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## A systematic approach for the preliminary design of stadium roofs

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**ABSTRACT:** Stadiums are iconic landmarks and historically significant structures. From an engineering standpoint they are large-scale, geometrically complex and test the limits of material, requiring sophisticated design techniques. Their construction is also a major contributor to total global emissions. Structural integrity, economic design and sustainability are important design considerations from an early stage. In the preliminary design stages, requirements for strength, stiffness and stability need to ensure structural safety and to minimise resource consumption. Design decisions made in this stage have the greatest potential to improve the costs, environmental impact and benefits attained with a structural form. In practice, several design alternatives must be assessed to arrive at an ideal or optimised solution, which makes traditional design techniques highly effort-consuming. In preliminary design, efficient design solutions can be created with the help of parametric modelling. However, parametric tools are typically applied to well-developed design problems rather than early conceptual design problems. In the present work a systematic parametric modelling approach to support the design and optimisation of open stadium roofs is proposed. It focuses on the structural typology and material usage of several stadium roofs. The need for a progressive approach to conceptual parametric design where complexity is progressively introduced in the parametric model is emphasised. This approach is studied in the parametric design of a radial stadium where variations of structural mass can occur when deciding between preliminary design parameters and comparing parametric solutions within a feasible empirical parametric space. Parametric design is shown to have large potential in significantly improving current design outcomes and enabling fully optimal automated stadium roof designs.

**KEYWORDS:** Preliminary Design, Optimisation, Parametric Modelling, Stadium Roof, Automated Design.

### 1 INTRODUCTION

Preliminary design is an iterative process at the beginning of a project where ideas are generated, evaluated and tested for rejection or further refinement [1]. This involves gathering design requirements, constraints and establishing several various design solutions that satisfy these requirements. The design steps of this procedure as defined by Okudan, Gul and Tauhid [2], are divergent idea generation followed by convergent idea assessment, prior to selection. The process of preliminary design involves much creativity and iteration of the many possible structural forms. It is noted that the emphasis of preliminary design is not on structural analysis but on requirements for strength, stiffness, stability, structural safety, to minimise resource consumption and to outline a structures form and function. Traditional methods of preliminary design involve hand sketches, and approximate hand calculations to test several ideas and to quickly arrive at an acceptable preliminary design solution. However, due to a series of factors, such as effort and cost, among others, only a small number of design solutions can be created using these methods [3]. As concerns over climate change, population increase and resource exhaustion becomes more urgent, the need for the design of structures to evolve, to understand structural efficiency and the objectives of future sustainable design, is paramount. With 25% of total global emissions now coming from the construction sector [4], engineers have an increased responsibility of making the most of the resources available to them and arbitrary decision making (or decision making based on “rules of thumb”) is not sufficient anymore.

In this context, more efficient design alternatives and solutions can be created with the help of computational design, (parametric modelling in particular). Computational Design is the application of strategies such as computer algorithms to a design process [5]. In most situations computational design is

applied to well-developed design proposals where the majority of the design parameters are known or have been already determined by the design team [6]. This is because of the detailed nature and amount of input required to describe a computational model. Computational design software needs a large number of design parameters such as geometry inputs, structural member sizes and material strength grades early on to produce a model with an acceptable structural design solution. Such data very early in the design acts to interrupt the process of iterative decision-making and forces the designer to prematurely make decisions, frequently in an arbitrary manner. A detailed discussion on the different benefits that such computational implementation can promote in the design of structures is presented in [7]. In the practices of design, there is a separation between the act of design and the act of analysis [1]. This results in the preliminary design stages confined within the domain of so-called expertise, hand calculations, sketches, and some less complex forms of analysis to validate decisions.

One of the main challenges of stadium-roof design in its early-stages is to develop a holistic understanding of the degree of complexity in structural systems that may suffice an adequate structural form.

The present work discusses computational parametric modelling as a technique for preliminary design and investigates the extent to which it can influence design outcomes in the preliminary stages. It emphasises the importance of computational design techniques to be incorporated into the design process from the beginning. The ultimate goal of this discussion is to foment discussion on a rationale that can be used in a systematic form and enable automated preliminary brainstorming of structural forms, quantified by their efficiency in relation to some form of performance measure.

## 2 COMPUTER-AIDED PARAMETRIC DESIGN AND OPTIMISATION

Computer-aided parametric design provides a promising solution to deal with the sheer number of unknown parameters limiting the use of more detailed design alternatives. In it, a model can be built with very little knowledge of the design space and variables can be changed using parametric relationships. Its usage can decrease an engineer's workload significantly by performing several repetitive processes with varying inputs to optimise and greatly increase the efficiency of a design. It allows the design to change and reorder even in the late stages of the design process with little consequence. It is known that several design alternatives must be assessed to arrive at the ideal and optimised solution [8]. This is difficult and time consuming when carried out without the support of computational tools that allow a systemic implementation.

### 2.1.1 Types of Parametric Design and Tools

Parametric design is a process based on algorithmic thinking that enables the expression of parameters and rules that together define, encode and clarify the relationship between design intent and design response. Three main types can be highlighted:

- Interactive design focuses on the user's experience of hardware and programmable systems. It consists of six main components, user control, responsiveness, real-time interactions, connectedness, personalisation, and playfulness. It provides interactivity by focussing on the capabilities and constraints of human cognitive processing [9].
- Generative design is a design exploration process with design goals that generates design alternatives with rapid performance feedback [10].
- Algorithmic design creates large design spaces, highly complex geometries and performance simulations which allows the designer to explore a wider range of possibilities rapidly and with little effort [11].

Different tools are available for parametric design. A common approach is to use a visual script (a flowchart with parameters interconnected). This is advantageous for visual design particularly in the conceptual stages because the designer can control and visualise the design and design process. Grasshopper is one of the alternatives that uses a scripting software and graphical algorithm. This operates within Rhinoceros and produces powerful generative and parametric modelling that incorporates parameter control, programming functions, generative and randomness capabilities. It is the tool applied in the present implementation.

### 2.1.2 Design Processes and Decision-Making Techniques

Future design practices according to [12, 13] includes iterating the following three steps: parametric modelling (step 1), as an enabler of the generation of numerous design alternatives; performance simulation (step 2) to imitate real world conditions and produce values for quantitative parameters that can be used to assess a structures performance; and design optimisation (step 3) to create design solutions that satisfy multiple, potentially conflicting, performance criteria.

Design optimisation, in particular, will play a major role in the achievement of highly efficient design solutions in the preliminary phases of design. Optimisation in this context includes Single Objective Optimisation (SOO), Multi Objective Optimisation (MOO) and Multi-Disciplinary Objective Optimisation (MDOO) [14]. If correctly used these have the potential to improve current conceptual workflows by generating high performance designs at any stage of the design procedure.

## 3 PARAMETRIC APPROACHES IN STADIUM ROOF DESIGN

Designing stadium roofs parametrically has been used before, however only in a limited form for early-stage design and prototyping different schemes.

There has been research carried out for generating variable seating bowls using parametric modelling [9]; associating seating bowls with specific roof structures [15]; optimising structural [16], energy [16], wind and solar [17] performances based on specific types of geometry; focusing on architectural design variables; studying the structural performance of large indoor arenas and full coverage roof structures using parametric modelling [14]. [9] explores a flexible parametric model composed of the stadium's pitch, bowl, and roof structure; where the roof structure focuses on three structural types (grid-shell, spaceframe, and truss beam). [16] focus on the structural efficiency, operational energy efficiency and architectural expression of long span design. They use multi-objective optimisation for the generation and selection of high performing long span structural solutions for structural typologies that are not purely rectangular or regular geometric shapes. The paper concludes that future work should build on the optimisation model in terms of structural systems and understanding trade-offs between design objectives. [13] present a computational method for the design of sports buildings in the early stages of design using performance simulation tools and multi objective algorithmic optimisation. Design variables include the roof geometry (curvature and dimensions), the position of skylights, building rotation and the properties of the construction materials. The optimisation algorithms used Self-Organising Maps and Hierarchical Clustering on an interactive dashboard to convey the various interacting objectives in the design space and to search for high performance solutions. The research also included multi-disciplinary optimisation during the conceptual stages of the design process. This simultaneously considered the performance criteria and design requirements needed for different disciplines leading to an optimal solution. The paper discusses the complexity of sports building roofs and concludes with the explanation of ongoing future work, including additional testing of case studies and further integration of computational methods.

## 4 SYSTEMATIC APPROACH TO PARAMETRICALLY MODELLING STADIUM ROOFS

For parametric design in stadium roofs to be realistic for the designer, they must not require a large amount of knowledge of the design space to create an efficient workflow. Ideally the number of inputs required in the model should be the minimum number that carries approximately all the information about the problem in-hand. Although no design process is ever simple,

parametric design, digital workflows, and decision-making techniques such as optimisation, aim to automate these processes to make the overall design process efficient. The objective of the present work is to create a standardised way for decision making, or a methodology (systematic framework) for the preliminary design of stadium roofs using parametric modelling. The following 8 steps are proposed to initiate a framework that automates the parametric design in the preliminary stages. These are to some extent self-explanatory of the steps that a designer needs to follow to set-up a parametric model with several degrees of freedom. In practice, preliminary design starts from a full parametric space where all degrees of freedom are available. Then the designer progresses from the system of systems to component level locking different degrees of freedom. (S)He uses *a priori* knowledge to perform this procedure. If an automated procedure is aimed at systematically applying this process, then it should be able to, in a structured way, follow the same line of thought and be able to iterate through it.

**STEP 1: Parametric Design Modelling Program and Design Process.** This initial self-explanatory step will frame the computational support layout required for a parametric approach to preliminary design. It is not part of the iterative procedure and the layout defined should take the software's parametric design abilities into account and their synergies with the stadium problem in-hand (ease in which parameters can be set and changed). It should also include design types, design processes and decision-making techniques. For example, as stadiums are expected to be multi objective, the optimisation process should be able to support this.

**STEP 2: Stadium Function(s) and Location(s) – Inner-Outer Boundaries.** In this step, the capacity of the stadium, the bowl shape, the roof coverage requirements (e.g., indoor, outdoor), the sporting event (pitch shape) and the functionality of the space being designed needs to be considered. These elements will establish the inner and outer boundaries of the parametric model. In this step, within the parametric space, there is a fully-free experimental design. Any structural systems are feasible, and any discrete connection of points within the parametric boundaries is a solution. Several different bowl shapes and sizes can be used.

**STEP 3: Design Outcomes(s) and Objective(s).** Once step two is complete, the designer must decide what design outcomes are important in the project such as efficiency in terms of environmental impact and cost. The design objectives associated with this outcome included minimising the self-weight of the structure and optimising the cross sections of the elements. Other relevant quantitative design objectives could include layout optimisation, structural typology efficiency, minimising operational energy, optimising construction sequence and fabrication, acoustic atmosphere, and natural lighting. More objectives can be added if required.

**STEP 4: Stadium Structural System(s) – Systems.** Once the stadium function, location and design objective(s) have been decided, the structural systems that are best suited for the implementation are selected, considering the appropriate load paths and any spectra of existing knowledge. This step reduces the fully-free parametric space to a combination of structural systems, within the inner and outer boundaries. A subset of structural systems from a wider range of available systems

constrains the preliminary design. Parametric variables that are related to the system of systems are identified in this phase too (e.g., spacing between structural system).

**STEP 5: Stadium Structural System(s) - Component(s).** Once the structural system(s) are decided on, the variables that each structure have in common must be examined. These variables will establish the parametric relationships in the model. This includes the identification of degrees of freedom that exist in each structural system, as a system of components. It also includes the identification of any model dependencies for each (e.g., how the individual component variables in the parametric model, can be altered, and what type of impact each will have on the structural system). In this phase the experimental design for the preliminary design is further reduced to combinations of parametric systems.

**STEP 6: Initial Parametric Model.** With the parametric components established in steps 2-5, the geometry of the various structures can be created.. Each structural system can be designed using lines and parametric relationships corresponding to each variable. After the parametric script is set-up, changes between structural systems and system variables are expected to require virtually zero design efforts.

**STEP 7: Structural analysis – Establish feasible domains.** Once step 6 has been completed, the structural analysis suitable for the design decisions can be implemented into the parametric model. With the design standards, limits and checks established the model can be analysed. It is here that structural engineering knowledge and expertise is applied for the model to be realistic and ensure structural stability and safety for the preliminary design. The preliminary analysis can take load bearing capacities, buckling, vibration and deflection limits into account. If designer input is considered, limits must include rules of thumb for ranges of variables. All will constrain the parametric space to a space of feasible parametric solutions.

**Step 6a & 7a: Rolled Parametric Design (Update/ Augment the parametric model).** With the design variables, geometry, parametric relationships and analysis modelled, the designer can revisit the design, objectives, parameters, functions, and additional systems in the model. An initial parametric model is established that can be updated or further parameterised if required. Step 6a and 7a involve looping through the previous steps 2-6 if required.

**STEP 8: Parametric Decision-Making.** Using the decision-making technique enabled in Step 1, the design objectives from Step 3 and the system components from Step 4-5; the parametric evaluation of the model, built in Step 6 and constrained in Step 7, can take place. If parametric optimisation is applied, results can be visualised and various solutions examined.

**Step 8a: Re-evaluation.** The decision-making should follow an iterative design process. In this step a decision should be made regarding whether to return to **step 6a** or **7a** and update/augment the parametric model; or accept the current parametric solution. Useful decision criteria should include any variables that converged to the boundary of the design space. This means that there is an interest for an augmented spaced to be rolled back to the previous steps (that is, an increased parametric range). Any new ranges should be re-evaluated, to give new parametric solutions, and if any new solution does not improve the previous outcome, the previous outcome can be accepted.

If scope is identified in augmenting the parametric variables, not only in range but in characterisation, then these should be added in **step 7a**. If new client requirements or inputs external to the parametric model are added, they should also be included in augmented models. Figure 1 gives an overview of the structure discussed above.

## 5 IMPLEMENTATION OF A PARAMETRIC MODEL IN PRELIMINARY DESIGN

Following the approach described in section 4, a progressive parametric preliminary design model was generated to illustrate the benefit of thinking systematically in parametric design and the potential it has to improve the outcomes of design. It combines the software Rhino with Grasshopper along with several plug-ins. The Grasshopper model consists of four sections including input parameters, geometry, a structural analysis, and an optimisation. By examining the information extracted from literature and using design requirements, each design decision was made with the idea that it could be changed, re-analysed or increased in complexity in the future, i.e. being progressive in nature. Figure 2 presents the structure

of the parametric script developed. It describes a stadium roof with parametric radial trusses. The interested reader is directed to [7] for a detailed explanation of the model.

### 5.1 Input Parameters

To begin the modelling process several key starting points, optimisation parameters, user defined parameters and fixed parameters were established. These included 6 parameters; capacity, material, truss internal spacing, angle (referred to as height above the pitch), truss depth and number of truss bays. An initial radial system was considered, but the model indicated how additional structural systems might be incorporated into the script.

### 5.2 Geometry and Check

The model incorporated five rounded polygonal curves which defined its geometry based on the capacity, pitch outline, sightlines, viewing angles, rows of seats and the grandstand structure below. These curves constrained the geometry of the stadium to a specific boundary. The curves were split into sections and all structural elements. An example of the stadium roof model is presented in Figure 3.

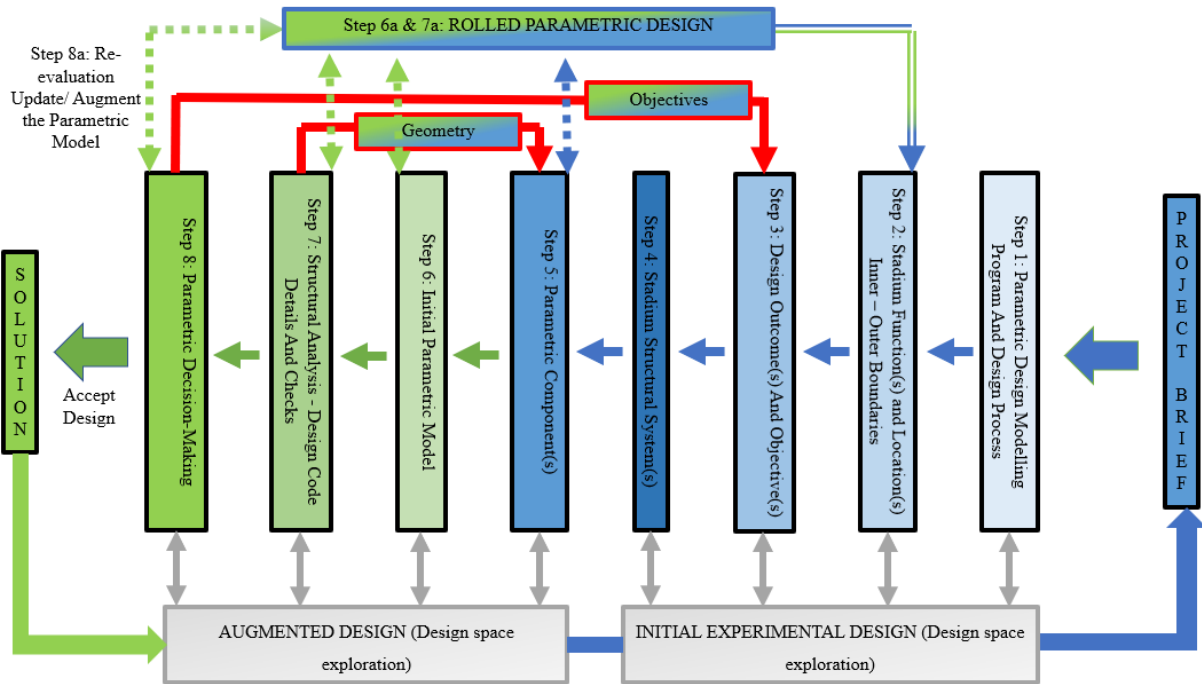


Figure 1. Example of the systematic structured procedure for preliminary progressive parametric design.

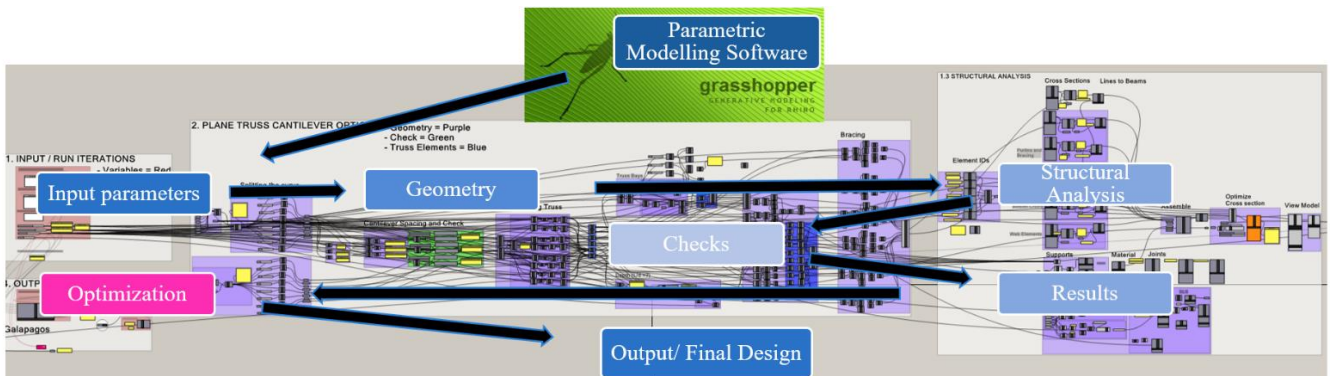


Figure 2. Structure of the model of the radial based truss system, parametric stadium roof developed.

### 5.3 Preliminary Structural Analysis

A simplified finite element code (Karamba3D), suitable for calculation in the preliminary design stages, was used to conduct the structural evaluation of the parametric solutions. In this code, design decisions for the analysis included the application of cantilever steel trusses with UC sections as top and bottom chords with purlins and bracing as square or rectangular hollow sections with simple connections. The supports used in the model were the two bottom nodes and the first top node. Each roof truss had a uniformly distributed load along the top chord to represent the weight of the cladding, services, and wind. Ultimate (ULS) and Service (SLS) limit states load combinations were considered. Utilisation ratios and deflection limits also constrained the parametric space.

### 5.4 Optimisation and decision criterion

The goal of the analysis was to merge optimisation with preliminary design so that the full benefit of parametric modelling in preliminary design could be attained. In the present example one objective (the mass) was considered. The optimisation was run using 4 parameters (no. of truss internal spaces, angle, truss depth, and number of truss bays). A Genetic Algorithm (GA) was applied to solve the optimisation. GAs are well-suited to be applied with parametric models, in bi-level approaches [18].

### 5.5 Results

An optimisation run on the 4 parameters mentioned above ran in approximately 10 minutes. Figure 3 presents a feasible solution of the parametric space. Results for different feasible parametric solutions are presented in Figure 4. The ranges of values for each variable in Figure 4 are represented by vertical axes (increasing in value from bottom to top) and each line represents a different design solution. The point where each line intersects the vertical axes represents the value of a

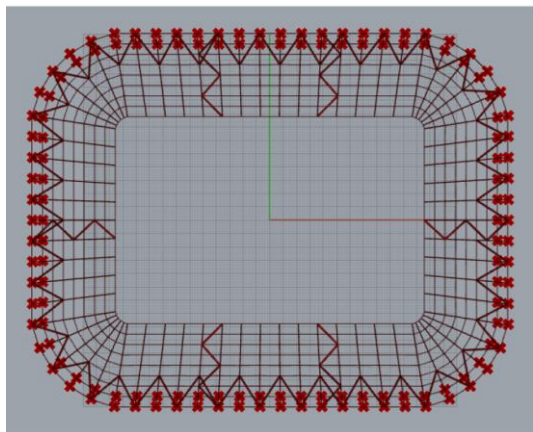


Figure 3. Example of a feasible parametric solutions for the roof stadium. It is noted that each radial line is a truss system.

corresponding design variable for a particular design. The red line in Figure 4 represents the design with the minimum mass. The variable values include 12 spaces (9.5m spacing), 12m height above pitch, 9 truss bays and 4.5m in depth. These variables correspond to 4500 tonnes of steel. This equals 11,025,000 kgCO<sub>2</sub>e of embodied carbon, according to the EPD of British steel. A total cost of €55,125,000 and a social environmental impact cost of €661,500.

It is possible to infer that simple parametric changes can lead to a high variation in the weight of the structure. Structural mass can change in up to 25% of the minimum mass attained within the parametric ranges considered. In this cantilever structure for 25,000 capacity if 15 spaces (7.5m spacing), 12m height above pitch, 8 truss bays and 4.5m in depth, a final mass of 6000 tonnes is attained. This is a 1500 tonne increase in mass with a relatively minor change in the design parameters, which is a significant representation of how simple arbitrary decisions that can be made in preliminary design can lead to significant changes in the design outcomes.

The parametric outcomes allow designers to study also the influence of the design variables, where the spacing between radial trusses and height of the cantilever can be quickly identified as range variables to augment in further iterations. This is of interest if an automated construction of space is sought, where results can inform the roll-back of the parametric design, as highlighted in steps 6a, 7a and 8a in the framework proposed. With such consideration a learning approach can be used to inform new parametric design exploration in the preliminary stages where all the degrees of freedom are still available for the designer, regardless of this learning being done in a supervised or unsupervised approach.

## 6 CONCLUSIONS

### 6.1 Current state of the work

The present work studied parametric design as a tool for the preliminary design of roof stadiums. It showed that a systematic approach to parametrically designing stadium roofs rapidly produces and analyses design alternatives, integrates a variety of tools into one environment and can customise optimisation and decision-making strategies to produce suitable designs. The results show that the ability to define and modify the geometric and non-geometric parameters of a design in a flexible and user-friendly environment without significant effort to regenerate geometry and re-assign attributes can be attained using parametric modelling. Parameterisation of the design significantly increases the complexity of the design task since in it there is a need to not only model the structure but also make it one that has as many parametric relationships as possible. Nonetheless, once this work has been completed, the design is automated which significantly reduces the time required to change and re-analyse outcomes. A systematic approach for parametric progressive

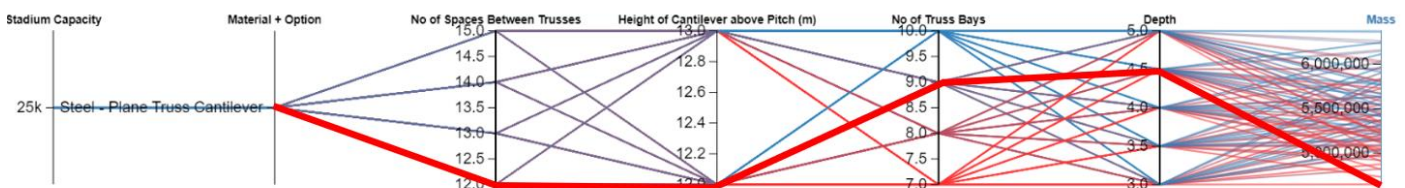


Figure 4. Example of feasible space and parametric optimal solution. The optimal solution is represented by the (red) bold line.

preliminary design was also proposed. Its foundation is in the assumption that, despite preliminary design being highly explorative by nature, it still consists in a series of systematic steps. It has large reliance on the experience of the designer to take decisions, therefore, if a large enough spectrum of projects already exists, then there is scope to automate the task. The approach proposed here consisted of structuring the different steps that are taken in preliminary and parametric design. Finally, a representative implementation of a parametric stadium was developed to research the benefits of using a parametric implementation in the preliminary stages of design. With a limited CPU time it was possible to achieve an optimal parametric solution for the implementation. Moreover, it was shown that up to 25% of variations in mass could occur due to simple parametric changes (in the present work 4 parameters were used for reference). It was shown that empirical decisions are not adequate to achieve efficient solutions. For reference, a simple increase in the number of spaces of vertical truss members from 12 to 15, even with a decrease of other variables, increased the mass in the overall system approximately 25%.

Several recommendations for future work are presented below, nonetheless, the results obtained are representative of the untapped potential that exists in parametric design, in particular in preliminary design where decisions made will lock up many of the degrees of freedom in the design.

## 6.2 Future work

Potential avenues for the future include developing an augmented design approach, design coordination and developing artificially intelligent designers.

Future work could address the need to progressively increase the complexity of the model by augmenting the design space, developing additional components or by offering new strategies altogether. There is scope to use as many variables as possible in the parametric script, which can all be implemented in an iterative procedure until a convergence criterion is achieved. The design alternatives explored in this work were limited and topological variations were not fully explored. Increasing the number of structural systems analysed in the model and making the script produce solutions more quickly are also potential avenues for future research. Results in the model could also be improved by adding additional analyses or load combinations.

Further research could also address the need to examine optimisation methods that can tackle larger and more complicated design spaces. This could result in further developing the systematic framework proposed in the present work and examining the potential it has to automate design. This could involve building an "artificially intelligent designer" (that uses a spectrum of completed examples to inform the parametric learning). It could use only the inner-outer boundaries to set-up a parametric model, and eventually an optimal structural system form for a stadium roof. This is something that is of interest to stadiums, but also for any other type of structure. Additionally, a parametric model in the future could incorporate the entire stadium structure as well as a detailed structural analysis. The benefits of such a model could include coordinating communication between various designers for example, a design team could generate and improve a design, a contractor could use it in a similar way and the client could visualise the outputs.

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