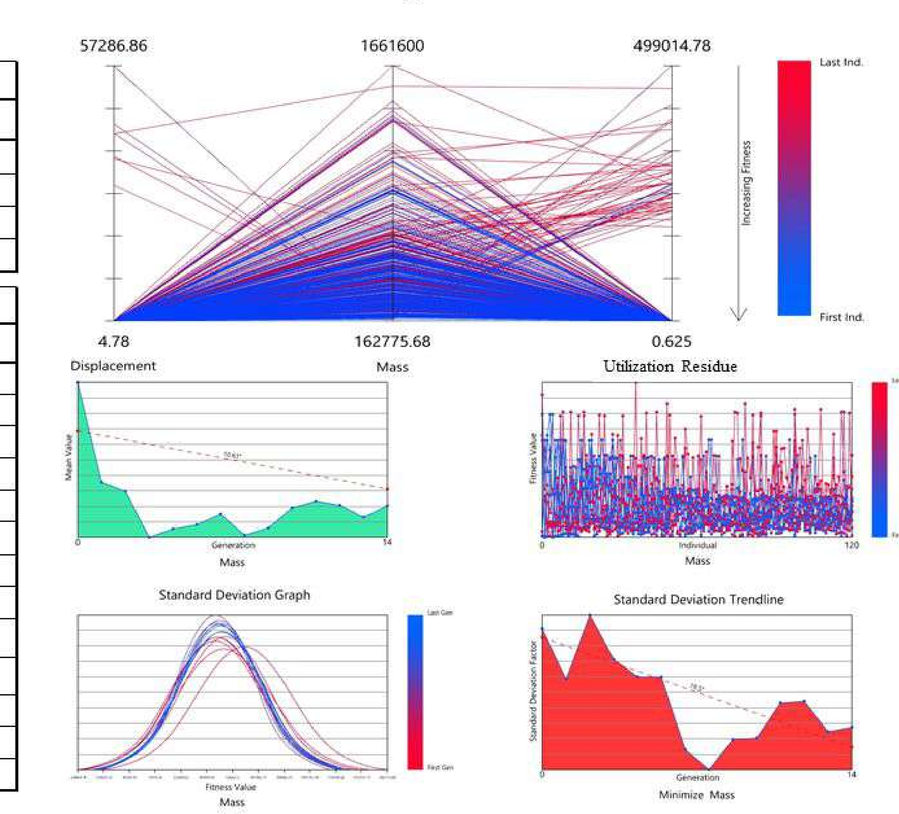
Pareto Front Domain

Model Setup

Variables	Values	
	Min	Max
Ring Division	3	12
Main Frame Profile	352	493
Secondary Frame Profile	352	493
Bracing Profile	80	121

Setup of Variables		
Description	Units	Values
#Waves		16
Width	m	98
Length	m	118
Roof Height	m	26.7
Transition Curvature	Scale Factor	0.65
Transition Height	m	24.4
Wave Heigth(Transition)	m	0.50
Fillet Curve	m (radius)	45.00
Min Heigth Wc	m	4.25
Variation Heigth Wc	m	0.50
Third Floor Height	m	9.25
Factor Selfweigth	Scale Factor	1.00
Uniform Dead Load	kN/m^2	1.00

Graphs Results



1 Generative Design Roof Structure
1 : 200

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Project Name
Stozice Arena
SLOVENIA

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DESIGNER
ID LICENCE:
STAMP:
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SHEET NAME:
GENERATIVE DESIGN ROOF STRUCTURE

SHEET NUMBER:
A-14

SHEET TO
REVISION

APPROVAL DATE:
TOMO CEROVSEK BIM + A
ANDREJ LAVRIC

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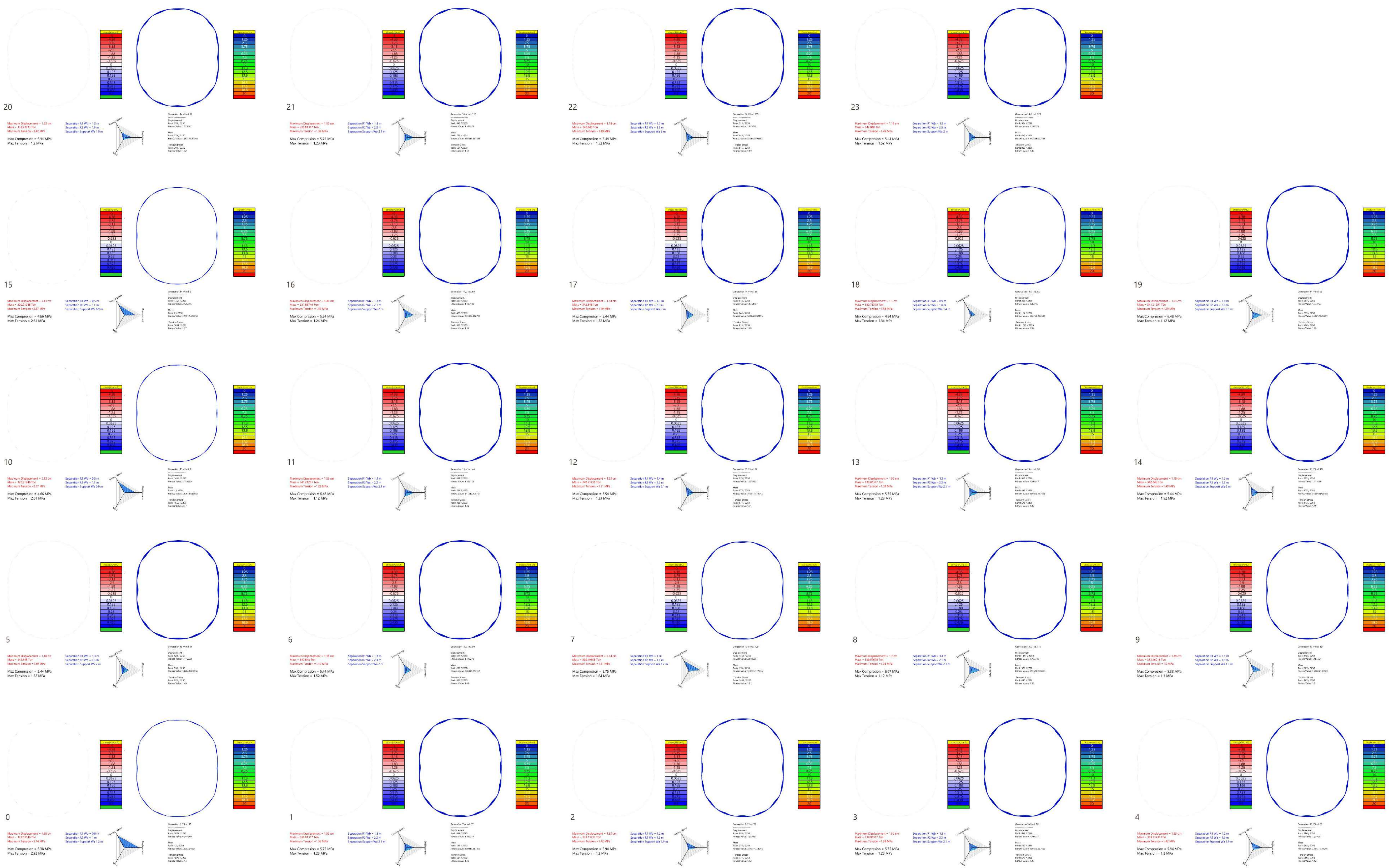
SCALE:
1 : 200

DRAW BY: Author
DESIGN PHASE:
DESIGN BY: Designer
PROJECT NUMBER: 0001
CHECKED BY: Approver
FILE CAD:
APPROVAL BY: Owner
REVIEW DATE:



1 Facade Form Pareto Front
1 : 200

Conceptual Design

Project Name

Stozice Arena

SLOVENIA

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FOR:

BIM A+ European Master in Building Information Modelling

Erasmus+

DISCIPLINE: ARCHITECTURAL

SIGN: ING. JOSÉ LUIS RODRÍGUEZ HERNÁNDEZ

DESIGNER

ID LICENCE:

STAMP:

NOTES / SYMBOLS:

SHEET NAME:
GENERATIVE DESIGN FACADE FORM PARETO FRONT

SHEET NUMBER:
A-15

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REVISION

APPROVAL DATE:

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ANDREJ LAVRIC

IF THIS BAR DOES NOT MEASURE 25mm, ADJUST THE PLOTING SCALE.

SCALE: 1 : 200

DRAW BY: Author

DESIGN PHASE:

DESIGN BY: Designer

PROJECT NUMBER: 0001

CHECKED BY: Approver

FILE CAD:

APPROVAL BY: Owner

REVIEW DATE:

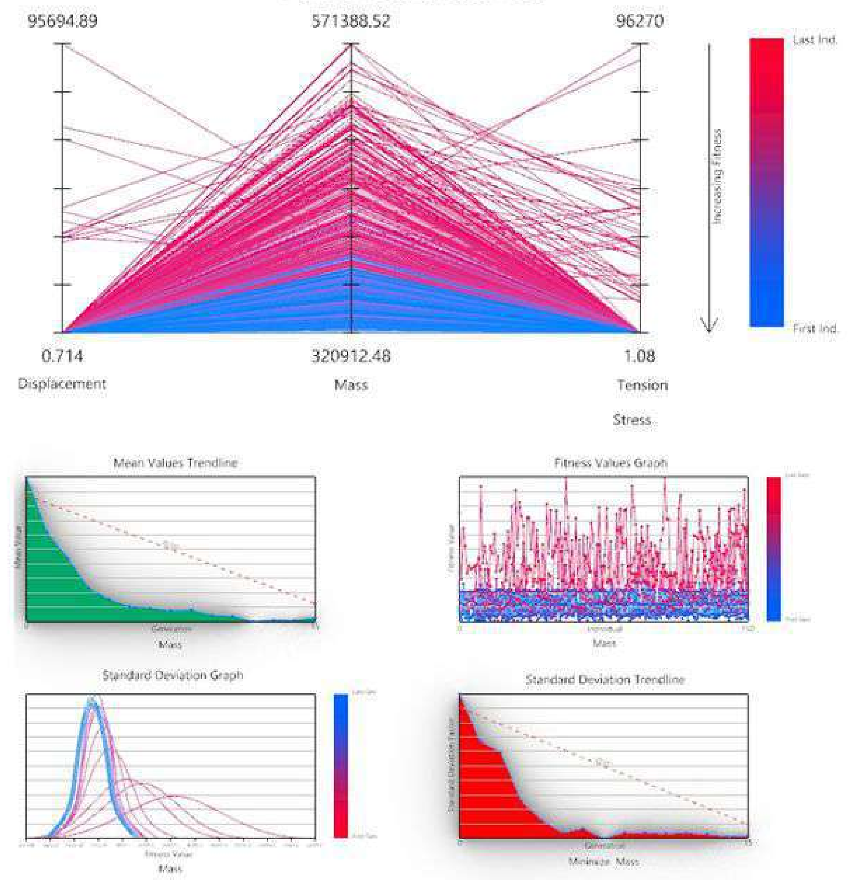
19/09/2021 01:36:27 a. m.

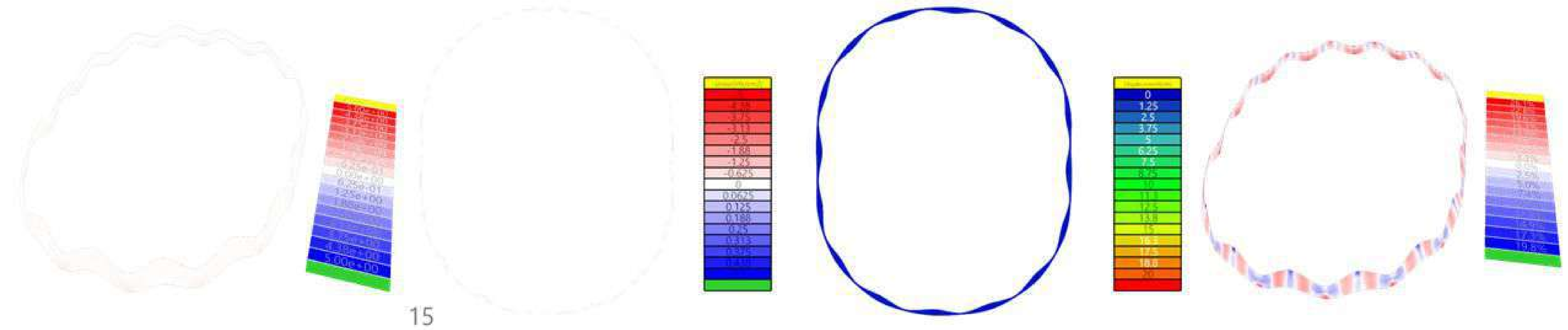
Model Setup

Variables	Units	Values Min	Values Max
Separation R1 Wb	m	0.5	4.5
Separation R2 Wa	m	1.0	7.5
Separation Supports Wa	m	0.5	7.0
Variable Thickness	cm	7.00	15.00

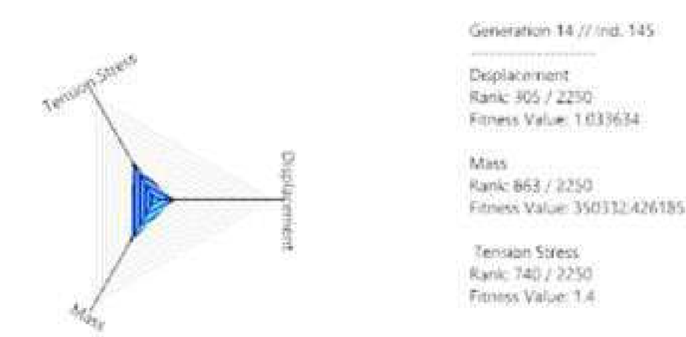
Constraints & Fix Values	Units	Values Min	Values Max
#Waves		Fix Value	
Wave Heigth(Transition)	m	0.25	
Roof Height	m	Fix Value	
Transition Height	m	Fix Value	
Transition Curvature	Scale Factor	Fix Value	
Fillet Curve	m(radius)	45.00	
Width	m	Fix Value	
Length	m	Fix Value	
Factor Selfweigth	Scale Factor	1.50	
Thickness	cm	15.00	
Shuffle Height Wc		Fix Value	
Min Heigth Wc	m	4.25	
Variation Heigth Wc	m	0.50	
Third Floor Height	m	9.25	
Second Floor Height	m	5.5	
Min Heigth Wa	m	4.25	
First Floor Height	m	1.1	

Graphs Results





Stresses Dir 2 | Stresses Dir 1 | Displacements | Utilization Percentage



Constraints & Fix Values	Units	Values Min	Values Max
#Waves		Fix Value	
Wave Heigth(Transition)	m	0.25	
Roof Height	m	Fix Value	
Transition Height	m	Fix Value	
Transition Curvature	Scale Factor	Fix Value	
Fillet Curve	m(radius)	45.00	
Width	m	Fix Value	
Length	m	Fix Value	
Factor Selfweigth	Scale Factor	2.50	
Thickness	cm	15.00	
Shuffle Height Wc		Fix Value	
Min Heigth Wc	m	4.25	
Variation Heigth Wc	m	0.50	
Third Floor Height	m	9.25	
Second Floor Height	m	5.5	
Min Heigth Wa	m	4.25	
First Floor Height	m	1.1	

Variables	Units	Values Min	Values Max
Separation R1 Wb	m	0.5	4.5
Separation R2 Wa	m	1.0	7.5
Separation Supports Wa	m	0.5	7.0
Variable Thickness	cm	7.00	15.00

Compresion

Tension

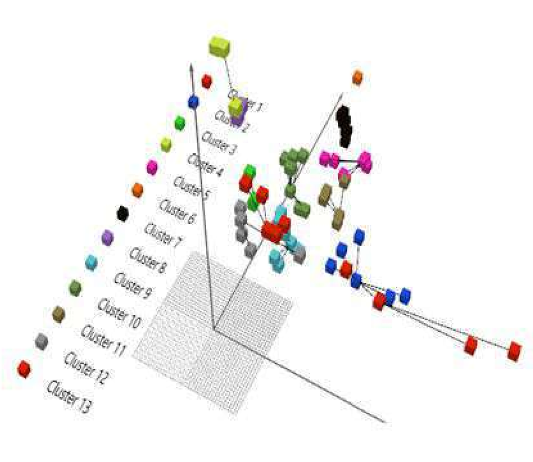
Population	
Generation Size	150
Generation Count	15
Population Size	2250

Algorithm Parameters	
Crossover Probability	0.8
Mutation Probability	1/n
Crossover Distribution Index	25
Mutation Distribution Index	25
Random Seed	2

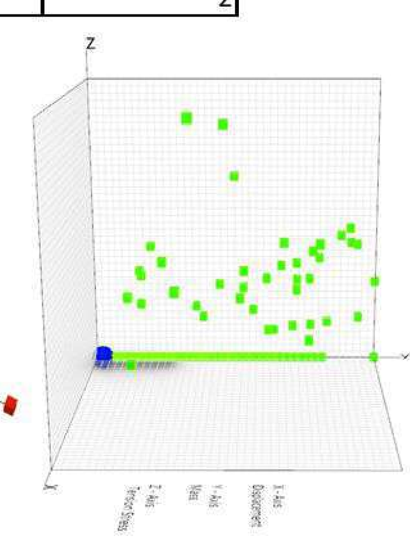
Simulation Parameters	
N° of Genes (Variables)	3
N° of Values	173
N° of Fitness Objectives	3
Size of Search Space	1.80E+05

Non-Supervised Machine Learning	
Method (Algorithm)	Kmeans
# Clusters	13

Result and Analytics	
Pareto Front Solutions	149
# Evaluation of Solutions	16
# Filter Solution	2



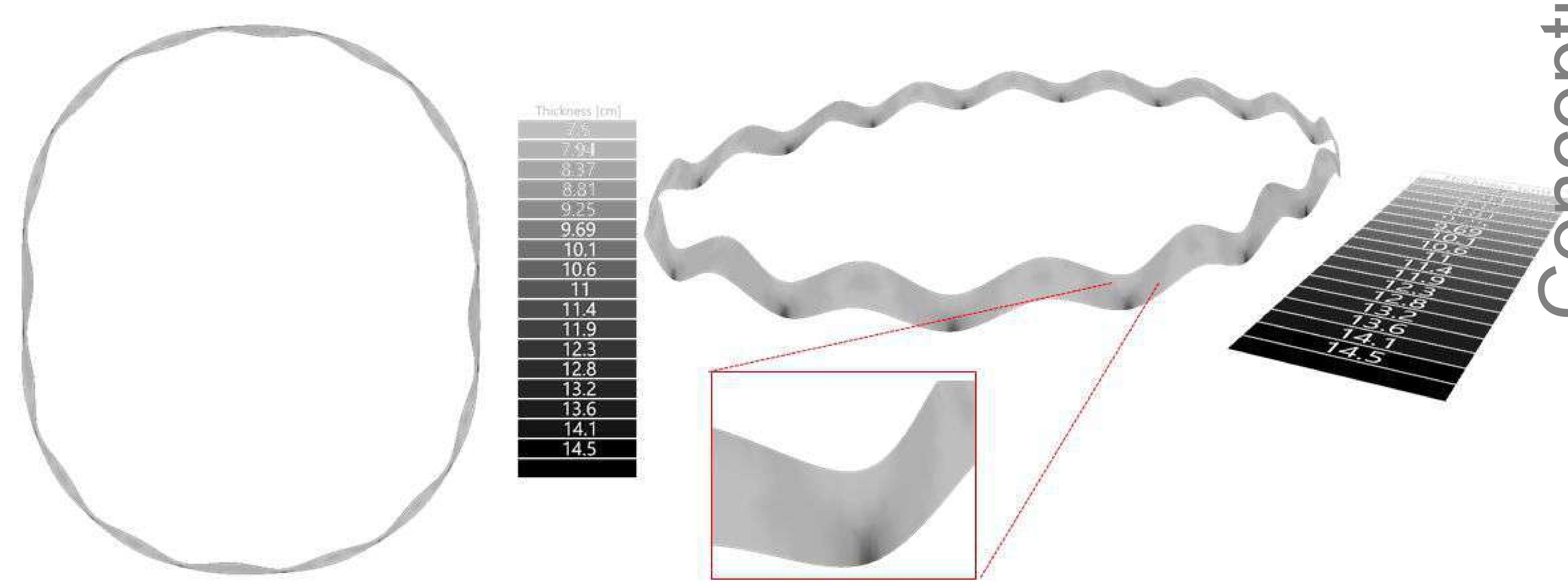
Pareto Frontier Clustering



Pareto Front Domain

1 Generative Design Facade Form

1 : 200



Conceptual Design

Graph of variable Concrete Cast in Facade

19/09/2021 01:36:27 a. m.

Project Name

Stozice Arena

SLOVENIA

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FOR:

BIM A+ European Master in Building Information Modelling

DISCIPLINE: ARCHITECTURAL

SIGN: ING. JOSÉ LUIS RODRÍGUEZ HERNÁNDEZ

DESIGNER

ID LICENCE:

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NOTES / SYMBOLS:

SHEET NAME:

GENERATIVE DESIGN FACADE FORM

SHEET NUMBER:

A-16

SHEET TO | REVISION

APPROVAL DATE:

TOMO CEROVSEK BIM + A | ANDREJ LAVRIC

IF THIS BAR DOES NOT MEASURE 25mm, ADJUST THE PLOTING SCALE.

SCALE: 1 : 200

DRAW BY: Author	DESIGN PHASE:
DESIGN BY: Designer	PROJECT NUMBER: 0001
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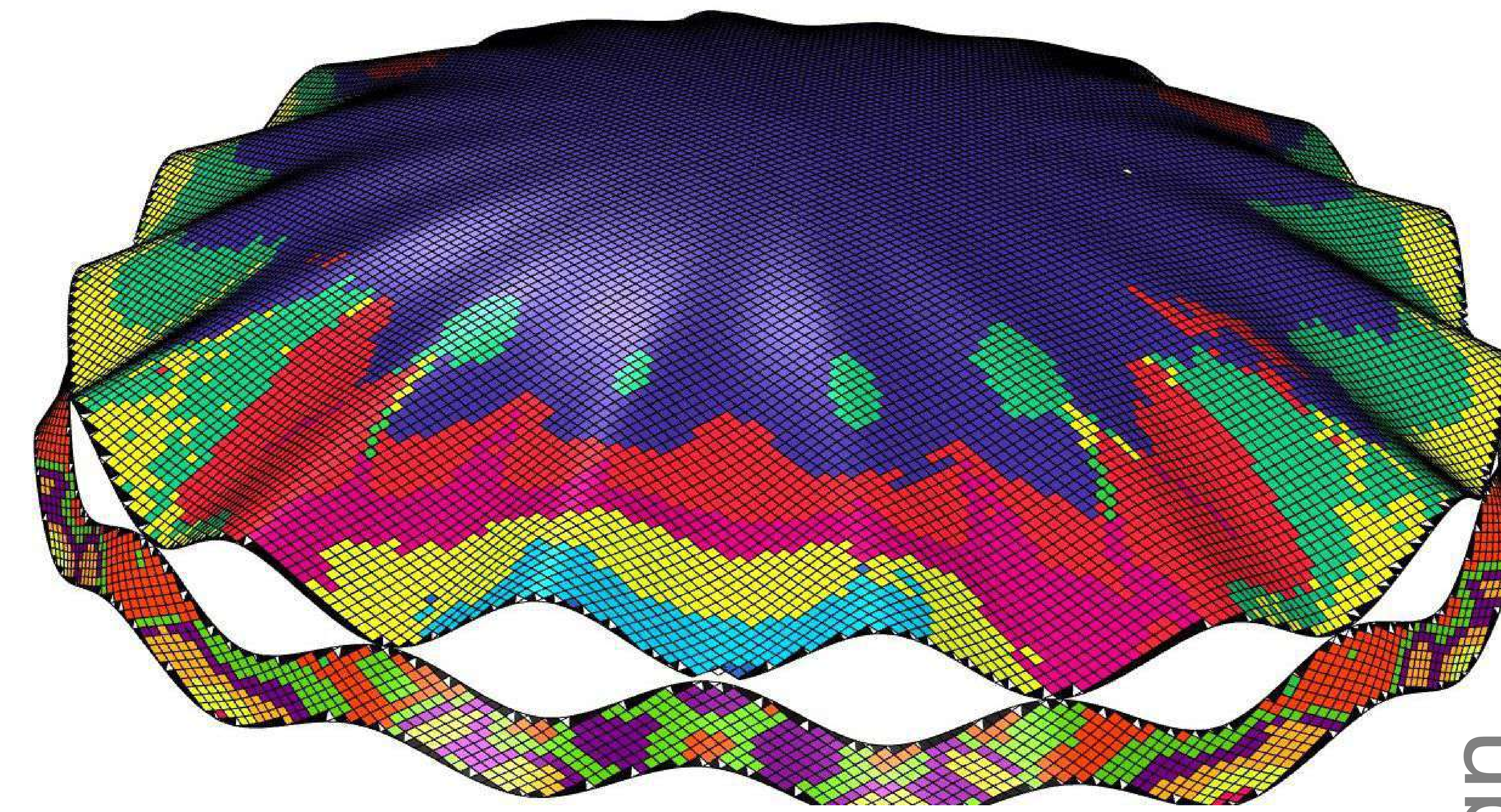
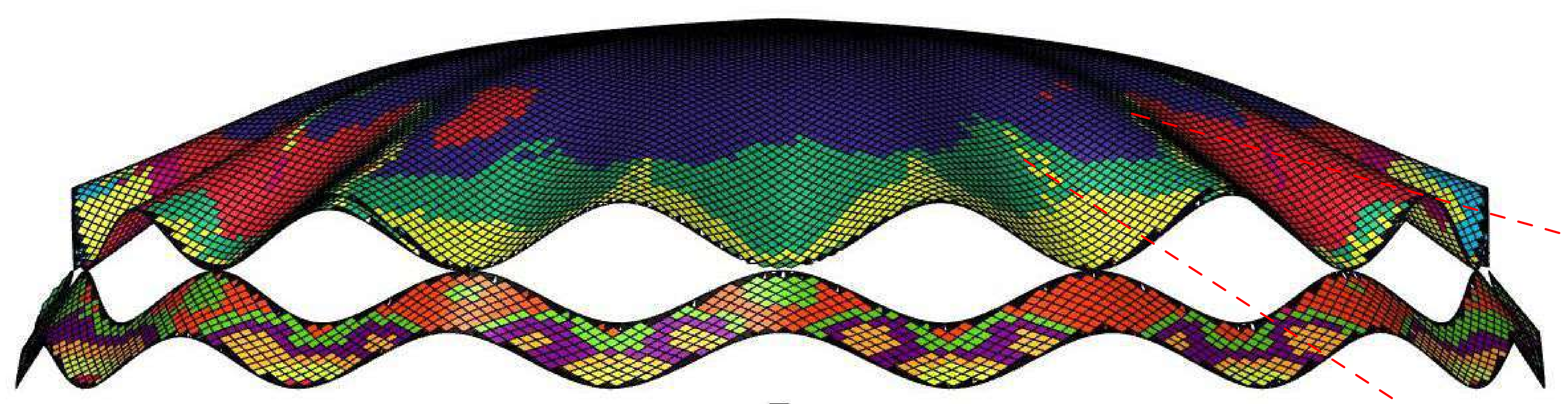
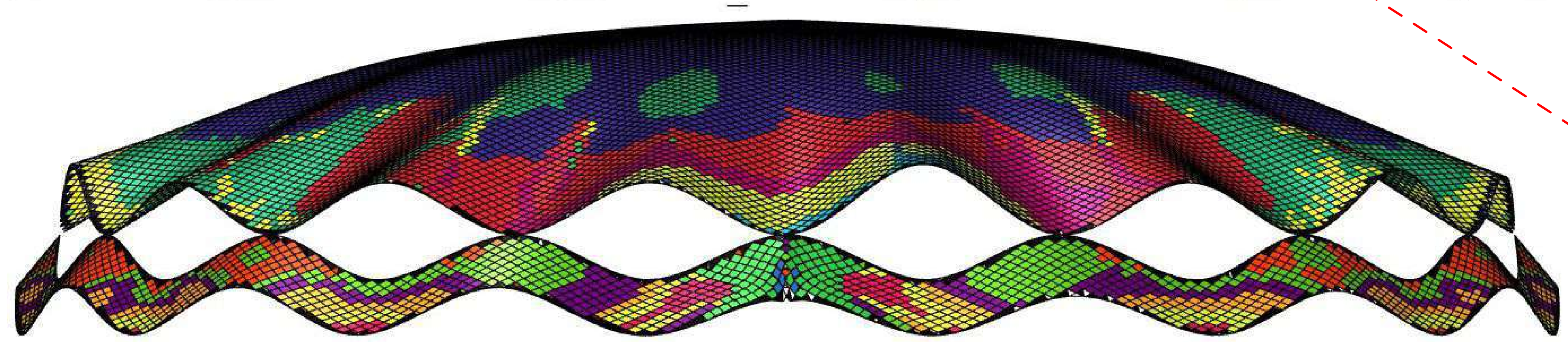
APPROVAL BY: : Owner	REVIEW DATE:

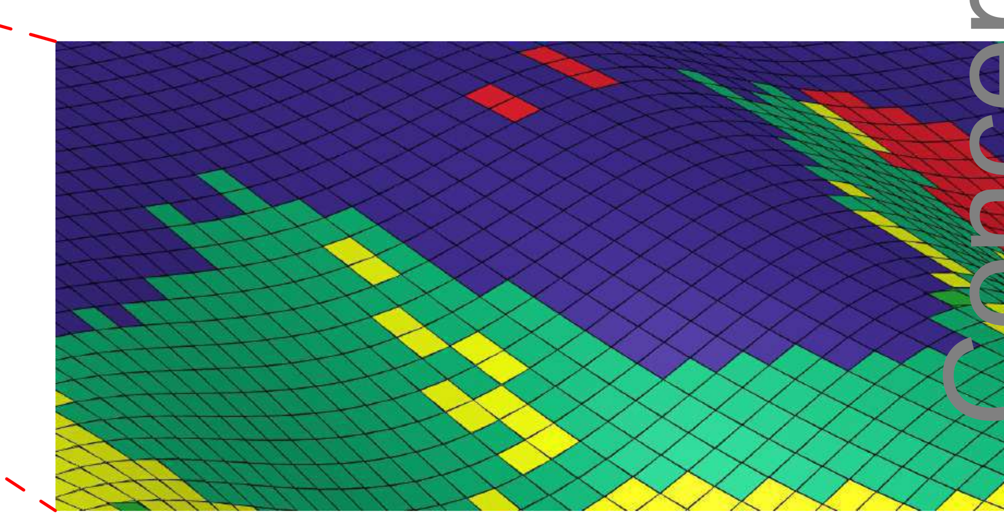
Relaxation Parameters	
Description	Unitary values
Initial U divisions	27
Initial V divisions	580
Collide Strength	600
On Mesh Strength	1500
Length Strength	5
Goal Length Strength	76 cm
Hinge Strength	15
Goal Hinge Strength	90°
Equal Angle Strength	6

Relaxation Parameters	
Description	Unitary values
Initial U divisions	208
Initial V divisions	246
Planarize Strength	200
Smoth Strength	3
Length Strength	100
Plastic Anchor	1
Clap Length Strength	3
Boundary Strength	1000
On Mesh Strength	1000
Min Panel Size	75 cm
Max Panel Size	76 cm









Conceptual Design

Zoom of Title Clustering

Initial Setup of Variables	
Description	Information
Area	12967.25 m²
Main Type of Title	Diamonds
Secondary Type of Title	Triangles
Expected length per edge	75 cm
Expected clearance per panel	less than 5 mm

Tools and Techniques for Optimization	
Description	Information
Paneling	By U and V
Initial Method of optimization	Surface Relaxation
Package for Relaxation	Kangaroo
Grouping Similar panels	Machine Learning
Package for Machine Learning	LunchBox ML
Standardization title process	Average geometry

Panel Type 01
BMark= DP-01
Number of Titles = 667
Dimension = 75.1x75.1 cm
Color RGB = 243, 57, 0

Panel Type 02
BMark= DP-02
Number of Titles = 9290
Dimension = 76.2x74.6 cm
Color RGB = 237,33,49

Panel Type 03
BMark= DP-03
Number of Titles = 125
Dimension = 74.5x72.1 cm
Color RGB = 226,17,83

Panel Type 04
BMark= DP-04
Number of Titles = 470
Dimension = 75.2x75.2 cm
Color RGB = 205,0,118

Panel Type 05
BMark= DP-05
Number of Titles = 110
Dimension = 75.2x75.2 cm
Color RGB = 108,0,120

Panel Type 06
BMark= DP-06
Number of Titles = 2048
Dimension = 75.2x75.2 cm
Color RGB = 64,44,145

Panel Type 07
BMark= DP-07
Number of Titles = 1386
Dimension = 75x74.9 cm
Color Identification =
Color RGB = 32,95,174

Panel Type 08
BMark= DP-08
Number of Titles = 2910
Dimension = 75x75 cm
Color RGB = 1,192,229

Panel Type 09
BMark= DP-09
Number of Titles = 2950
Dimension = 75x75 cm
Color RGB = 15,181,116

Panel Type 10
BMark= DP-10
Number of Titles = 604
Dimension = 74.7x74.8 cm
Color RGB = 42,181,58

Panel Type 11
BMark= DP-11
Number of Titles = 630
Dimension = 75.5x75.4 cm
Color RGB = 86,189,9

Panel Type 12
BMark= DP-12
Number of Titles = 830
Dimension = 74.6x74.6 cm
Color RGB = 213,234,31

Panel Type 13
BMark= DP-13
Number of Titles = 53
Dimension = 75.2x75.2 cm
Color RGB = 224,240,26

Panel Type 14
BMark= DP-14
Number of Titles = 116
Dimension = 75.3x75.3 cm
Color RGB = 236,250,9

Panel Type 15
BMark= DP-15
Number of Titles = 338
Dimension = 75.2x75.2 cm
Color RGB = 247,159,20

Panel Type 16
BMark= DP-16
Number of Titles = 543
Dimension = Variable
Color RGB = 0, 0, 0

Panel Type 17
BMark= TP-01
Number of Titles = 305
Dimension = Variable
Color RGB = 0, 0, 0

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Project Name

Stozice Arena

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DESIGNER

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GENERATIVE DESIGN TITLE STANDARDIZATION

SHEET NUMBER: A-17

SHEET TO	**REVISION**

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TOMO CEROVSEK BIM + A — ANDREJ LAVRIC

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SCALE: 1 : 200

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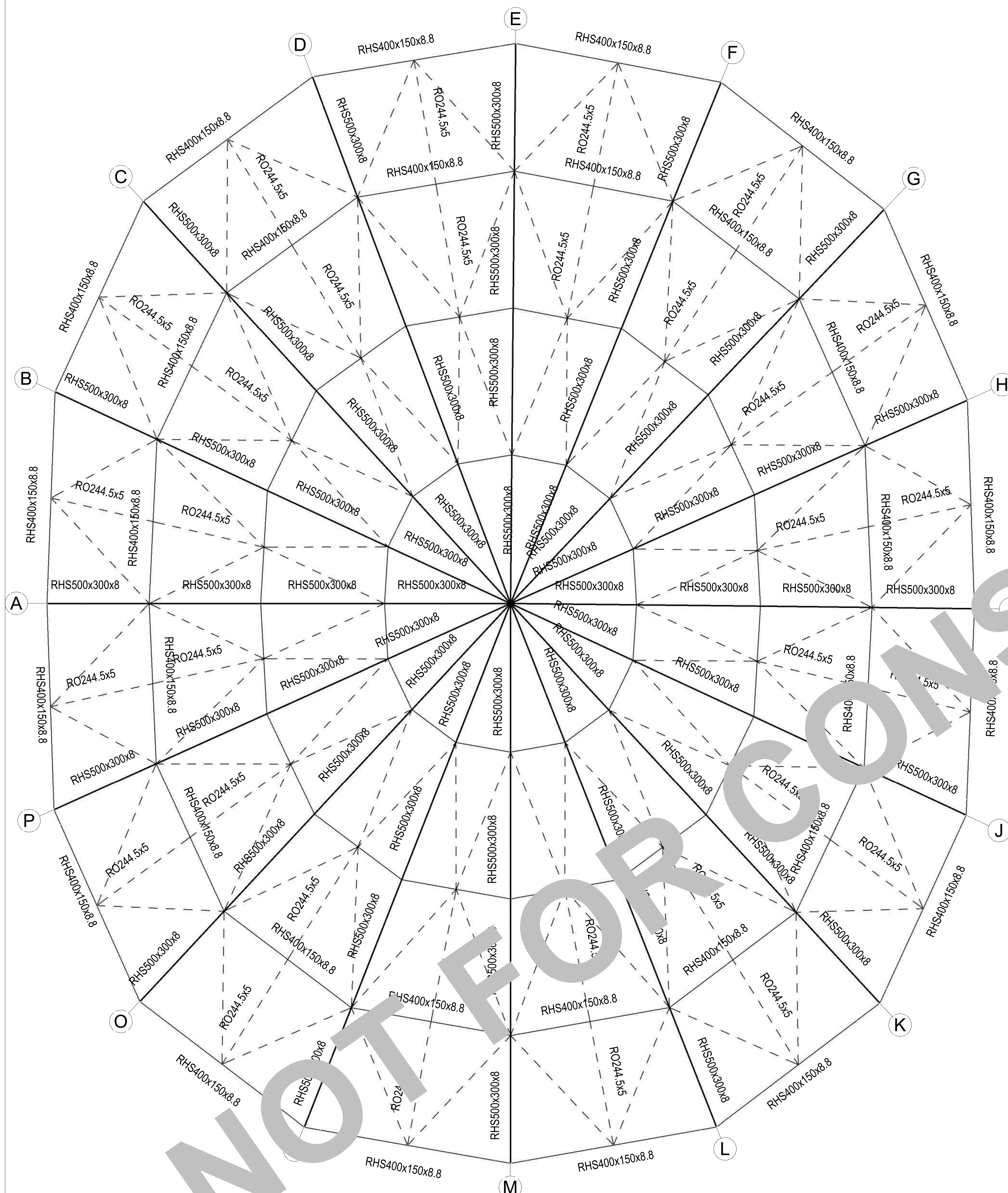
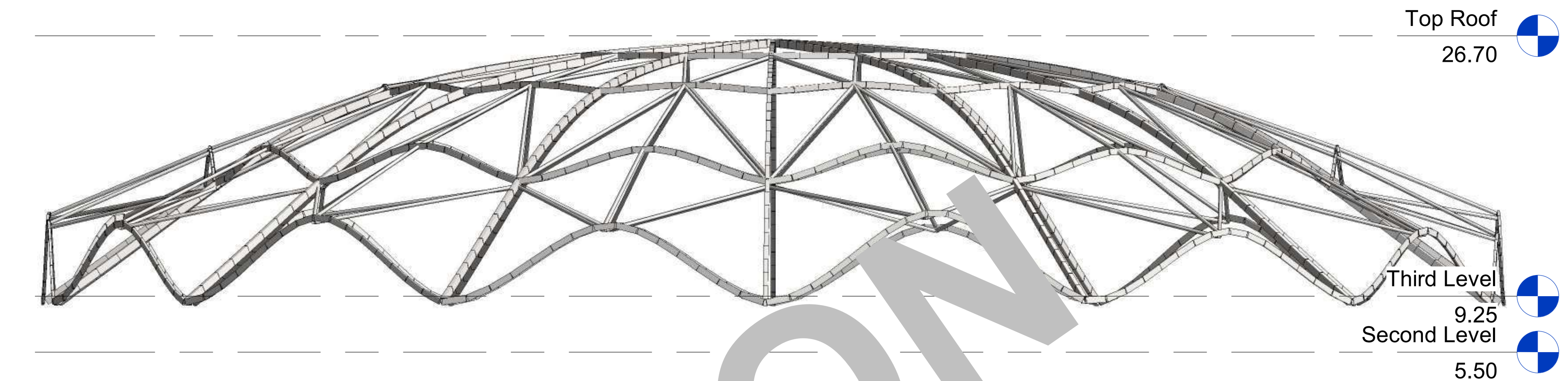
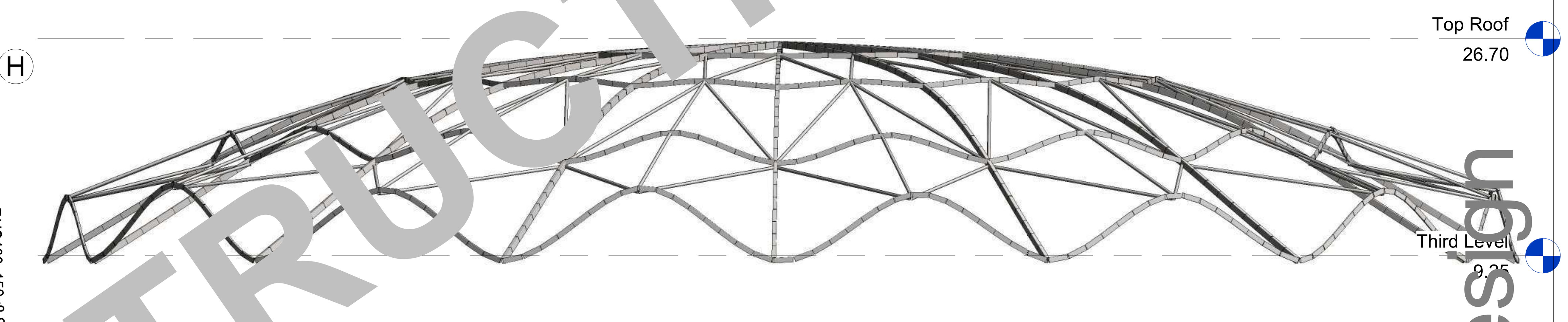


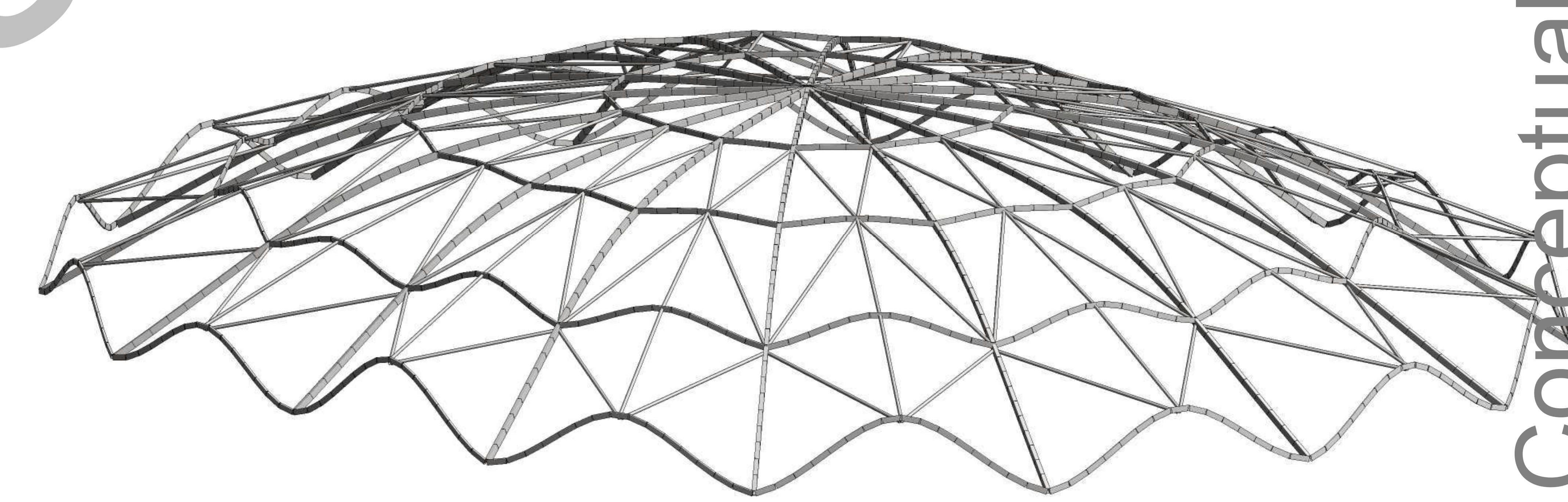
1 Structural Plan
1 : 300



2 West Structural
1 : 350



3 Structural North
1 : 350



4 Structural 3D Model

Structural Framing Schedule			
Type	Cut Length	Volume	Weight
RHS400x150x8.8	960.96	8.21 m³	64.53
RHS500x300x8	958.98	14.96 m³	117.59
RO244.5x5	1952.04	7.34 m³	57.72
Grand total: 1292	3871.98	30.51 m³	239.84

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SHEET NAME:
STEEL STRUCTURE

SHEET NUMBER:
S-01

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SCALE:
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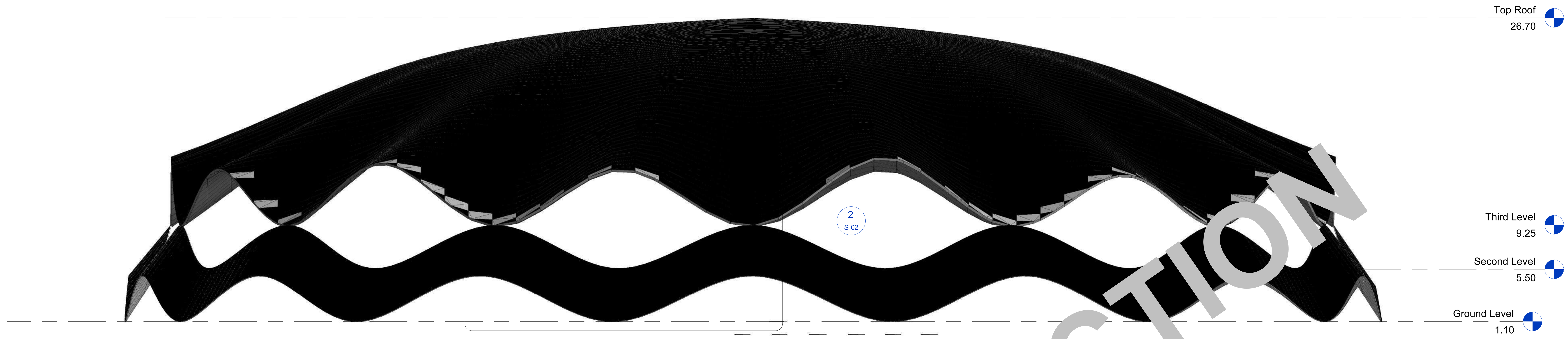
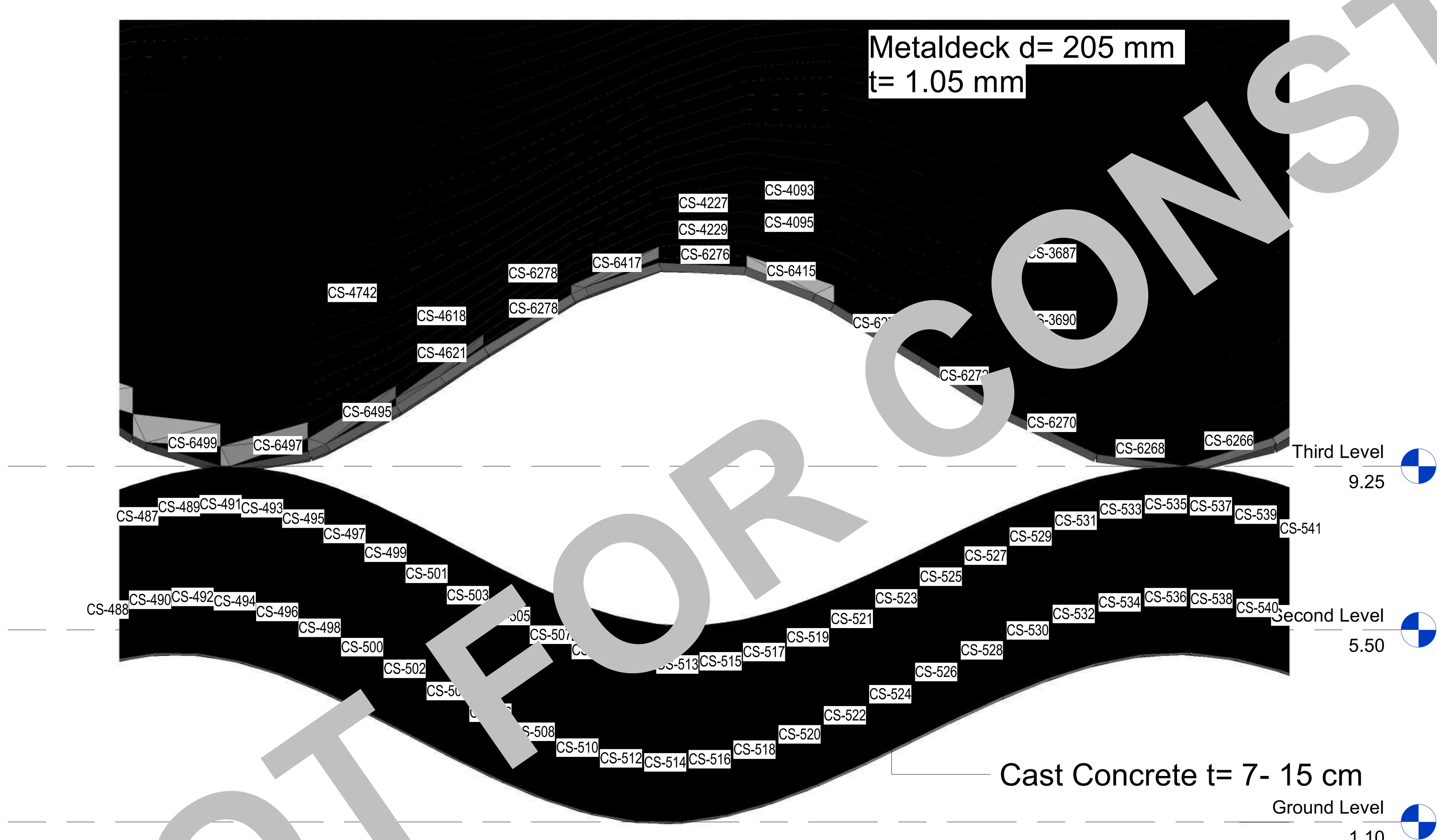


1 West View
1 : 200



2 West View - Tag Example
1 : 100

Conceptual Design

Concrete Facade

Count	Type	Area	Volume	BMark
192	Concrete Slab t= 8 cm	4 m²	67.62 m³	Conc-F
522	Concrete Slab t= 8 cm	5 m²	196.36 m³	Conc-F
714			263.97 m³	

Metaldeck Roof Area

Count	Type	Area
5811	Metaldeck d= 205 mm	19839.7 m²
5811		19839.7 m²

Metaldeck Roof

Count	Type	Area
8	Metaldeck d= 205 mm	0.0 m²
11	Metaldeck d= 205 mm	0.1 m²
10	Metaldeck d= 205 mm	0.2 m²
9	Metaldeck d= 205 mm	0.3 m²
5	Metaldeck d= 205 mm	0.4 m²
3	Metaldeck d= 205 mm	0.5 m²
7	Metaldeck d= 205 mm	0.6 m²
8	Metaldeck d= 205 mm	0.7 m²
12	Metaldeck d= 205 mm	0.8 m²
6	Metaldeck d= 205 mm	0.9 m²
10	Metaldeck d= 205 mm	1.0 m²
6	Metaldeck d= 205 mm	1.1 m²
7	Metaldeck d= 205 mm	1.2 m²
13	Metaldeck d= 205 mm	1.3 m²
28	Metaldeck d= 205 mm	1.4 m²
12	Metaldeck d= 205 mm	1.5 m²
17	Metaldeck d= 205 mm	1.6 m²
16	Metaldeck d= 205 mm	1.7 m²
13	Metaldeck d= 205 mm	1.8 m²
11	Metaldeck d= 205 mm	1.9 m²
8	Metaldeck d= 205 mm	2.0 m²
17	Metaldeck d= 205 mm	2.1 m²
10	Metaldeck d= 205 mm	2.2 m²
10	Metaldeck d= 205 mm	2.3 m²
12	Metaldeck d= 205 mm	2.4 m²
16	Metaldeck d= 205 mm	2.5 m²
17	Metaldeck d= 205 mm	2.6 m²
20	Metaldeck d= 205 mm	2.7 m²
19	Metaldeck d= 205 mm	2.8 m²
8	Metaldeck d= 205 mm	2.9 m²
3	Metaldeck d= 205 mm	3.0 m²
4	Metaldeck d= 205 mm	3.1 m²
949	Metaldeck d= 205 mm	3.2 m²
943	Metaldeck d= 205 mm	3.3 m²
648	Metaldeck d= 205 mm	3.4 m²
631	Metaldeck d= 205 mm	3.5 m²
480	Metaldeck d= 205 mm	3.6 m²
579	Metaldeck d= 205 mm	3.7 m²
494	Metaldeck d= 205 mm	3.8 m²
337	Metaldeck d= 205 mm	3.9 m²
200	Metaldeck d= 205 mm	4.0 m²
119	Metaldeck d= 205 mm	4.1 m²
55	Metaldeck d= 205 mm	4.2 m²
19	Metaldeck d= 205 mm	4.3 m²
1	Metaldeck d= 205 mm	4.4 m²
5811		

Project Name

Stozice Arena

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SHEET NAME:
FLOOR SYSTEM

SHEET NUMBER:
S-02

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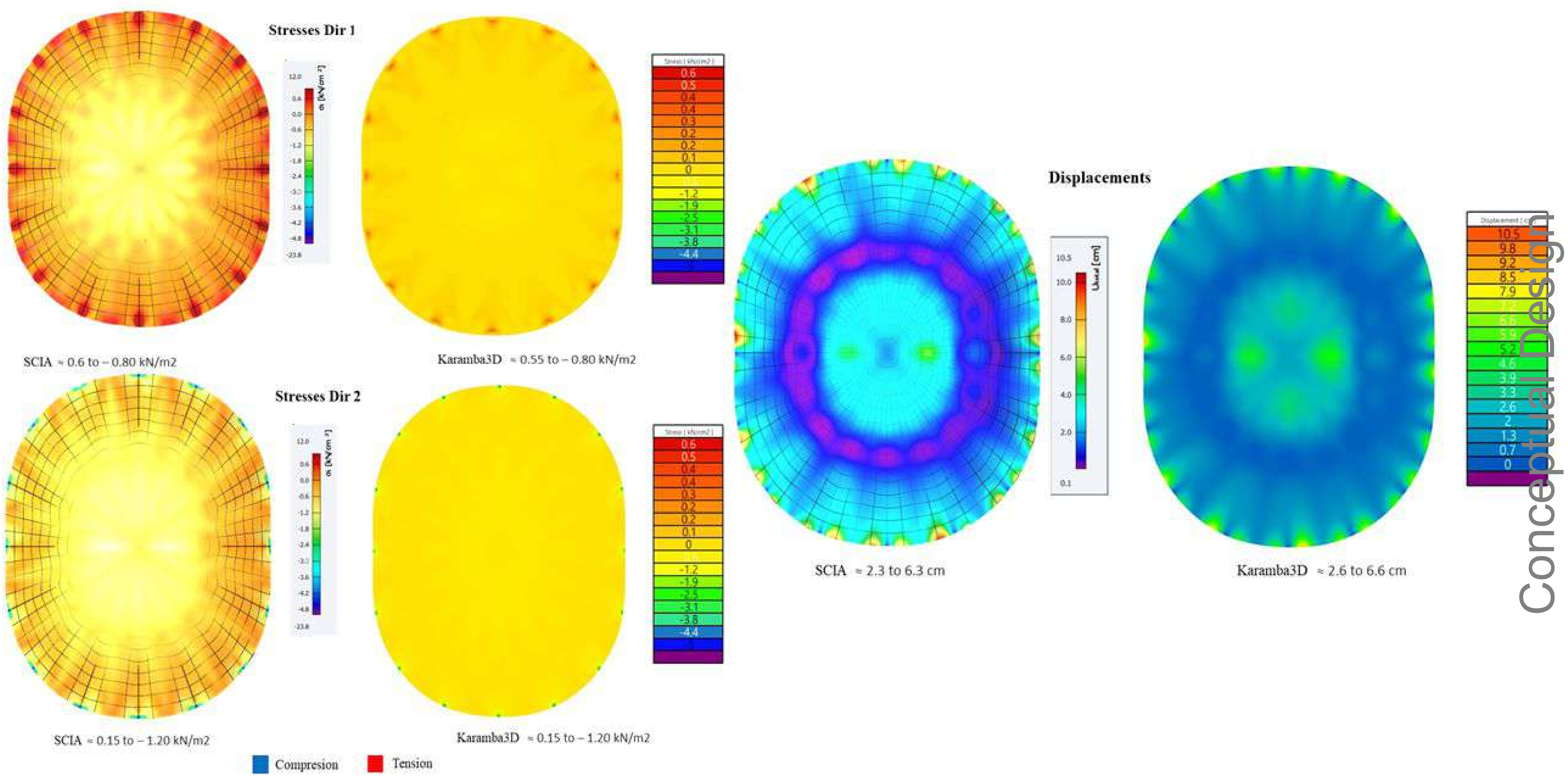

1 Comparison SCIA vs Karamba3D

1 : 200

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NOTES / SYMBOLS:

SHEET NAME:
COMPARISON SCIA VS KARAMBA3D ROOF FORM

SHEET NUMBER: S-11

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