# Analysis and Optimisation of Modular Stadium Design with Machine Learning

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# Abstract

This practice-led research explores the problem of multi-objective and multi-scale optimisation of modular stadium design based on the quantitative assessment of its performance. Stadiums are one of the largest and more challenging building genre to construct, with its design process traditionally separated by different disciplines. This can prevent a holistic understanding of an interconnected system of drivers that determine the design and performance of stadiums, which is especially challenging in stadiums designed for more than one function. This research examines the benefits and limitations that machine learning might bring to the design process, focusing on the spectator experience in relation to sightline quality, internal layout, and circulation.

The research asks:

1. *How can a combined functional and structural stadium design approach based on a modular and parametric design model improve the design process and optimise the performance of multi-use stadiums?*
2. *How can multi-use stadium design be analysed as a problem of sightline quality, the optimisation of circulation distances and the provision of legally regulated functional spaces and captured in a parametric design model?*
3. *How can the proposed design method for multi-use stadiums, requiring multi-objective optimisation and performance assessment, benefit from machine learning-based data analysis?*

The first part of the research uses machine learning to analyse the spatial and organisational properties of stadiums to identify their key design drivers. Classified by the UK Building Regulations as places for assembly and recreation, the thesis focuses specifically on modular stadiums. It contextualises these through a study of their historical development and increasing design and performance legislation. A typological study, along with the literature review, are used to determine a set of shared parameters that define modular stadium design. Sightline quality, circulation, and layout are found to be critical to the spectator experience, as they define the slope of the seating stands, crowd flow and escape distances, and the overall building organisation and morphology.

The second part of the research uses these design drivers to develop a parametric model to simulate stadium designs. This model captures the typical modular scales of stadiums: 2D section, 3D bay unit, stands, and whole stadium. The model is used to generate, analyse, and compare

existing stadium designs and to establish performance benchmarks for key design metrics. As the parametric model is based on shared typological characteristics, the data produced is not detailed enough for construction but useful for the comparison of design performance criteria.

In the third part of the research, the RIBA Plan of Work stages are used to develop a set of workflows to test the parametric model and relevant performance criteria and design optimisation. To overcome the lack of linear relation between the parametric inputs and the resulting performance, the study explores three distinct workflows. These test a multi-objective evolutionary optimisation, semi-supervised learning, and supervised learning approach.

The aim of combining typological analysis, parametric modelling, and an utilisation of the workflows is to facilitate, optimise, and enrich the design process through the study of both existing and previously unattainable design solutions. The research is relevant to both practitioner and academic audiences by expanding the current use of machine learning in design development and evaluation.

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# Abbreviations

The following abbreviations are used throughout the thesis.

2D: Two-dimensional

3D: Three-dimensional

BIM: Building Information Modelling

CAD: Computer-Aided Design

CLC: Construction Leadership Council

DfMA: Design for Manufacture and Assembly

FIFA: Fédération Internationale de Football Association

Green Guide: Guide to Safety at Sports Grounds

MOO: Multi-objective optimisation

NN: Neural network

IOC: International Olympic Committee

PoW: Plan of Work

RIBA: Royal Institute of British Architects

SOM: Self-organising map

UEFA: Union of European Football Associations

# Parametric and Machine Learning Models

The parametric and machine learning models developed during this research are available online by clicking on the link below or copy and pasting the URL to an internet browser.

https://github.com/AOMSDML/AOMSDML/

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# Author's declaration

During the period of registered study in which this thesis was prepared the author has not been registered for any other academic award or qualification. The material included in this thesis has not been submitted wholly or in part for any academic award or qualification other than that for which it is now submitted.

Signature: Date:

# Chapter 1 Defining a Stadium Design Research Agenda

Stadiums are among the largest and most complex architectural genres to build and operate. Based on recent developments in computational technology and the UK building procurement environment, this thesis re-evaluates how multi-functional stadiums are designed and analysed. Exploring the problem from architectural, engineering, and data-driven perspectives, this interdisciplinary, practice-led research proposes a design framework grounded in multi-objective, multi-scale optimisation, based on performance quantification within a modular context. The research aims to improve the ways in which a stadium can be designed by architects and engineers as an interconnected system of quantifiable design drivers using machine learning.

The stadium first emerged as a morphological and organisational type in antiquity, and its design has remained rooted in principles developed thousands of years ago. Despite the continued public interest in stadiums, the way both professionals and academics address stadium design is still largely based on legislative norms rather than an integrated, performance-based optimisation system that works across all the design disciplines.

## 1.1 The stadium as a psycho-political machine

In his anthropotechnic critique of the Olympic movement, Peter Sloterdijk (2000) defines competitive sport as a psycho-political machine aimed at producing victors and victories. The power of this apparatus rests entirely on the spectacle – the celebration of reaching the limit beyond which there is only one winner and a set of competitors who have failed. Sloterdijk (2000) allows us to take a step back and see the role of the spectators in this system as a homogeneous mass in which members of society no longer use their physical experience as a means for self-evaluation, but 'see themselves through the spectacles of mass media, discourses, modes, programmes and personalities.' In other words, by entering the domain of the mass event, the spectator loses their individuality and becomes part of a mass media event. The stage for this associative and transformative event is the stadium – one of the prominent typologies within the urban plan that acts as a platform for the expression of the self-perception of both players and spectators.

There are as many definitions as there are interpretations of what the stadium is and how it relates to its physical and conceptual environment. Scholars, however, agree that the major elements that influence its architectural design are the performers/players, the spectators, and the stadium itself (Kähler et al., 2012). The players and the playing field are a primary focus of the experience: they constitute the expression of the function of Sloterdijk's psycho-political machine. Through the ritual of entering the arena, the players separate themselves from the rest of society and, at the same time, become the manifestation of the skills and power of the town or community associated with the performance. According to Sloterdijk, their success is everyone's achievement, and their failure is also shared by the whole community.

In a very subtle way, this process reorganises the way history is written – within this artificially created environment, and within a performance controlled by strict rules, the public event becomes a record of the period. The primary driver that defines the importance of these events in social history is the interaction, and diminishing boundary, between the player and the spectator. The spectator is at the same time a passive observer of the performance and an active participant in the event. Furthermore, the spectator is the one who remembers the story and tells it to others.

Architecture, understood as the art of creating human-made space, is therefore the force that both hosts and limits the event. The grass of the playing field or the synthetic surface of the running track are the ultimate platform for the celebration of the human body and its abilities. They are the pedestal on which architecture positions movement and adaptability to respond to individual and collective changes for all to observe. The intimacy between the stage and the spectators, the urge to see but not be able to physically interact, is core of the creation of this social experience. This research builds on the juxtaposition of space, ritual, and record through the quantification of the primary elements that define this system of interactions and establishes the foundation for the representation of both building and event through computational means.

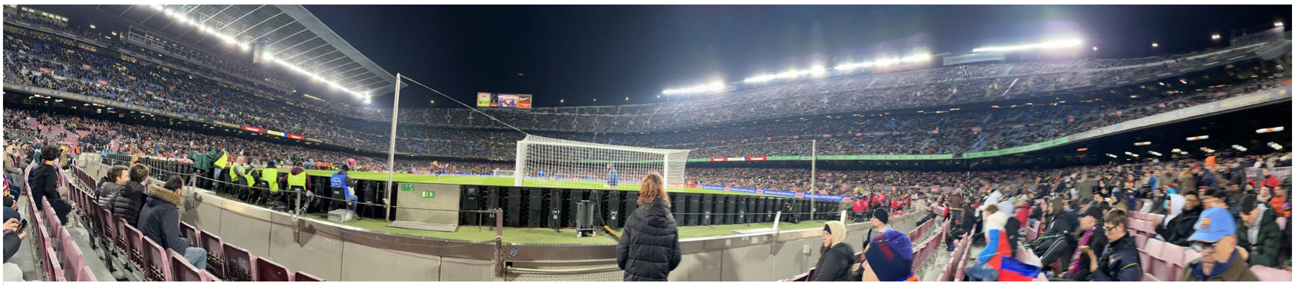


*Figure 1.1. FC Barcelona's Spotify Camp Nou before the 2023 reconstruction, an embodiment of Sloterdijk's psycho-political machine*

Stadium design is an inextricable part of the development of the genre of public assembly buildings within architecture. However, it is a subject that is the primary interest of a limited number of architects, and it is explored even less in academia. Due to the public fascination with the spectacle and the development of the stadium within recorded history we have descriptions of each of the phases of its conceptual growth, from its inception as a building for religious ritual up to the role it plays in the current mass media era. The major phases of stadium development are generally agreed upon by researchers, but each interpretation is based on the specific perspective of the author. The relationship between the psychological experience of the spectator and the political implications for society are a pivotal point for all scholars.

This reading is a starting point for this research because it defines the basic elements within the controlled system of stadium experience: it highlights the major forces that generate the experience and its social impact and establish a point of departure for the exploration of how those elements can be analysed and developed quantitatively. Leacroft & Leacroft (1984) trace the history of theatre design to its role in religious ritual, while John and Parker (2020) establish the link between the theatre and the stadium as design concepts. The primary difference between the three

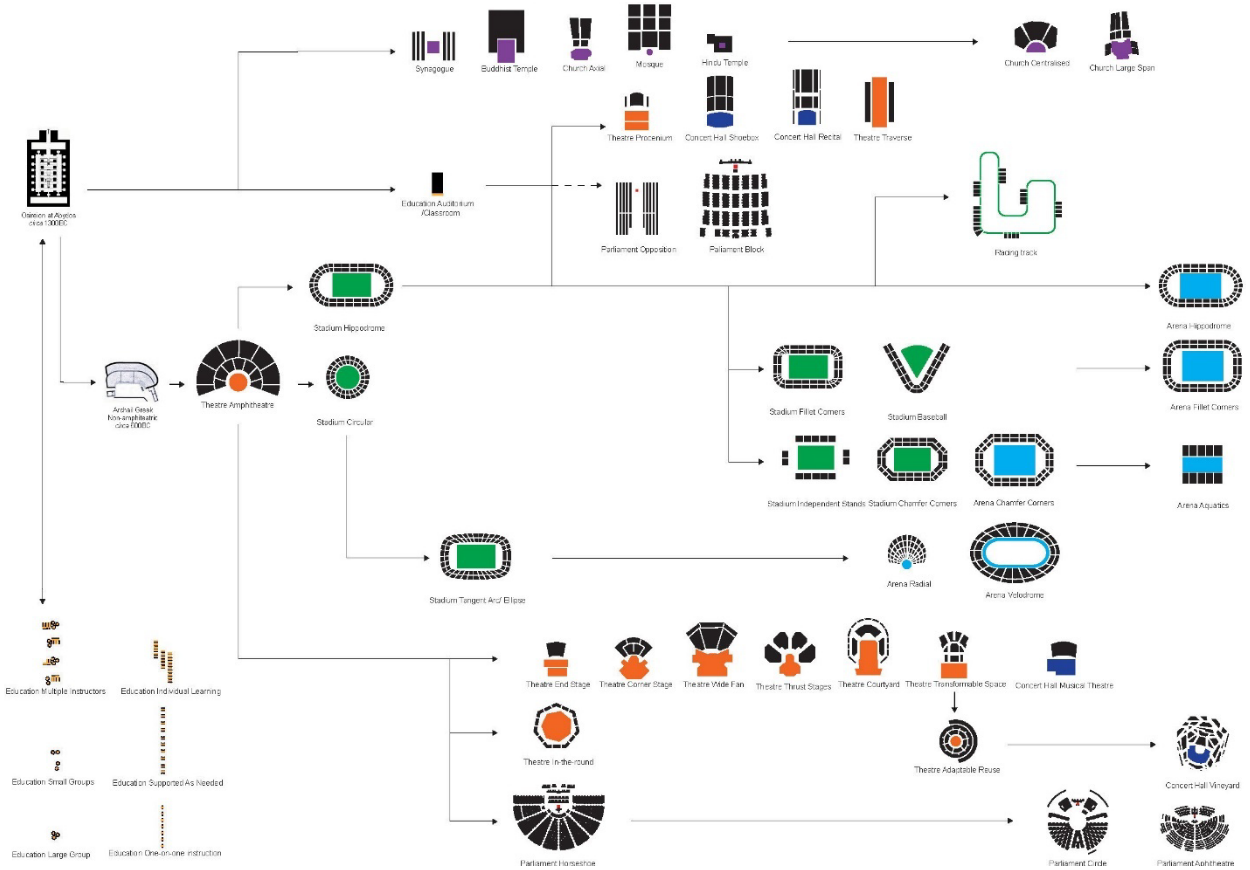



*Figure 1.2. Chrono-morphological development of the public assembly building type based on Leacroft & Leacroft (1984), Braun (2008), Welch (2009), Stegers and Baumann (2010), XML(2016), John and Parker (2020)*

building types and their derivatives is the location of the stage – either at one side of the building, in the case of sacred and theatre buildings, or centrally, in stadiums and arenas.

Volkwin Marg is an architect who translates Sloterdijk's psycho-political interpretation into practice. The work of his studio, gmp, is deeply rooted in translating those ideas into built form. For Marg (2010), stadiums can be understood through the dual lenses of politics and commercialism. In terms of politics, he focuses on the notion of the control of the masses, and he identifies three major eras of stadium design – antiquity, post-Industrial Revolution, and contemporary. These three categories correspond with the major eras of development of European civilisation – pre-Christian, Christian, and the Industrial Age. As with most scholars in the field, Marg does not focus on the medieval period, as no permanent stadiums were built then, but this period also contributes to our understanding of modularity and adaptability in stadium design. For Marg (2006), the stadium is a tool for the creation of identity – first that of the polis, then the empire, then the nations of the industrial age, and finally a new global society in the contemporary period. This identity is a means by which society controls its members, their behaviour and self-perception – not only in their free time, in the stadium, but also in their daily life. The means to do so that Marg (2010) identifies are the designs of the seating bowls and the facilities associated with each section. Just as in Roman times, today's stadiums have multiple tiers, with each tier dedicated to a specific social class. The services that are provided for each of those event packages correspond to the value of the ticket. In this way members of each class create their own self-awareness in reference to the rest of the audience, based on these facilities. The spectacle is the cohesive force that creates the community – despite their economic differences, all members of the crowd experience the same spectacle with representatives of other communities, within the limited timespan of the event.

As for the actual design of the architectural elements, Marg (2006) refers to the work of J. W. von Goethe: 'the architect envisages the design of the crater which will become the amphitheatre through the medium of art, and he makes it as simply as possible so that ornament may be the public itself' (von Goethe, 1970). The theme of simplicity is pivotal in the work of many scholars in the field – simplicity is one of the architectural strategies that aim to provide a safe experience for the masses. This reductive approach is also part of the practice focus of this research and the analysis of the spatial relationships in stadium design. Marg (2006) also brings together the experience itself and the visual nature of the event. Graphic media play a major role in the construction of the event and the communication between spectators and players (Kähler et al., 2012). Media is key to the event's translation to the global stage and the control of the masses through self-identification with products, carefully marketed by commercial organisations within the event.

In contrast to Marg's approach, Rod Sheard's (1996) interpretation of the stadium spectacle takes in a more detailed reading of the last two centuries – Sheard reads the history of stadiums from the perspective of commercialism, interconnectivity, and information. His practical approach focuses on the experience of the spectator since the codification of the rules for the major sports in the mid-nineteenth century and the way those requirements generated changes in stadium architecture (Provoost and Nederlands Architectuurinstituut, 2000). For Sheard, modern stadiums emerged through the development of the infrastructure of travel between towns – modern sports, as we understand them today, only emerged when spectators from one community could travel regularly to other places. It was a century before the next influential development: the invention of television and mass communication. By extending the audience from the physical domain of the stadium to the context of the broadcast, viewer revenue expanded dramatically. As a result, the design requirements of each group developed as well. The physical spectator became part of the television broadcast while the home viewer demanded a visually satisfying product at a suitable time (Provoost and Nederlands Architectuurinstituut, 2000).

Sheard identifies the third generation of stadiums as beginning with the opening of the first Walt Disney theme park and the idea that spectators expect to find 'happiness and knowledge' there (Provoost and Nederlands Architectuurinstituut, 2000). For Sheard (2005), happiness means an optimised spectator experience – the provision of facilities for all the target groups and the efficient utilisation of these. The second part – knowledge – is Sheard's major contribution to the discourse: bringing information that spectator might find useful became a central focus of stadium design. The building needed to communicate with both its physical and its remote users in every viable way: in other words, the psycho-political machine of sport had to become a digitalised set of information that could be sold. In addition, other commercial entities could use the information infrastructure of the stadium as a channel to broadcast their own messages.

Both Marg and Sheard present readings of how the stage for Sloterdijk's psycho-political machine can be seen to adapt to changing social and economic needs through history. The work of Martin Wimmer, later with Anna Martovitskaya, Simon Inglis, and Geraint John, breaks down these major phases in stadium development into practical design drivers that can be analysed and form a system of spatial and functional relationships.

Wimmer's work began in the 1970s, and its primary focus was multifunctional Olympic stadiums. As such, its periodisation follows the cycles of the Olympic Games – basic or no stadium at all prior to the London Olympics in 1908, then limited purpose-built facilities until the 1952 Helsinki Olympics, and, from the 1970s, the modern Olympic stadium (Wimmer, 1976). For Wimmer, the main driver for change in stadium design is construction technology and the presence of a roof. He also considers how multifunctionality develops: his post-World War II typology was based on the distinction been the multipurpose athletics stadium and the purpose-built football stadium (Wimmer, 1976). In his later work, with Martovitskaya (Wimmer and Martovitskaya, 2016), he also identifies more recent developments and the renewed push towards multifunctionality and integration with the urban environment. In several books the two researchers explore the idea of the stadium as a hub for modern society with varying uses and programmes (Martovitskaya, 2016; Wimmer and Martovitskaya, 2016). They also focus on Marg's concept of simplicity of plan and Sheard's advocation of the continuous use of the facility through its integration in the urban environment. Wimmer and Martovitskaya's work is important for the conceptual framework of this research because it captures the way in which distinctive design drivers work and relate to each other.

Simon Inglis is an influential author and historian whose work is closely related to that of John and Sheard. Writing in the early 1990s after the Hillsborough disaster, his classification is heavily influenced by a focus on safety. Like Sheard, he traces the origin of modern football ground design to the mid-nineteenth century and the codification of sports (Inglis, 2005, 2000, 1990, 1988). However, his reading also includes a social and historical perspective – he describes the early attempt to create multi-functional venues from cricket grounds, then the development of single-use privately owned football grounds, and their consequent piecemeal development up to the 1990s (Inglis, 1988). His classification of the major phases of stadium development is the only analysis that relates this development directly to the two world wars and the social and architectural changes that these brought.

## 1.2 Framing of data-based stadium design studies

If I distinguish the text from the book, I shall say that the destruction of the book, as it is now under way in all domains, denudes the surface of the text. That necessary violence responds to a violence that was no less necessary. (Derrida, 1976)

The conceptual vantage point for this research can be found in Jacques Derrida's initially unsuccessful doctorate, which was later published as a collection of essays on the independence of writing from speech. *Of Grammatology* was an introduction to Derrida's (1976) concepts of deconstruction and ontology and an attempt to define a new science that explores the properties of writing. In an analogous way to the French philosopher's reading of linguistics and semiotics, this research argues that today architecture has reached a threshold where automated design is approaching maturity and is becoming an entity that is separate from human-generated design, which can also be studied as a separate discipline. This design research practice explores the possibilities created by reducing or entirely removing human input from design through machine learning-supplemented workflows.

The primary issue in the process of identifying and predicting patterns in a dataset is the control over the information analysed and the output of the model. Currently AI text-to-image generators produce highly detailed, convincing images. However, when observed closely, mistakes begin to emerge – people with six or more fingers, for instance, and other minute errors. This could be acceptable if a designer uses the images to illustrate an idea. However, the strictly regimented process of designing and constructing a building requires a framework which translates the solutions generated by computation to other design disciplines, the contractor, the manufacturers, and the other stakeholders.

The image on the following page, generated by Midjourney (Milev/Midjourney, 2022) exemplifies these issues. The whole looks like a diagram of a stadium, but on closer inspection circulation elements, such as gangways and vomitories, are missing, and the video screens are randomly distributed.

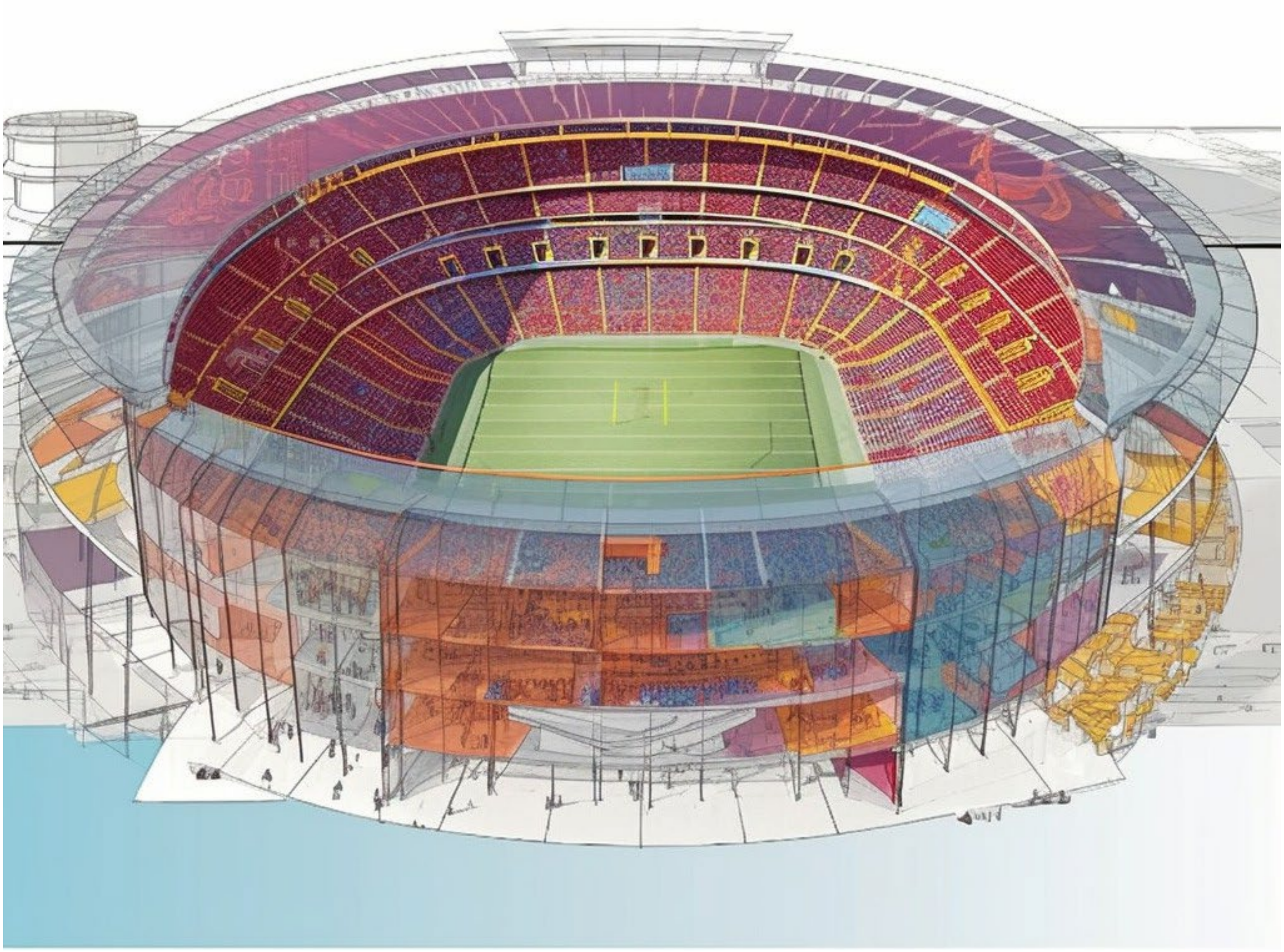


*Figure 1.3. Stadium diagram produced by text-to-image AI generator (Milev/Midjourney, 2022)*

Bringing the analogue world of stadium design to machine learning is a process that uses algorithms with different requirements and outputs. The way this research approaches the encoding of analogue information into digital models is based on the concept of defining the shared organisational and morphological properties of public assembly buildings and developing a model based not on a digital copy of a specific design but on shared design principles. This set of relationships is used by the research as a foundation for the development of a parametric model that generates design variations within this typological framework. This approach is a heuristic method that ignores minor design specificities and focuses on the major elements that drive the design. This method allows for comparison, analysis, and benchmarking across case studies and viable solutions that are useful to the planning stages of stadium design. It approximates to the design of existing case studies, but the simulation utilises directly neither architectural drawings, models, or conceptual or as-built designs, but rather the author's interpretation of those designs within the encoding system of the typological framework for the objectives of the study.

The second theme of this research is the utilisation of multi-objective optimisation techniques based on a parametric model aimed at developing a design space with a set of design solutions that are variations within a specific set of design constraints. This approach to performance-based design is common in the engineering field, but it is rarely used in architecture. The process itself is entirely based on maximising computational ability to process large sets of numerical data, enabling a quantified reasoning for the selection of design solutions. Considering the changes in the procurement landscape as reflected in the RIBA PoW (2020), a modular approach to constructing a parametric model has been adopted, which allows it to integrate with BIM platform software and has the potential to significantly reduce the workload associated with the technical design stages by introducing BIM families early in the design process.

*Table 1.1. Taxonomy of terms*

| **Term** | **Definition** | **Application** | **Reference** |
|---|---|---|---|
| Parametric design | A process where a description of a problem is created using variables, a design space is created by changing the variables, and based on preestablished criteria a design solution is selected | ▪ Describe stadium design and relate design drivers<br>▪ Produce design space | Hudson, 2008 |
| Machine learning | Autonomous computer-based predictive analysis and statistical learning aimed at analysing datasets in order to build generalisable models that give accurate predictions or find patterns | ▪ Identify types<br>▪ Reduce design space based on multiple objectives | Müller and Guido, 2016<br>Bakshi and Baksh, 2018 |
| Multi-objective optimisation | Framework process that utilises parametric representation and machine learning analysis aimed at identification of best performing design solutions based on multiple, often conflicting, objectives | ▪ Identification of best performing design solutions | Nguyen et al, 2014<br>Turrin, 2014, 2012, 2011 |
| Supervised learning | Type of machine learning where the model is trained with labelled data | ▪Within the practical section where the optimisation framework has to identify best performing solutions | Goodfellow et al., 2016<br>IBM, 2021 |
| Semi-supervised learning | Type of machine learning that utilises both labelled and unlabelled data. Most commonly the model is trained | ▪Within the practical section where the designer choices are used to train the | Brøndum et al., 2021 |

| | | | |
|---|---|---|---|
| | on labelled data in order to label the unlabelled data. | machine learning model | |
| Unsupervised learning | Type of machine learning where the model is trained entirely on unlabelled data. | ▪Within the typological study where shared characteristics are identified | Na, 2010<br>Migge, 2019<br>Ahmed, 202 |
| Evolutionary optimisation | An approach to finding the optimal or near optimal solution that utilises principles of natural selection | ▪Within the practical section where the problem has narrow design space | Vierlinger, R., 2014 |
| Design space | Set of possible design solutions | ▪Within supervised and semi-supervised workflows in the practical section | Brown and Mueller, 2019 |
| Parameter | A variable that influences the algorithmic model | ▪Throughout practice side of research | Brown and Mueller, 2019 |
| Hyperparameter | Machine learning model setting or configuration that is used to control the model's learning process | ▪Within supervised and semi-supervised workflows in the practical section | Aggarwal, 2018<br>Bishop, 2006, 1995 |

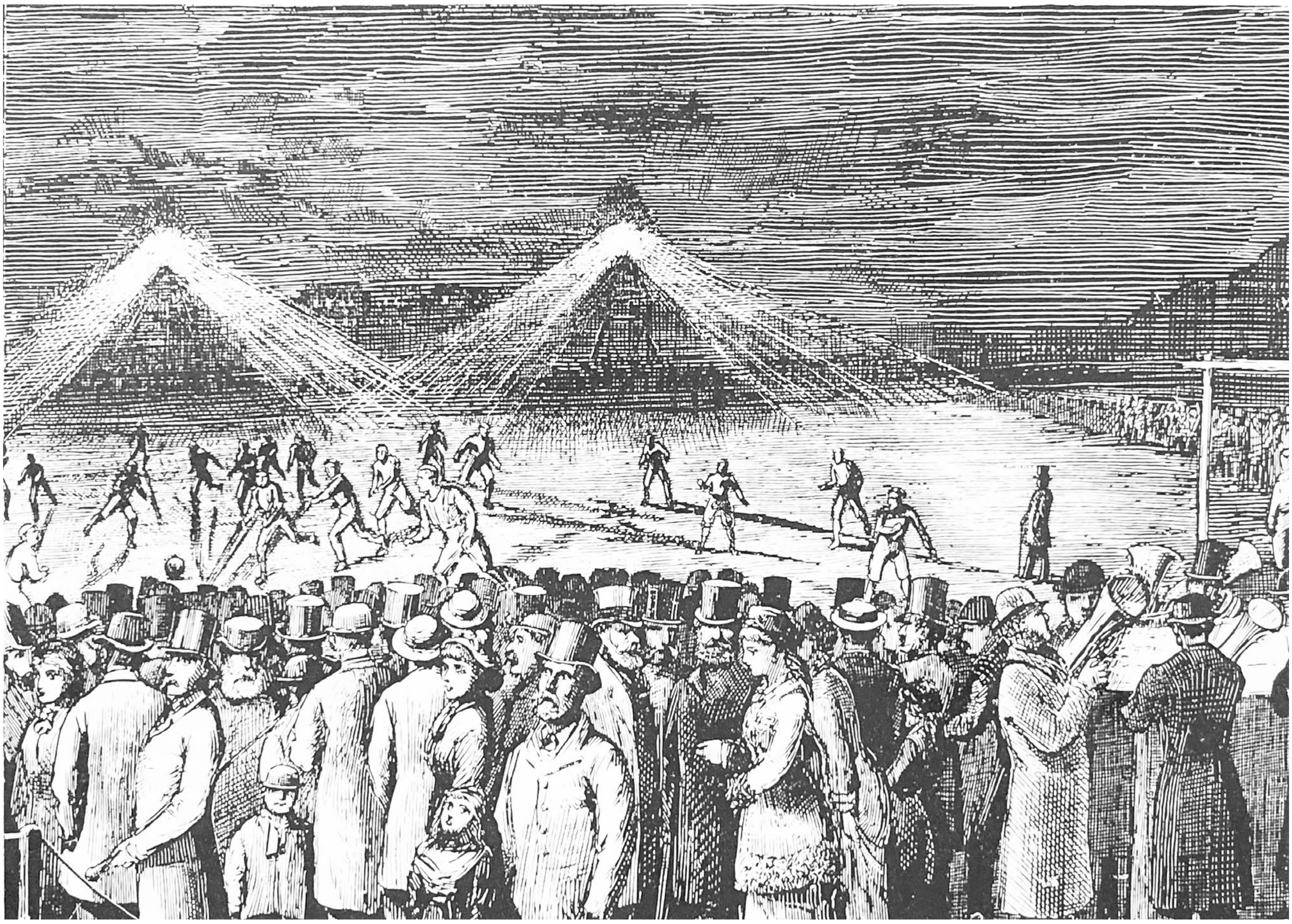


*Figure 1.4. Early floodlit game at The Oval, November 1878. Clapham Rovers v The Wanderers (Benson, 1987)*

## 1.3 Research gap

Stadium design is strongly related to the socio-economic development and function of modern western societies - stadiums have significant social impact, they are expensive to construct, design mistakes are extremely costly and pose risk to the wellbeing of large groups of people. Stadiums are also one of the core element in the urban plan that shape the self-perception of the local and associated communities. In terms of design methodology, however, stadiums have tremendous potential for reconceptualization – the utilisation of CAD and parametric design has long history but there is no focus on quantification of design performance across the whole design and modern analytical tools like machine learning. As with all large scale projects the design is compartmentalised which results in extensive coordination, expensive design development, and unequal distribution of liability. Further on, the integration of structural and architectural design is still based on the duality between qualitative and quantitative design. The architect designs then engineer re-designs – relationship that presupposes friction and mistakes because of the designer's objectives where quantified performance is more of an afterthought, rather than a driving force of the design. The building procurement can also be optimised to fit the DfMA overlay expectations and multi-objective optimisation yet to be integrated in the architectural design.

The research identified several areas in our current understanding of stadium design that present strong potential for development. There is no previous systematic study of the formal and organisational principles that guide the design of this building type and the modular aspects of its development through recorded history. This research addressed this gap through mapping of public assembly buildings and stadiums types in terms of design drivers and stadium design evolution in terms of modularity to improve design, sustainability, and fabrication. In addition, stadiums have benefited significantly from the strengths of CAD design but no previous study has addressed this problem from the perspective of machine learning-supplemented analysis. The construction of a parametric model allowed for analysis and optimisation in 3D thus bringing commercial stadium parametrisation research to academia and utilisation of machine learning for performance-based 3D analysis and optimisation to open new avenues of design. There is no previous systematic assembly or generation of such spatial and structural data in academia and this gap was tacked through the creation of case study-based public assembly building dataset, parametrically generated stadium design case studies dataset, and performance benchmarks. Finally, there is no previous machine learning-supplemented framework based on stadium design requirements for early building procurement phases. As a result, the research developed machine learning-supplemented performance-based stadium design analysis and optimisation workflows for RIBA Plan of Work stages 0 -3 that focus on architectural design and automate aspects of the workflow thus allowing more efficient design development, lower cost, better building performance, and better integration with the rest of the design disciplines. This methodological framework also allows investigation and comparison across stadium case studies to make informed design decisions.

## 1.4 Research aims and objectives

This research aimed to resolve the previously identified stadium design problems and research gaps in academia and professional practice for architectural and structural design of multi-use stadiums through the utilisation of new approaches to stadium design analysis and optimisation with the use of computational technology in reference to modularity and data-driven design. Another research objective was to re-evaluate stadium design in the context of performance-based architecture in terms of sightlines, circulation, and layout. The research also aimed to develop and validate a set of machine learning workflows that fully utilise new developments in computational technology and modern procurement strategies.

This research has reviewed the existing academic and professional practices and propose a machine learning data-driven framework for the analysis and optimisation of the design of multi-use stadiums to integrate the workflows of designers, design assessors, manufacturers, and operators within the context of digital project delivery. The research framework addressed the previously unexplored problem of evaluating stadium design performance with computational means across case studies and potential solutions. This research aimed to develop a holistic approach to architectural and structural design, quantification of different stadium performance factors, and modularity.

To identify shared design generating characteristics, this research used typological analysis for heuristic evaluation of spatial and structural data for the selection of characteristics commonly shared by public assembly buildings and modular stadiums in particular, thus creating a framework for their comparison. Following the development of the parametric model, the framework not only captures the performance in the final stadium designs but works across multiple planning stages.

To evaluate the existing design process, this research has examined the benefits and limitations that machine learning brings to the complexity of stadium design and operation through the quantification of the spectator experience in terms of sightline quality, layout, and circulation. These measurable parameters were utilised in a parametric model, which enables their evaluation and subsequent optimisation using machine learning. The selection of the parameters related to these three design aspects is key to stadium planning, as they affect its primary function: to enable large groups of people to attend and view an event. The research has synthesised the machine learning-supplemented approaches to stadium analysis and multi-objective optimisation into new workflows that can reduce the designer's workload through automation, improve communication across disciplines, and develop safer and better-performing design solutions.

The research is grounded in professional practice through the exploration of machine learning workflows for a re-evaluation of design and decision-making processes within a continuously evolving building procurement landscape. This problem is analysed in the context of recent changes to the RIBA Plan of Work [PoW] (2020). Traditionally the design stages have progressively detailed delivery scopes, but the implementation of modern methods of construction has created a significant overlap between the work of the client, the designer, and the manufacturer.

Another problem explored by this research in the context of stadium design is the methodological approach to the analysis, comparison, and benchmarking of built and conceptual stadium designs through machine learning. Currently, stadiums are primarily compared based on characteristics such as the capacity or types of events hosted and through design discipline-specific properties – escape distances, for instance (Department for Culture, Media and Sport, 2018, 2008). A tool is needed that can capture these multiple characteristics and compare them to quantifiable performance criteria. The alternative machine learning approach to analysis allowed the development of innovative design workflows, enabling the exploration and analysis of previously unattainable design solutions.

## 1.5 Research questions

In response to the practice-led challenges identified in the stadium design process, the research asks:

1. *How can a combined functional and structural stadium design approach based on a modular and parametric design model improve the design process and optimise the performance of multi-use stadiums?*
2. *How can multi-use stadium design be analysed as a problem of parameters such as sightline quality, optimisation of circulation distances, and the provision of legally required functional spaces, and how can it be captured in a parametric design model?*
3. *How can the proposed design method for multi-use stadiums requiring multi-objective optimisation and performance assessment benefit from machine learning-based data analysis?*

## 1.6 Methodology

The methodology of this thesis is grounded in a cross-subject investigation of performance-based optimisation of stadium design, utilising data, parametricism, and machine learning. Qualitative and quantitative methods are brought together in order to develop automated workflows that can assist the designer, increase efficiency, accelerate and diversify optioneering, and quantify stadium performance in terms of sightlines, circulation, and layout.

The research design is based on critical assembly of analysis and optimisation methods from the two main stadium design dimensions – organisational and structural – which had been coordinated across a machine framework responding to the requirements of modern procurement strategies. The methodology was developed to reflect the RIBA PoW design stages, UK legal framework, and the requirements of the primary international sports organisations related to stadium design – IOC, FIFA, and UEFA. The approaches selected for this research are a reference to the established design practices in the professional field and are aimed at utilising machine learning for the analysis and optimisation of modular stadia design. The practice side developed in three distinct phases – typological analysis aimed at establishing stadia design drivers, construction of a parametric model that can work across real life case studies, and in the final phase – development of a set of machine learning-supplemented workflows within the RIBA PoW based on performance benchmarks. The design workflows and concepts established during this process restructure the current design knowledge of the functional and organisational architectural type based on modularity and implementation of machine learning analysis and multi-objective multidimensional multiscale optimisation.

The trans-disciplinary nature of the research presupposes a multi-layered approach to addressing the subject of the investigation. Architecture, structural engineering, and computer science have well-established and extensively developed research methods that allow for this study to be contextualised within the requirements of the respective research fields. The superimposition of different approaches, however, limits this overlap and forced the research to identify only the most important aspects that can serve as link to other inquiries. Another major issue that arises form this type of research is the blurring of the focus of the study due to the multiple perspectives which again can limit its potential. A further level of complexity can be identified within the type of research itself – whether it is qualitative or quantitative. This research aimed to overcome those limitations through an investigation of a subject that has deep roots in both ways of understanding architectural space. As it will be described in detail in Chapter 03, stadia originate in the quantitative definition of a space and their entire design development has been strictly related to geometric and spatial relationships. Further on, the function of those buildings is for large number of spectators to see a performance safely. There are two major design rules that emerge from this – there is a maximum distance for the performance to be seen and the spectators have to be able to gather together in an organised way in order to see the performance. Those design conditions and the relevant legislative dimensions set the basis of an approach to analysis and optimisation of a building type whose design principles are almost entirely dependent on quantified spatial relationships.

### 1.6.1 Data, structural topologies, parametricism, variation

Parametricism and its relation to structural topologies is a subject that is explored in the literature primarily as an aspect of the structural engineering field. The leading resources for algorithmic design thinking in the context of stadiums are Culley and Pascoe's *Sports facilities and technologies* (2009) and Hudson's *Aviva Stadium: a case study in integrated parametric design* (2011). From an architectural perspective, parametricism and topology are critically reviewed by

Schumacher in *Parametricism: a new global style for architecture and urban design* (2009) and *From typology to topology: social, spatial, and structural* (2017). Other important scholarly work includes Menges' *Computational design thinking* (2011) and Carpo's *The second digital turn: design beyond intelligence* (2017), which focus on the use of data in architecture and serve as a conceptual link between parametricism and machine learning. This section is included in this chapter as parametric modelling is a fundamental element in the development of the methodology of this research.

Kirsch (2002) defines topology in terms of structural engineering as a spatial sequence of members and joints. The function of those components is to transfer externally applied loads into the building's foundations (Silver et al., 2014). Engel (2013) uses the way the applied force is dispersed in the structure and transferred into the foundations to categorise the different types of structural systems found within stadiums – form active, vector active, section active, surface active, height active and hybrid. A number of structural engineering researchers, such as Block (Oval et al., 2019) and Bendsoe (1995), take this concept further to generate topological structural solutions that use the minimum amount of material to resist a given load. As the understanding of minimum structural compliance is not directly applicable to the current technological state of the building industry, this research takes Kirsch's practical understanding of topology to explore the sequences of structural members as elements within the semi-independent structural systems of the seating bowl, slabs and vertical elements, façade, and roof, as described by Culley et al. ( 2015) and John et al. ( 2013) .

The reason for the selection of parametric modelling for this research is its relevance to the established design and construction sequence in the building industry (Union of European Football Associations, 2011) and the possibility of grounding the practice side of the research in a parametric understanding of those systems. This was achieved through the study of the quantified design drivers derived from a typological study, which allowed the spatial properties of the case studies to be translated into a digital model that can be controlled parametrically. The research thus aimed to establish new links between parametrics and machine learning, as both design processes are reliant on data, and there is no extensive academic study to date on an integrated design methodology that utilises both perspectives simultaneously in the context of stadium design.

Hudson (2008) defines parametric design as a process by which a description of a problem is created using variables; the change in the values of the variables produces a design space, and based on pre-established criteria a design solution is selected. Hudson (2008) bases his definition on the process of exploring solutions in mathematics through the use of parameters and within the context of a rational resolution of a design problem as described by Simon (1996).

For Menges, parametrics has design implications way beyond the interdependencies of certain geometric constraints. When understood within the wider field of what he calls computational design thinking, parametric design is deeply rooted in systems theory and an understanding of the behaviour of form and forces and their representation as mathematical and geometric rules (Menges and Ahlquist, 2011). Menges (2011) also highlights Sanford Kwinter's important observation that the manifest form is a result of the interaction between internal rules and instrumental external morphogenetic pressures. In other words, the internal structure of an artifact is as much a result of its internal rules as it is a result of those rules being affected by the pressures of the other elements in its ecological system. This distinction is important for an understanding of internal stadium organisation and creates a context for understanding the particularities of each individual design by quantifying the external design pressures and integrating them into a parametric model.

In one of the seminal texts on the subject of algorithmic architecture, Terzidis (2006) points out that there is a clear distinction in the methodology of architectural design in relation to the use of computers. The architect either designs the building and uses the computer as a tool to digitalise his work or they use the computational power of the machine to produce designs.

Building on the work of Terzidis and Menges, Zarei (2012) brings a much more practical understanding to the use of parametrics in architecture. Zarei takes this methodological difference in design practice to map the way in which it is translated within the professional environment. He evaluates the overall understanding of the different approaches to traditional and parametric design within the profession, concluding that this methodology is not completely reliant on computers and that it expands the design possibilities through the complexity of the model. This research advances the existing work by exploring the parametric model as a tool for the evaluation of design space, as described by Brown and Mueller (2019a) in the context of stadium design.

## 1.6.2 Data-driven design and machine learning applications

The use of machine learning in typological analysis and the control of parametric models is a new research area, and only a small amount of work has been published to date. The following focuses on practice-based research such as Xiao-wei's 'Study on the intelligent system of sports culture centres by combining machine learning with Big Data' (2020), which explores building performance systems analysis in the context of sports architecture. In addition, the review focuses on performance-based morphological analysis using machine learning, as evaluated by Hong et al. in 'State-of-the-art on research and applications of machine learning in the building life cycle' (2020), and crowd modelling research such as Luque Sánchez's 'Revisiting crowd behaviour analysis through deep learning: taxonomy, anomaly detection, crowd emotions, datasets, opportunities and prospects' (2020).

There are several aspects of academic and practice-based machine learning research that are relevant to the methodology used in this research project. The previous sections of this review covered the importance of parameters in the creation of design and in analytical parametric models. From an engineering perspective, variables are used to optimise structures, while in architecture variation is used for both qualitative and quantitative ends. The selected parameters are extracted from the legal design requirements, guidance developed by international sports federations, and practice-based research by leading architects in the field.

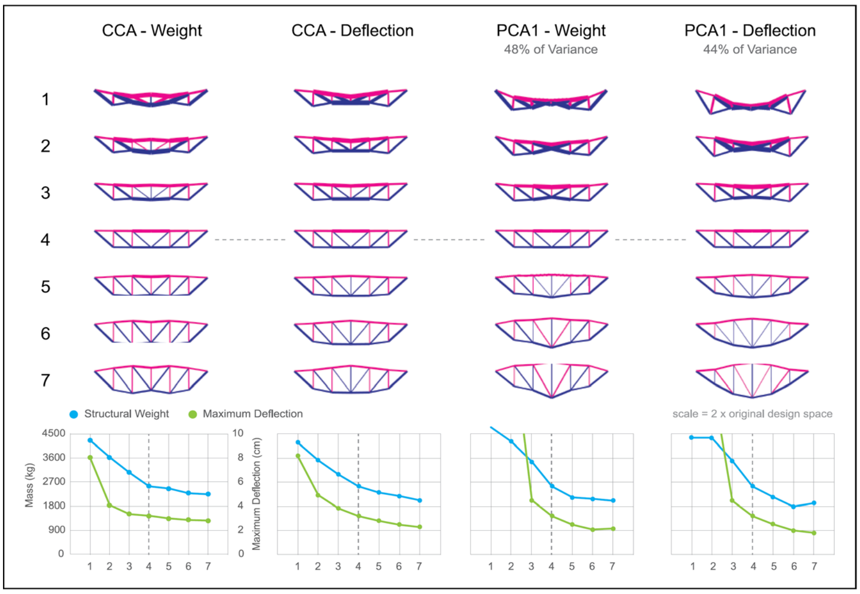


*Figure 1.5. Brown and Mueller (2019) Variable analysis based on development of design space for truss optimisation*

Brown and Mueller (2019a) propose a framework for a holistic approach to resolving design issues that brings together both engineering and architectural design aspects through the creation of parametric models and the evaluation of the weight of the variables in those digital representations. In terms of stadiums, parametric modelling is already deeply embedded in professional practice (John et al., 2013), and the use of the existing design parameters forms the basis of the hypothesis underpinning this research. Hudson (2010; 2011; 2008; 2007) describes the parametric design methodology for stadium projects within several themes: knowledge used to solve design problems, the analysis of existing projects and proposed design solutions, and the representation of design problems not as geometrical entities but as symbolic diagrams and programmatic descriptions.

In addition, Shepherd and Hudson (2007) describe a fully parametrically integrated design approach with RIBA Stage 4 for the façade of Lansdowne Road stadium, where the architectural design, structural design and optimisation, manufacturing, and construction are presented as a continuous process with different disciplines collaborating on the development of the same digital model. This methodology is further expanded in the study of the design for the façade of the Aviva Stadium in Dublin (Hudson et al., 2011), where the main relationships between the design originating from different disciplines are retained, but the process is further elaborated with the use of parametric models for the technical design of this section of the project.

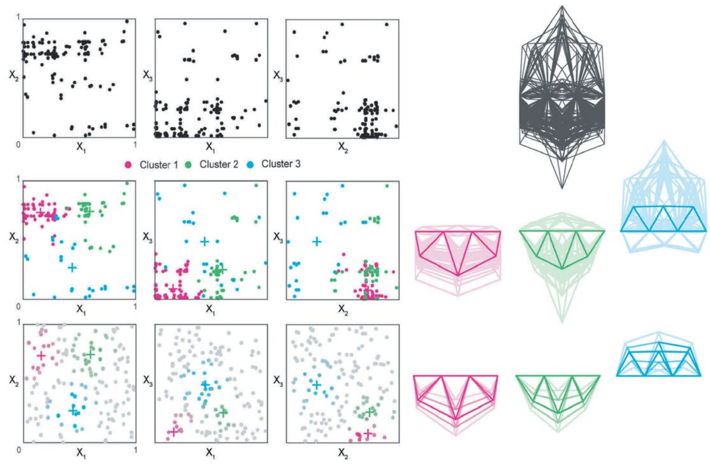


*Figure 1.6. Brown and Mueller (2017) Design space analysis and visualisation for truss optimisation with machine learning*

The contribution to knowledge that this research aims to make is to introduce design drivers selected from a typological study of the design of stadiums and develop a new methodology that uses machine learning in the analysis, generation, and optimisation of design solutions. The benefits of this approach include a greater integration of the various design requirements that are otherwise separated into different disciplines.  In comparison to previous approaches, this research aims to bring together methods from academia and professional practice that are concerned with specific design development stages.

Another aspect that is fundamental to the methodology of this research is the varying importance of parameters to the overall design process and thinking. The research by Brown and Mueller (2019a) and by Fuhriman and Ohbrock (2018) Combinatorial Equilibrium Modelling (CEM, in conjunction with typological analysis, form the basis for the creation of a methodology that can select and analyse parameters and design drivers through both unsupervised classification algorithms, such as k-means (Accord, 2017b), and supervised ones, such as neural networks [NNs] (Accord, 2017b). It is important to highlight that this evaluation covers both performance and morphological criteria and integrates both structural and architectural design.

Utilising machine learning from the outset of the analytical process, the practice side of the research aims to independently verify the design drivers identified in the literature. In addition to these, through the selection of the variables that are given the greatest weight in the classification process, practice-led considerations focus on the importance of variables such as plan morphology, the organisational pattern of functional space, user path, and structural types in different design areas. This expanded model of design drivers aims to improve design outcomes, as it adds more detailed and concrete parameters to the design model, which result in a greater overview of the entire design process and a more integrated design methodology across a greater number of disciplines involved in the delivery of a project.

Furthermore, in the context of his research on shell structures, Block et al. (2019) describes this entwining of data and objective as the driving force behind the generation of topological patterns and structural solutions. Another important research project in the field is the study by Turrin et al. (2011) of the implications of integrating engineering criteria to the architectural conceptual design phase. Their research focuses on the performance and complexity of geometric solutions from an interdisciplinary point of view. The objective of their research is to optimise the structural performance of long span roofs and the passive use of solar energy through the use of genetic algorithms, but the same methodology of selecting quantifiable objectives that influence qualitative objectives can be applied in a number of other scenarios. In terms of this research project, the variable selection is based on a similar strategy, but in the process of solution generation it has used both supervised and unsupervised machine learning algorithms, along with evolutionary optimisation.

According to Turrin et al. (2011) there are a number of social, financial, artistic, engineering, and other disciplines that affect interdisciplinary architectural design, but the data would be too complex for their model. To overcome this limitation in relation to representation, this research project has utilised a typological study to incorporate the perspectives of Turrin et al. (2011) as design drivers within the proposed machine learning model.

Wei (2018) describes three schools of thought on artificial intelligence and machine learning in architecture: Symbolism, Connectionism, and Behaviourism. These encapsulate the three basic approaches to generating architectural space using machine learning by using already established scientific methods, creating new relationships through machine learning, and adopting agent-based simulation. The first school of thought is a top-down approach that is analysis-focused, which enables greater clarity and greater efficiency, while the other two can be considered bottom-up methodologies that create new forms of spatial analysis.

This research project has utilised typological analysis and a topological understanding of structures within stadiums and arenas, as well as a practice-led selection of design drivers and parameters for the machine learning model, which aligns it most closely to Wei's Symbolist approach. Related to this, Cudzik (2018) presents methodologies for the practical application of the evolutionary and swarm-based utilisation of machine learning. If read through Wei's classification, these fall into the bottom-up approaches. However, Cudzik's (2018) research highlights the possibility of a rules-based machine learning methodology that can be embedded into architectural practice to generate a large design space and potentially previously unattainable design solutions.

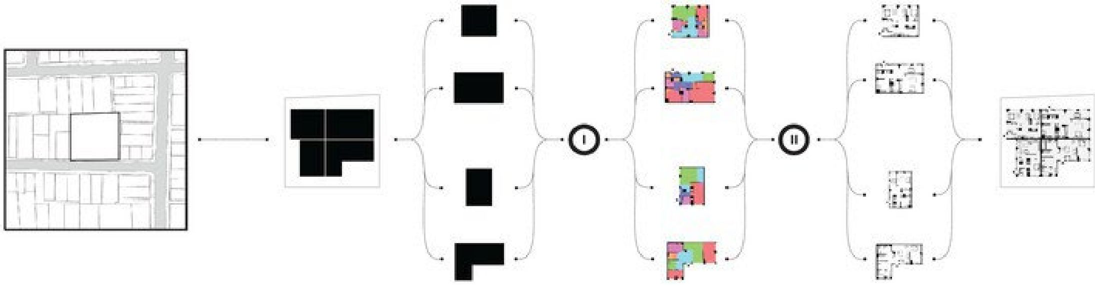


*Figure 1.7. Housing floor generation using GAN (Chaillou, 2019c)*

On the other hand, Chaillou's work (2020, 2019a) is an example of Wei's Connectionism and uses competing generative adversarial networks [GANs] to reassemble architectural housing plans from a two-dimensional image dataset of floor plans. Like Cudzik's, his work importantly highlights a methodology which is an alternative to standard practice, which has been explored in this research – that there is an input dataset and output generated though AI. But there is little control in his approach over the selection of parameters and the output. Another critique is that his work is based entirely on two-dimensional representations.

Newton (2019) takes the GAN utilisation a step further and uses it to analyse and synthesise architectural plans and models both in two and three dimensions. The focus of his research is explorative, and he uses different design styles as a starting point. A point of critique of these GAN research approaches is that the machine learning is unsupervised and lacks a foundation in specific design drivers – the algorithms analyse the designs as a whole, yet the output is entirely based on the properties of the machine learning algorithm, and the output has to be rationalised in order to bring it to the other design disciplines.

In contrast to the approaches of these three researchers, As et al. (2018) take topological architectural space representation based on graph theory (Cavalcante, 2013) and similar to Space Syntax (Hillier et al., 1987) and use machine learning to generate alternative spatial solutions. As et al's research is completely focused on 3D analysis and it is significantly more structured and combinatorial, due to a top-down approach that enables a clear identification of design parameters. As et al. (2018) also identify the basic limitations of purely analytical machine learning algorithms: they are not set up to generate new designs. To address this, they evaluate existing designs encoded as graphs, extract significant building blocks as subgraphs, and merge them into new compositions. However, again in contrast to Chaillou and Cudzik's approach, only after extracting significant design driver information do As et al. (2018) input this new design information into GANs to generate new designs. Another researcher, Koltun (2010), uses a similar approach to the generation of 3D models of houses using a Bayesian network algorithm. Koltun's (2010) approach is based on mimicking the process of design in an architectural office by creating relationship networks between the spaces, but he also uses ideas similar to Space Syntax and trains this data to train an algorithm.

Both As and Koltun's methodology is similar to the practice-led aspects of this research – after discovering latent topological features that constitute the essential building blocks of designs, Koltun (2010) recomposes the building blocks that meet the performance requirements and also explores feasible new variations using GANs.

In contrast, Standfest (2017) proposes a much more case-specific, practice-based methodology of building performance analysis that uses spatial features and overall morphology to study new analytical aspects. His methodology is based on the overlap between culturally constructed meanings of form and data extracted from case studies to construct a new understanding of building performance. Standfest's study presents a new approach to building performance analysis in relation to typological analysis with a primary focus on thermal transmission, isovist, connectivity, acoustics, and aggregation. His research is driven by concerns that are similar to those explored in this thesis and many aspects of his analytical methodology has been incorporated in the performance-based analysis for stadiums in terms of spatial planning, visual relationship between spaces and wayfinding, acoustics, and thermal and lighting analysis.

Crowd modelling is a pivotal aspect that justifies the use of machine learning to understand spectator circulation in the highly controlled environment of the stadium. In the early 2000s, Brocklehurst et al. (2005) took part in the process of establishing the EU spectator facility standard through his study of the crowd flow rates at Ascot racecourse. Using video footage recorded over a day at Ascot the researchers were able to assess route capacities, speeds, densities, and behaviour. Their research found an overprovision of crowd flow space in the *Green Guide* and the EU standard, as the crowd is reluctant to move at higher speeds if the area is overcrowded, and that only specific types of spectators cause a disturbance in the crowd flow. Brocklehurst et al.'s (2005) research is important for this thesis because it identifies the zones in a stadium configuration that can cause overcrowding and clarifies the types of spectators expected in the stadium and their anticipated behaviour. This information is vital because it allows the location of facilities on the concourse to be evaluated in relation to the type of user and the overall crowd flow found in stadiums.

Song and Sheng (2020) further present an overview of the use of machine learning in crowd analysis and simulation, based on two primary aspects: crowd size and time scale. The approaches to crowd modelling that they identify are flow representation and entity and agent-based simulation, depending on how the crowd dynamics are represented. They identify physical, social, and psychological factors as the three major influences on crowd behaviour.

Borja-Borja et al. (2018) focus on the types of machine learning that are currently used in crowd analysis using 2D image and video data. The researchers focus on the distinction in the behaviour of the individual and the crowd and the process of transformation from group to crowd behaviour. They use semantic behavioural features in order to train a machine learning algorithm to distinguish between the forms of social behaviour through atomic, or individual, behaviour and the mass behaviour of the crowd. This thesis employs a differentiation between users and crowd scale concepts to integrate them and differentiate between spectators, staff, and performance routes.

### 1.6.3 Approach to data generation / collection

A comprehensive review was conducted to identify research, theory, and practice in the analysis and multi-objective optimisation of architectural design through the adoption of machine learning. The review focused on existing qualitative and quantitative practices in stadium design analysis from the fields of architecture and engineering. The review also considered the historical development of modularity in stadium design through an analysis of design manuals. The primary features to be incorporated in the parametric and analytical models were identified through a typological study. Initially, this review addressed the overall legislative category of Places for Assembly and Recreation (Building regulations, 2010. Approved document B, Volume 2, Approved document B, Volume 2, 2020) and then narrowed its scope to stadiums based on shared organisational and structural properties.

Unsupervised learning played a pivotal role in the identification of design drivers. Due to their flexibility, ease of deployment, and wide adoption, clustering algorithms such as k-means have been used to identify patterns and relationships between design drivers and benchmarking metrics. The datasets utilised for the training of those models contain numerical and spatial data derived from existing case studies.

The development of a parametric model is based on the design drivers found in stadiums. The model is used for the historical analysis and representation of modularity and the analysis of key case studies, as well as the benchmarking and optimisation of stadium design through the reduction of design space. The model was developed in Rhino 7 using Grasshopper (Robert McNeel & Associates, 2020) and Python (Python Software Foundation, 2023) by the researcher and produces scalable 3D design models to permit the exploration of design configurations, the visualisation of morphology and performance metrics, and the linking up to BIM platform software such as Revit 2023 (Autodesk, 2023). The parametric model provides the basic 3D data that will be explored in the thesis.

The typological study Grasshopper models, the stadium generation model, and the analysis and optimisation parametric models were developed by the researcher. The components in those models are standard Grasshopper and various Grasshopper plugin operators. The contribution to knowledge of this element of the practice side is the arrangement of the components in a new way that allows meeting the research objectives. The research also produced a Python Grasshopper component that generates a stadium section.

### 1.6.4 Approach to parameters and parametric models

The concept of modularity is foundational for the development of the parametric model. Focusing on repeatability at various scales, modularity allows the creation of a design representation that captures different stadium typologies and permits the application of various interchangeable and reusable building information modelling [BIM] families at later stages during the design process. The modularity parameters and scales are derived from the analysis of existing modular stadiums and are incorporated into the development of parametric and machine learning models to enable the creation of a design space and the generation of design alternatives.

Shape grammars were deployed in the development of the parametric representations of stadium structural grids. This process allows the morphology of the case studies and design alternatives to be captured comprehensively and permit the allocation of functional, structural, and circulation elements in the parametric and machine learning models. The shape grammars were developed based on existing stadium designs and typologies and aim to ensure the generation of structurally feasible design alternatives.

Space Syntax analysis was used to evaluate the relationship between circulation and spatial arrangement. Based on the theory developed by Hillier (1987) this research defines this analytical approach as method for quantifying and evaluating spatial configurations as topologies. The method is derived from graph theory and introduces social aspects to the overall analysis. Working within the modular scales of the parametric model, Space Syntax enables the evaluation of accessibility, visibility, integration, and the distribution of programmatic elements, bringing insights to their functional and experiential qualities. As the layout data can be interpreted topologically, graph machine learning is a possibility. Nevertheless the scope of the research also includes morphological and sightline analysis which have different requirements and prevent the utilisation of this type of machine learning models.

### 1.6.5 Optimisation and benchmarking

This research employs multi-objective optimisation as a framework process that utilises parametric modelling as a design simulation tool and machine learning as design space reduction tool. The selection of case studies is based on their relevance, innovation, and successful implementation of typological principles, modularity, their use of parametric design, and relevance to modern methods of construction. These were used to establish benchmarks for the evaluation and optimisation of the design space. The performance metrics and design parameters were also used to calibrate the multi-objective optimisation algorithms and validate the research findings.

Evolutionary algorithms have been used to define one of the workflows for the multi-objective optimisation of stadium design aimed at improving the design performance of sightlines, circulation, and layout. Existing Grasshopper (Robert McNeel & Associates, 2020) plug-ins such as Galapagos (Rutten, D., 2017) and Octopus (Vierlinger, R., 2014) were utilised by the researcher for iterative searches of design alternatives that achieve the desired balance between objectives.

NN algorithms from the Accord Framework (2017a) within Lunchbox (Proving Ground, 2012) in Grasshopper in Rhino (Robert McNeel & Associates, 2020) have been deployed in a series of workflows aimed at analysing and reducing the design space. The aim of those workflows is to provide the designer with automated and semi-automated pipelines that expand the possibilities of evolutionary algorithms towards performance analysis and the evaluation of legal compliance. The reduction and redefinition of design space in the automated workflows was based on voting ensemble algorithms, while the semi-automated methods rely on manual design choices.

### 1.6.6 Testing and validation

The stadium designs and optimisation strategies generated were tested and validated through a combination of qualitative and quantitative methods. This involved the comparison of optimised designs with benchmarks derived from the case studies, as well as a machine learning analysis of the designs in relation to compliance and performance. The testing and validation process has ensured the accuracy, relevance, and applicability of the research findings in the context of modular stadium design.

| | Phase 1 | Phase 2 | Phase 3 |
|---|---|---|---|
| **Architecture** | **Typological analysis**<br>**objective:** heuristic evaluation of spatial and structural data<br>**outcome:** classification of case studies and identification of design drivers<br>**Public assembly buildings design drivers analysis**<br>**objective:** identification of shared design generating elements among public assembly buildings<br>**outcome:** outline of design elements that drive the design of public assembly buildings<br>**Stadium design drivers analysis**<br>**objective:** identification of shared design generating elements among stadia<br>**outcome:** design elements that serve as basis for the development of stadium design generating parametric model | **Space Syntax**<br>**objective:** spatial analysis<br>**outcome:** quantified representation of crowd flow and service/performer circulation, programmatic relationships<br>**Shape grammars**<br>**objective:** morphological analysis<br>**outcome:** quantified representation of stadium plan morphologies/circulation | **RIBA Plan of Work design development**<br>**objective:** identify design tasksper stage that can be improved through machine learning-based optimisation<br>**outcome:** a set of design resolution objectives and corresponding machine learning approach to their fulfilment |
| **Engineering** | | **Parametric representation**<br>**objective:** stadium design spatial representation as a system of quantified design drivers<br>**outcome:** typological parametric model that works across case studied | **Multi-objective optimisation**<br>**objective:** identification of best performing design solutions based multiple objectives<br>**outcome:** development of workflows for performance-based multi-objective stadium design optimisaiton |
| **Computer science** | **Classification analysis of public assembly buildings with machine learning** (Part-to-part / Part-to-whole)<br>**objective:** identification of public assembly buildings design drivers weights based on quantitative analysis<br>**outcome:** identification of public assembly buildings design<br>**Classification analysis of stadia with machine learning** (Part-to-part / Part-to-whole)<br>**objective:** identification of stadia design drivers weights based on quantitative analysis and analysis of parametrically generated dataset<br>**outcome:** identification of stadium design drivers and identification of the most efficient proportional parametric design driver relationships per function for stadia | | **Supervised, Semi-supervised, Unsupervised, Evolutionary machine learning analysis**<br>**objective:** Train machine learning models to identify best performing solutions within specific RIBA Plan of Work design stages<br>**outcome:** A set of machine learning workflows tested within RIBA Stages 0-2 design development requirements |

*Table 1.2. Research objectives alongside their corresponding methods*

# Chapter 2 Design Drivers: Definition Through Typological Study

The first methodological challenge faced by machine learning-supplemented approaches to stadium analysis and design is the question: 'What is it?' This research follows the established classification of building types within the UK Building Regulations ('Building Regulations and Approved Documents Index', 2022), examining stadiums as a genre within the overarching category of Places for Assembly and Recreation. The purpose of this is to identify shared design drivers within the larger group of building types and then to narrow down the selection to features that can be translated into stadium-specific parametric relationships. Digital representation enables the creation of a dataset with examples of all the designs that fall into the wider legal category. Deconstructing those designs into their functional and organisational properties is based on the basic data carried by a computer-aided design [CAD] drawing: functional types, areas, distances, and adjacencies. When represented digitally those properties are already quantified and their values can be analysed and compared with machine learning. From a typological perspective, these designs share a set of properties and when analysed solely on the basis of these characteristics they can be understood as variants of each other.

To define types, the machine learning algorithm selected must be capable of grouping the case studies together. The aim of the analytical process is not only to identify the functions that the stadium shares with the other building types in the legal classification, but also to identify distinct spatial and organisational properties that make them unique. Identifying the best performing case is not one of the primary objectives for this stage of the research so all the studies are conducted through unsupervised learning with k-means. This is an iterative process that takes several steps to complete – first the research identifies case studies; their properties are then quantified, and the importance of each design driver is evaluated through its effect on the delineation of types – whether it clearly identifies specific groups, or whether the results are mixed. The well-defined classifications based on specific design drivers then become the basis for a structured representation of the design drivers for the category of Buildings for Assembly and Recreation in the Building Regulations, which is then narrowed down to stadiums.

In the first phase, the primary typological characteristics for the study are extracted from the seating layouts and architectural drawings of existing case studies. This mixed approach is the result

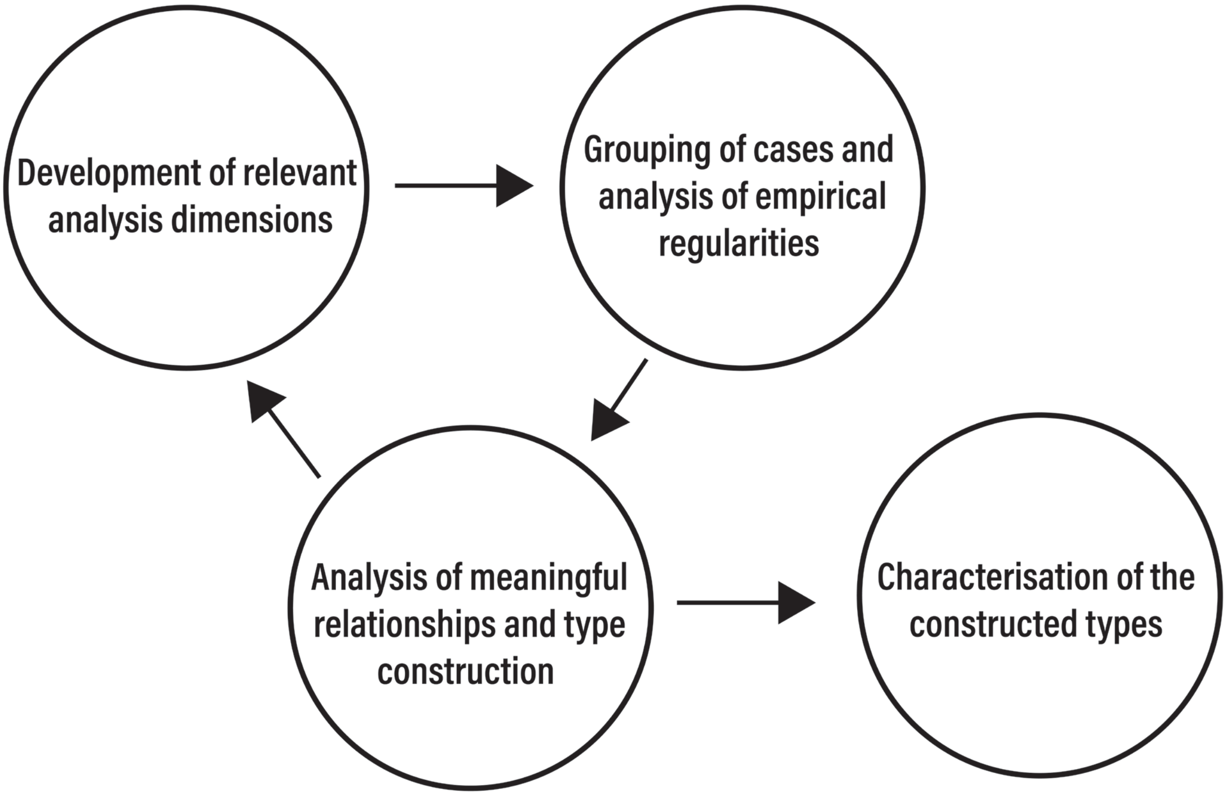



*Figure 2.1. Grounded construction of types, based on Kluge (2000)*

of the lack of available as-built drawings and the evident link between the organisation of the seating space and the structural grid. Borrowing methods from the empirically grounded construction of types and typologies in qualitative social research (Kluge, 2000), first the practice identifies the dimensions of the analysis, then groups them based on empirical regularities; these are then related in meaningful types. If this stage is successful, the final characteristics of the types are identified and analysed; if not, the process returns to the start.

## 2.1 Typology

The interpretation of type has evolved throughout history, and our current understanding is an amalgamation which contains from an academic perspective what Eisenman (1984) refers to as traces, a system of signs beyond representation, with the sole value of marking the event of reading. The three fictions that Eisenman (1984) uses to define the period of the Classical - representation, reason, and history – are also closely related to the development of the understanding of type, and they define type through ideas of truth, meaning, and timelessness. Lathouri (2011) locates the origin of the word etymologically to the Greek word typos, meaning a model, matrix, imprint or figure in relief. Other scholars, such as Broadbent (2016), expand on this direct correlation with the juxtaposition of two other terms, telos and eidos – the physical manifestation in the human domain and its ideal counterpart in the domain of the divine. Plato (1997) links those two entities though the work of the artist – the representation that the artist creates is the vessel that brings the ideal to the physical. Furthermore it is possible to add two more characteristics to the evolution of the understanding of type – logos, or the discourse and reasoning on the process of grouping things together, and chora – as understood through Derrida and Eisenman's (Derrida et al., 1997) reading of Plato, it is the person who defines the place: thus, the place cannot exist without the person. This combination of ideas was so powerful that it dominated the built environment for more than two millennia and it was not until the advent of Eisenman's (1984) second fiction, reason, that the status quo was challenged and a more systematic and malleable grasp of type emerged. Understanding of the basic reading of type is important for this research because it sets the framework and boundaries of what type is and allows for the later breakdown of type into a manageable set of characteristics.

The history of the modern reading of typology can be traced to the eighteenth century, in which the establishment of what we perceive as architecture today as a separate academic discipline developed, concurrently with the emergence of the understanding of type as a timeless entity constrained within the realm of the divine. Quatremère de Quincy was the first to challenge the assiduous copying of what is perceived to be an ideal. For him, type does not represent an image, or a thing to be replicated, but rather an idea to be followed, an inspiration that gives birth to new work (Broadbent, 2016). It is an abstraction which is detached from any historical and cultural milieu (Jacoby, 2015). Architecture is limited in terms of its ability to imitate nature and as such it is forced to enter the domain of artificiality. Type is the standard which allows this transition, through its capacity to communicate otherwise abstract theory (Jacoby, 2015). However, the physical representation is always incomplete, and it is this incompleteness that allows the original abstraction. In this way, type is an object after which the artist can create works that do not resemble each other but are based on an original ideal (Quatremère de Quincy and Kent, 1837). Inspired by the naturalists of the eighteenth century, de Quincy linked type to a particular form which defined the fundamental purpose of the building (Lathouri, 2011). De Quincy's work is important for this research as it is the basis of the modern definition of type. He also challenges the idea of reproduction – by grouping physically unrelated artefacts he allows the possibility of recognising and linking patterns beyond the actual manifestation of the object. In other words, his definition of type presupposes a system of relationships which can be quantified, and are based on rules – but at the same time these relationships define a qualitative abstract concept.

Jean-Nicolas-Louis Durand developed de Quincy's dislocation of type as a formal ideal into the notion of type as an abstract pattern through the use of geometry (Durand and Durand, 2000). Working within the neoclassical tradition of the period, Durand based his practice on the rigid techniques developed by the early Egyptian and Greek master builders, for whom spatial organisation and structure were heavily overlapping concepts, and extracted the essence of those plans as geometric patterns. For Durand, type was a result of geometrical organisation and it should be applied to the layout of the building in an as unadulterated way as possible (Oechslin, 1986). The resulting architectural designs relied heavily on modularity, organised by axes and symmetry. As the distinction between structure and architecture was not as fully developed as it is today, Durand's

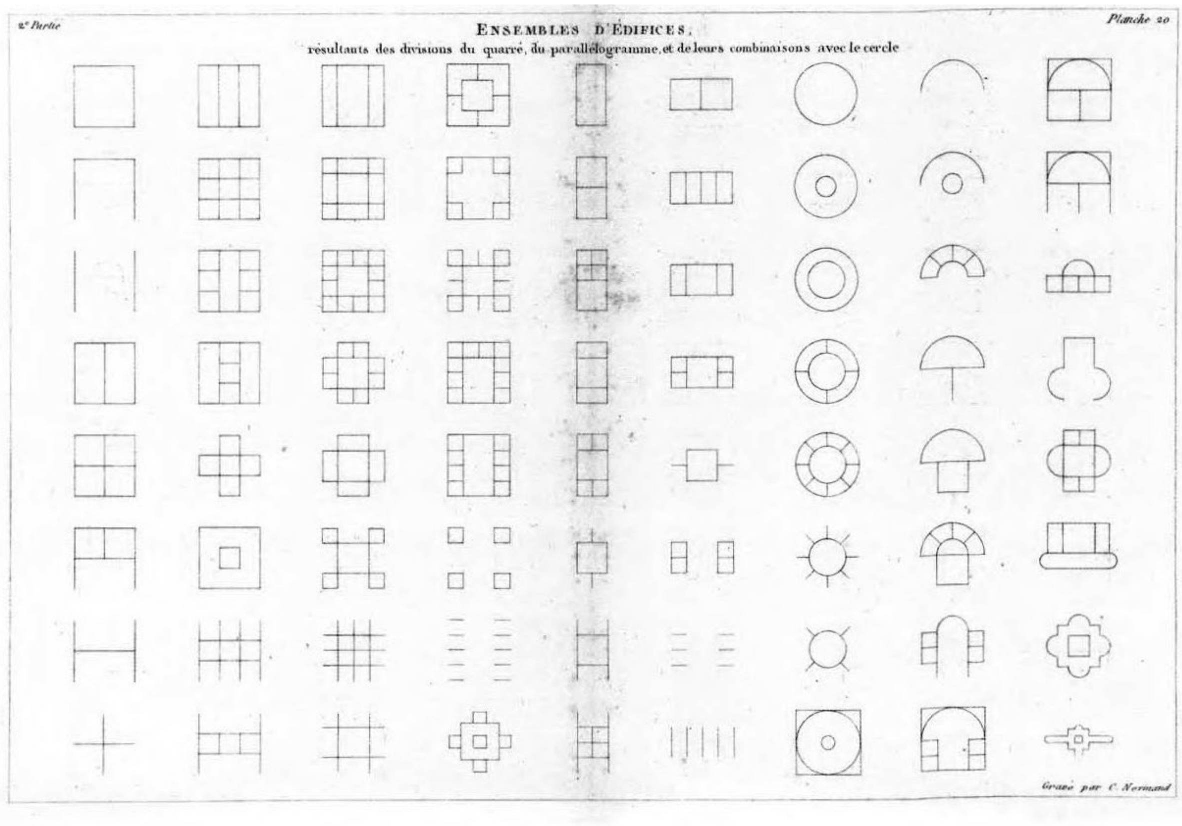



*Figure 2.2. Geometric studies for floor layouts (Durand and Durand, 2000)*

modules were based on the combination of building elements such as columns, walls and openings, which were then arranged to form parts of the building. Durand's work is important to this research not only because of the patterns and designs which follow strict rules, but also because of his modular approach to building. Depending on the scale of analysis – object, room, dwelling, building, city – there are different types and potential groupings, while at the same time there is a vertical interrelationship between the different scales, as all of them are the result of the same design process.

The work of Alexander Klein and his concept of Existenzminimum has remained at the margins of mainstream architectural theory since its inception (Bevilacqua, 2011). Klein was one of the first architects to attempt to create a rigorous approach to planning based on minimal dwelling requirements that do not constrain the user of the building (International Congresses for Modern Architecture et al., 1930). His systematic approach to resolving the relation between the space required for the occupants, the circulation between the different areas, and the relation between space and building orientation (Klein, 1928) is pivotal for this research. Klein's ability to quantify architectural space in terms of area, movement and orientation has informed the practical section of this research and creates the basis for the

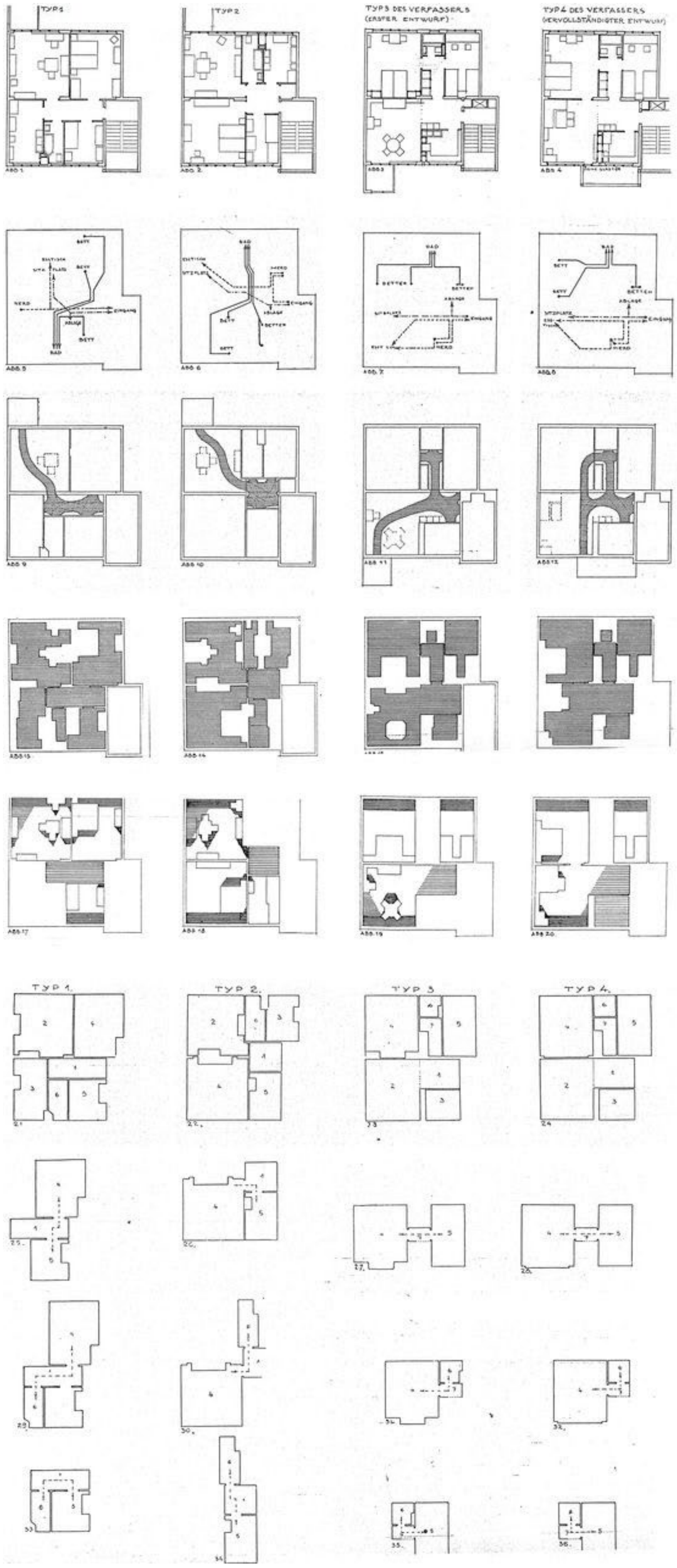


*Figure 2.3. Graphical studies of dwelling layout Klein (1928)*

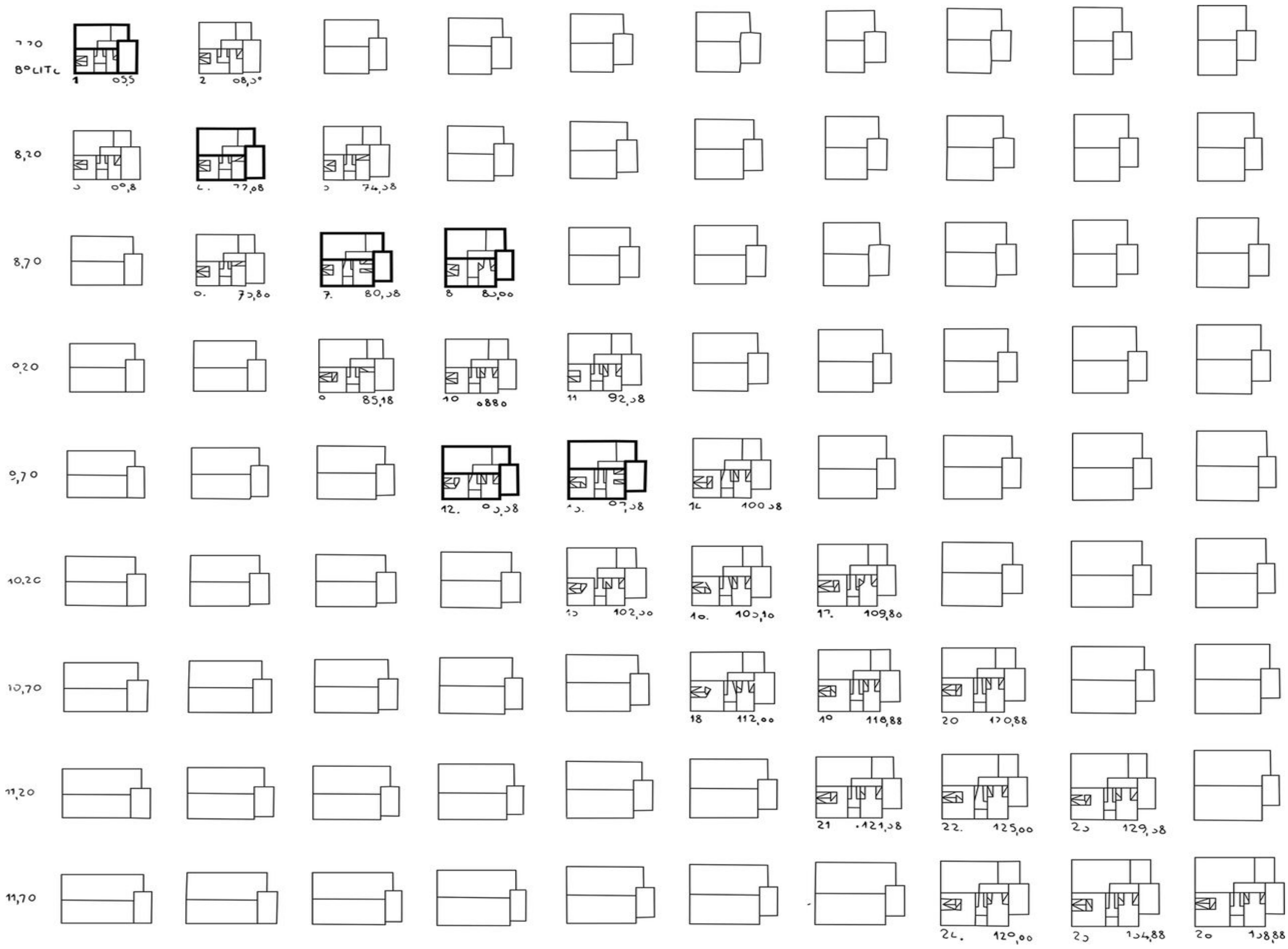


Figure 2.4. Generation of floor layouts through quantitative variation: Klein (1928)

methodology to define architectural typologies. Klein's approach to the graphical representation of typological systems (Klein, 1929) enables a clear visual analysis of both existing buildings and the possibility of generating alternative layout solutions based on parametric variation.

Christopher Alexander (1978, 1974) was one of the first architects to challenge the functionalist credo of the Modern movement through his attempt to define a system of actions that inform architectural design and later through the application of a typological analysis of American vernacular architecture in order to define an architectural language which

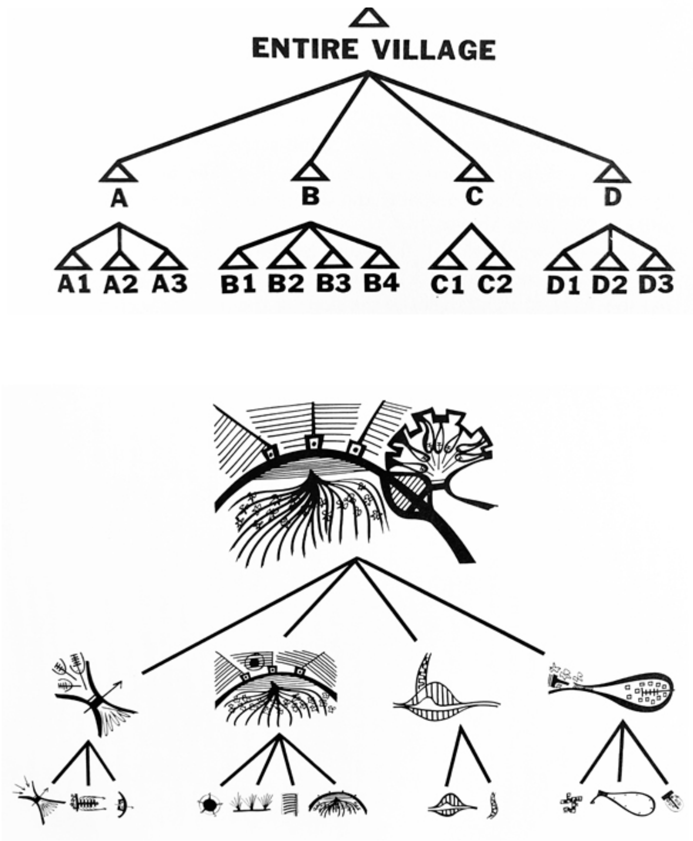



Figure 2.5. Hierarchical urban system analysis: Alexander (1978)

is rooted in the building forms and urban compositions that already exist. For Alexander (1974), the ultimate end of architectural design is form, but this form is a result of a sequence of quantifiable processes with independent subsystems of variables that inform the final outcome. Elements are tested to identify how they fit in with both the overall conscious and subconscious design process and the relationship between form and context in terms of the real world, the creator's perception, and the representation that results from the creator's perception (Alexander, 1974). In *A Pattern Language* Alexander (1978) redefines architecture as a network of solutions which is accessible not only to the architect but also to the layperson. His language is based on the idea of scale: city, building, building element – all of these are identified and classified within an overarching system. On the other hand, Alexander (1978) also admits that this system is not necessarily the final architectural approach that everyone should follow: he proposes it as a tool which can be used for the creation of other languages, based on the specific needs of their creators. Alexander (1978) suggests that what the next language creator should take from his work is the systematic approach to the problem and not the solution itself. Alexander's work is important for this research because of his approach to architectural design. The system of identifying building elements at the corresponding scales, identifying their properties and then applying them to new designs is a methodology which corresponds with the aim of this research. Another important aspect is his understanding of type as a quantifiable pattern which can be translated to computer-based analysis.

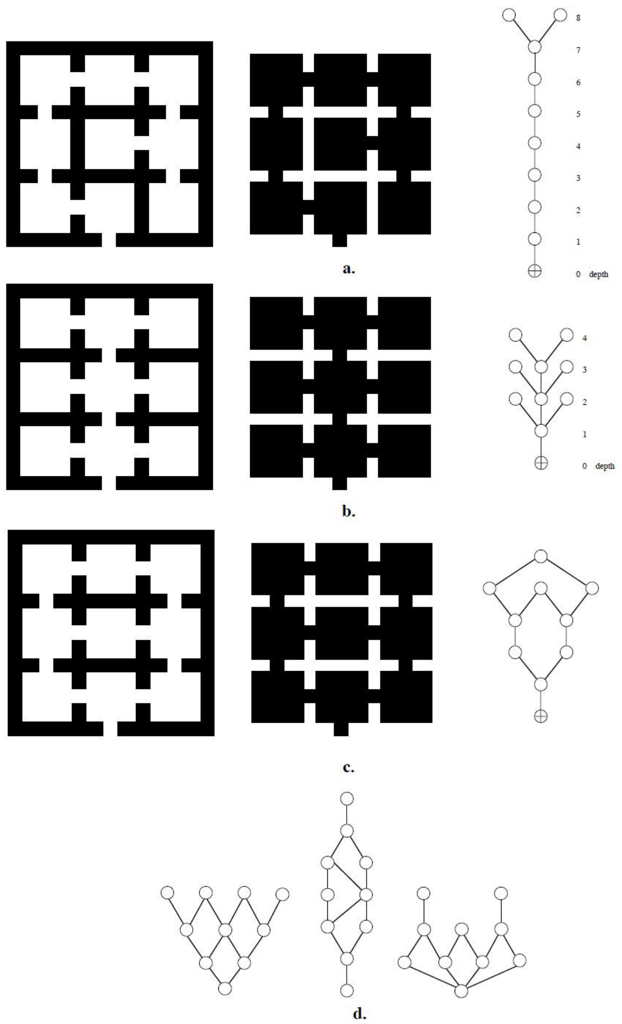


*Figure 2.6. Topological principles of Space Syntax (Hillier, 2015)*

Alexander's work prompted global interest in the theory of quantifying architectural space and identifying the underlying patterns that shape our built environment. Hillier (2015; 1987; 2005) was one of the researchers who took Alexander's theory forward through the introduction of another dimension – he asked whether there is a relation between space and social life. Hillier's (2005) critique of Alexander's approach was that his theory was too influenced by the contingent properties of configurations and his over-reliance on hierarchical forms of spatial arrangement. By introducing the social dimension, Hillier (2015) aimed to produce a descriptive account of the morphological features of the built environment through the lens of social processes and structures. His research also aimed to produce a reciprocal account of the morphological features of society that are already translated into spatial form. In this way Hillier wanted to identify how spatial patterns can carry social information and content. His starting point was that the built environment acts as a restriction to random social interaction, a limit which constrains and defines communication in society.

The result of this programmatic input was a set of techniques for the representation, quantification, and interpretation of social configurations in buildings and urban structures. The basis of his theory that society expresses itself in space is rooted in the logic of space itself. If a person can go from one space to another, this means that the two spaces are related to each other. Nevertheless, this relationship does not carry meaning until the relationship of those spaces to a third space is established and a configuration is formed. This third space can be considered as a root – the basis of the hierarchy of the spaces related to it. This hierarchy is based on depth and the number of spaces a person must pass through to get from the root space to the space in question. Hillier also introduces the possibility of getting to a space through a number of routes and the level of integration between different spaces (Hillier et al., 1987). All these elements are studied quantitively and produce a genotype for the building or urban system. An example of the potential of machine learning to utilise the data produced with Space Syntax is the research by Wang and Huang (2019), in which these tools are used to analyse and predict crowd movement.

In the years that followed the publication of *The Social Logic of Space* (Hillier and Hanson, 2005), a number of practical applications and elaborations of the configuration theory presented in the book emerged. These include a number of software applications that apply these ideas to the mapping and analysis of several different urban situations (Hillier, 2015). The work undertaken by Nourian (2018) is significant: he explores the possibilities for spatial arrangement from the perspective of graph theory. His methodology originates in Hillier's work, but Nourian expands it through the introduction of the orientation of buildings, advanced space division, and the holistic analysis of buildings as a topology of circulation paths.

Another methodology in the existing research that is relevant to the typological analysis of buildings is the approach developed by Stiny and Gips (2015a; 1972). Shape grammars are rule-based systems for describing and generating designs. These are visually based methods aimed at generating designs by directly computing 2D or 3D shapes (Knight and Stiny, 2015). The basic concept relies on an original base shape which is modified by a rule and then transformed into new one. The process can be repeated indefinitely. In terms of aesthetics the resulting shapes and forms are evaluated for their simplicity of specification and visual complexity. The aim of this method is to use formal generative techniques to produce art objects and also to identify what makes a good art object by reversing the technique (Stiny and Gips, 1972). Originally this method was developed for painting and sculpture, but researchers have applied the same principles to architecture,  as presented by Flemming (1987) in his investigation of late nineteenth-century American vernacular buildings, by Duate (2005) for the generation of plans for mass-produced housing in Portugal, and by Benros (2018) for the formal generation of the principles of a Palladian villa. Recently the quantifiable principles of shape grammars have been utilised by Lee and others (2016). Lee's research (2016)  is of particular interest because it focuses on the generation of new structures based on rules deriving from architecture. This method produces design alternatives with no bias towards pre-existing structural types: the resulting structures are directly linked to the original design problem and the structural solution can be updated through changes in the architectural requirements.

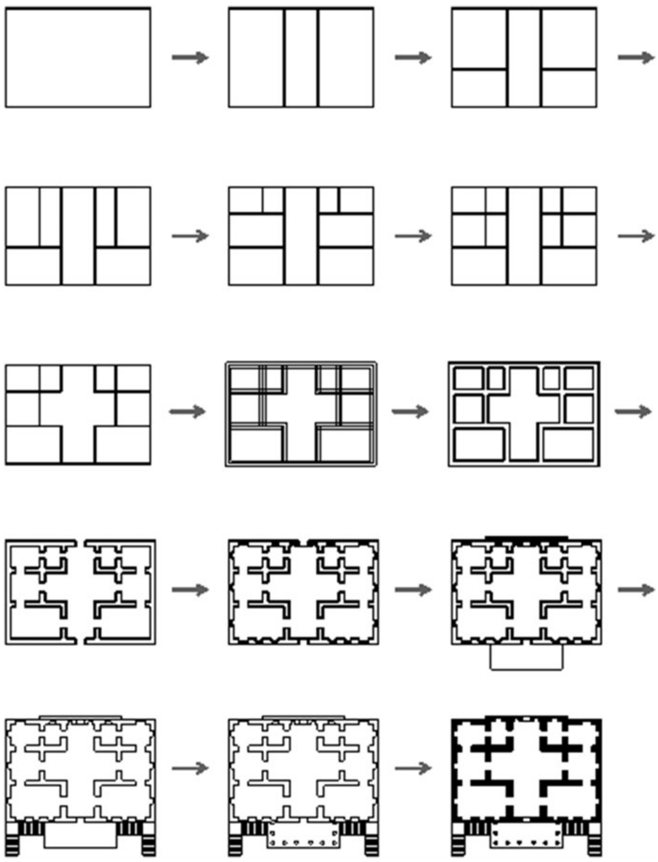


*Figure 2.7. Benros (2018) Generation of Palladian villa layout through shape grammars*

## 2.2 Identification of the shared characteristics of public assembly building types

The methodology for identifying shared typological characteristics is based on extracting the base typologies through a literature review, classifying them in terms of their circulation, layout, and morphological characteristics, and then summarising their shared properties in type layout drawings. First, simplified auditorium structural grids, circulation patterns and seating arrangements are identified and drawn from the seating layouts of a full set of public assembly building case studies. Other important data like Space Syntax, shape grammars, footprint, capacity, and year of completion/last renovation are also compiled in this initial step. All the analysis and quantifications is conducted manually, based on the method described by Kluge (2000), as the available information is not structured in a way that can be directly processed with machine learning. Due to the large number of subgroups in the Building Regulations ('Building Regulations and Approved Documents index', 2022) Places for Assembly and Recreation category, secondary types that share a significant number of characteristics with other types, such as cinemas, museums, and libraries, were omitted for the purpose of clarity. Early in the process it also became evident that stadiums predominantly have rectangular playing field while the rest of the case studies have varying stage shapes.

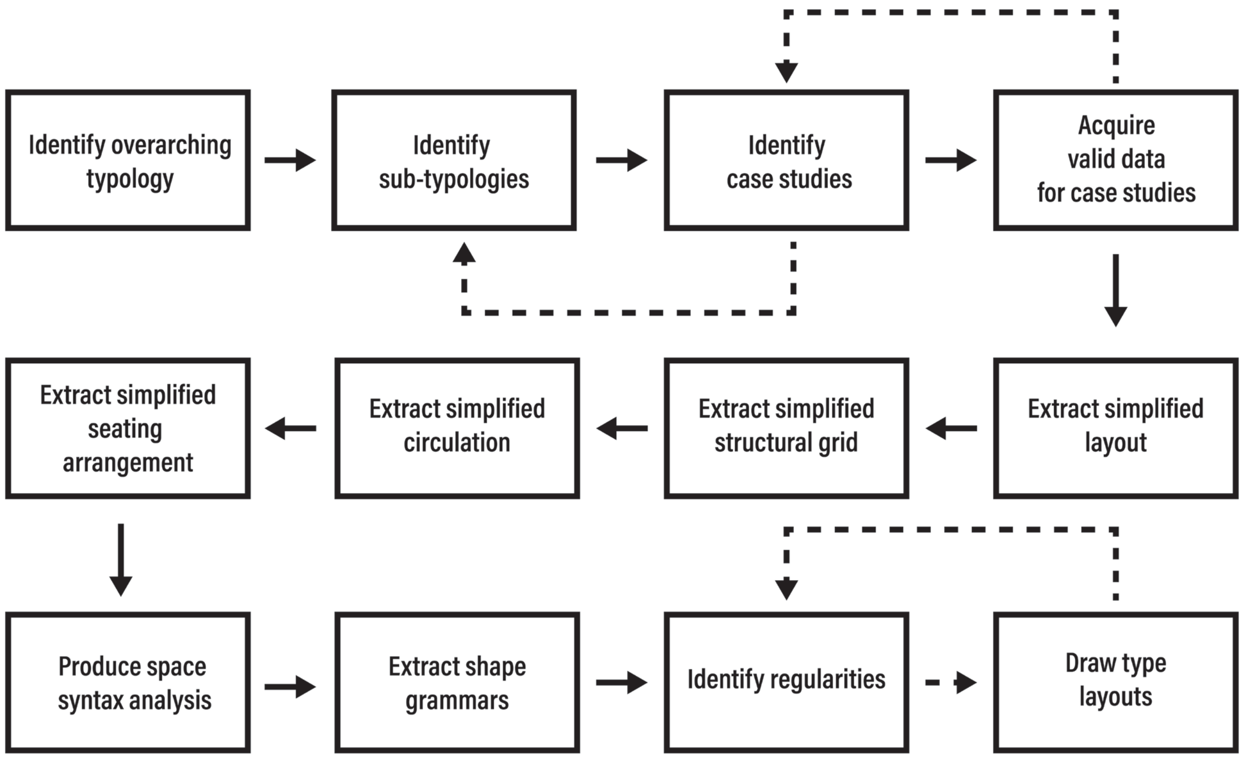



*Figure 2.8. Development of analytical dimensions*

## 2.3 Case study selection methodology and criteria

The selection process and criteria for the case studies originate in the requirements of the typological investigation – designs that have functions and characteristics that fit within the focus of the research. The research followed the existing taxonomy in legislation and literature based on function until there was enough information for alternative classification based on shared quantified characteristics. The identification and selection of case studies within each functional category is based on designs that had been fully described in literature with full sets of plans. Further on, the selection process was also based on the historical period and location of the design – the objective was to compare buildings designed or refurbished within the last hundred years in Europe. The reason for this approach is the continuous development of construction technology and the application of similar construction approaches. Where no example could be identified within this time period or geographic area, the scope was expanded to the Americas, Australia, Asia, and Africa and a larger time period. In terms of scale, the selection process was based on buildings with similar footprints and capacities within their respective functional categories. As described in the previous section, the parameters characterising each case study beyond time period, location, and scale fall into the categories of layout, circulation, and morphology. The reason for the inclusion of morphology rather than sightlines is the influence of form to the sightline aspect but also towards the overall architectural and structural organisation and performance.

### 2.3.1 Public assembly buildings case studies

*Table 2.1. Public assembly buildings case studies*

| Genre | Auditorium type | Name | Location | Built (renovated) | Capacity |
|---|---|---|---|---|---|
| Stadium | Circular | Melbourne Cricket Ground | Melbourne, Australia | 1853 (2013) | 100 024 |
| | | Wankhede Stadium | Mumbai, India | 1974 (2011) | 33 108 |
| | | Hangzhou Olympic Tennis Stadium | Hangzhou, China | 2007 | 10 000 |
| | | The Kia Oval | London, UK | 1845 (2016) | 25 500 |
| | Ellipse | Stadio San Nicola | Bari, Italy | 1990 | 58 270 |
| | | Diego Armando Maradona Stadium | Naples, Italy | 1959 (2019) | 54 726 |

| | | | | | |
|---|---|---|---|---|---|
| | | Olimpiastadion | Berlin, Germany | 1936 (2016) | 74 667 |
| | | Olimpiastadion | Munich, Germany | 1972 | 69 250 |
| | Hippodrome | Helsinki Olympic Stadium | Helsinki, Finland | 1934 (2020) | 36 251 |
| | | Kiev Olympic Stadium | Kiev, Ukraine | 1923 (2011) | 70 050 |
| | | Stadio Renato Dall'Ara | Bolognia, Italy | 1927 (2015) | 36 000 |
| | | Stadion Vasil Levski | Sofia, Bulgaria | 1845 (2016) | 44 000 |
| | Tangent arc | Deutsche Bank Park | Frankfurt, Germany | 2005 (2023) | 51 500 |
| | | Stade France | Saint-Denis, France | 1995 | 75 000 |
| | | Arrowhead Stadium | Kansas City, USA | 1972 (2010) | 76 416 |
| | | Wembley Stadium | London, UK | 2007 | 90 000 |
| | Fillet corners | Twickenham Stadium | London, UK | 1902 (2006) | 82 000 |
| | | Emirates Stadium | London, UK | 2006 | 60 706 |
| | | Allianz Arena | Munich, Germany | 2005 | 75 024 |
| | | King Power Stadium | Leicester, UK | 2003 | 32 261 |
| | Chamfer corners | Hard Rock Stadium | Miami Gardens, USA | 1987 | 64 767 |
| | | Raymond James Stadium | Tampa, USA | 1998 | 65 618 |
| | | Arthur Ashe Stadium | New York, USA | 1997 (2016) | 23 771 |
| | | Bay Arena | Leverkusen, Germany | 1958 (2009) | 30 210 |
| | Independent stands | Anfield Stadium | Liverpool, UK | 1884 (2023) | 53 394 |
| | | John Smith's Stadium | Huddersfield, UK | 1994 | 24 500 |
| | | Stadio Luiggi Ferraris | Genoa, Italy | 1902 (1982) | 36 600 |
| | | Vitality Stadium | Bournemouth, UK | 1910 (2010) | 11 329 |
| | Baseball | Dodger Stadium | Los Angeles, USA | 1962 (2013) | 56 000 |
| | | Yankee Stadium | New York, USA | 2009 | 47 309 |
| | | Busch Stadium | St Louis, USA | 2006 | 45 538 |
| | | Chase Field | Phoenix, USA | 1998 | 48 686 |
| | Motorsport | Indianapolis Motor Speedway | Speedway, USA | 1909 (2014) | 257 327 |
| | | Hockenheimring | Hockenheim, Germany | 1932 (2002) | 120 000 |
| | | Monza | Monza, Italy | 1932 (2017) | 113 860 |

| | | | | | |
|---|---|---|---|---|---|
| | | Autódromo José Carlos Pace | São Paulo, Brazil | 1940 (2017) | 60 000 |
| Arena | Radial | Royal Albert Hall | London, UK | 1871 (2004) | 5 272 |
| | | SSE Hydro | Glasgow, UK | 2013 | 120 000 |
| | | 3Arena | Dublin, Ireland | 2008 | 13 000 |
| | | The Forum | Inglewood, USA | 1966 (2014) | 17 500 |
| | Fillet corners | O2 Arena | London, UK | 2007 | 20 000 |
| | | American Airlines Arena | Miami, USA | 1998 | 19 600 |
| | | EagleBank Arena | Fairfax, USA | 1985 | 10 000 |
| | | Manchester Arena | Manchester, UK | 1995 | 21 000 |
| | Chamfer corners | Barclays Center | New York, USA | 2012 | 19 000 |
| | | Talking Stick Resort Arena | Phoenix, USA | 1992 | 18 442 |
| | | Spectrume Center | Charlotte, USA | 2005 | 20 200 |
| | | AT&T Center | San Antonio, USA | 2002 | 18 797 |
| | Hippodrome | Capital One Arena | Washington, D.C., USA | 1997 | 20 656 |
| | | Bridgestone Arena | Nashville, USA | 1994 (2015) | 19 395 |
| | | Honda Center | Anaheim, USA | 1993 | 18 336 |
| | | Madison Square Garden | New York, USA | 1968 (2013) | 19 812 |
| | Swimming pools | London Aquatics Centre | London, UK | 2011 (2014) | 3 800 |
| | | Melbourne Sports and Aquatic Centre | Melbourne, Australia | 1997 | 1 800 |
| | | Beijing National Aquatics Center | Beijing, China | 2007 | 4 598 |
| | | Tokyo Tatsumi International Swimming Centre | Tokyo, Japan | 1993 | 3 735 |
| | Velodrome | Lee Valley Velopark | London, UK | 2011 | 6 750 |
| | | Anna Meares Velodrome | Brisbane, Australia | 2018 | 1 500 |
| | | Izu Velodrome | Ariake, Japan | 2019 | 3 600 |
| | | Velodrom | Berlin, Germany | 1997 | 6 887 |
| Theatre | Proscenium | Wexford Opera House | Wexford, Ireland | 2008 | 850 |
| | | Oslo Opera House | Oslo, Norway | 2008 | 1 350 |
| | | Jerwood Vanburgh Theatre | London, UK | 2000 | 204 |
| | | Hackney Empire | London, UK | 1901 (2004) | 1 311 |
| | End stage | Northern Stage | Newcastle upon Tyne, UK | 1970 (2006) | 697 |
| | | Nederlands Dans Theatre | Den Hague, The Netherlands | 1987 (dem.) | 1 300 |

| | | | | | |
|---|---|---|---|---|---|
| | Corner stage | National Theatre | London, UK | 1976 | 1 150 |
| | Wide fan | Barbican Theatre | London, UK | 1982 | 1 156 |
| | | Bayreuth Opera | Bayreuth, Germany | 1876 | 1 925 |
| | Amphitheatre | Generic example | | | |
| | Thrust stage | The Crucible Theatre | Sheffield, UK | 1897 (2009) | 980 |
| | | Donmar Warehouse | London, UK | 1992 | 251 |
| | | Guthrie Theatre | Minneapolis, USA | 2006 | 1 100 |
| | In-the- round | The Crucible Theatre | Sheffield, UK | 1897 (2009) | 980 |
| | | Stephen Joseph Theatre | Scarborough, UK | 1996 | 404 |
| | Courtyard | Cottesloe at the National Theatre | London, UK | 1977 (2014) | 450 |
| | | The Swan, Royal Shakespeare Company | Stratford-upon- Avon, UK | 1986 | 450 |
| | Traverse | Generic | | | |
| | Transformabl e | Cerritos Center for Preforming Arts | Cerritos, USA | 1993 | 900 - 1950 |
| | | Milton Keynes Theatre | Milton Keynes, UK | 1999 | 800 - 1040 |
| | | Studio space at Copenhagen Opera House | Copenhagen, Denmark | 2005 | 1 468 |
| | Adaptable reuse | The Roundhouse | London, UK | 1846 (2006) | 1 800 |
| | | Théâtre des Bouffes du Nord | Paris, France | 1876 (2005) | 530 |
| | | King's Cross Almeida | London, UK | (2001) | 550 |
| Concert hall | Shoebox | The Harmony Hall | Fukui, Japan | 1997 | 1 456 |
| | | Fukushima Concert Hall | Fukushima, Japan | 1984 | 1 002 |
| | | Ishikawa Concert Hall | Ishikawa, Japan | 2001 | 1 560 |
| | | Kyoto Concert Hall | Kyoto, Japan | 1995 | 1 833 |
| | Vineyard | Elbphilharmonie Hamburg, Grosser saal | Hamburg, Germany | 2017 | 2 100 |
| | | Danish Radio Concert Hall | Copenhagen, Denmark | 2009 | 1 800 |
| | | Shenzen Concert Hall | Shenzen, China | 2007 | 1 576 |
| | | Muza Kawazaki Symphony Hall | Tokyo, Japan | 2004 | 1 997 |
| | Recital | Taisetsu Crystal Hall | Asahikawa City, Japan | 1993 | 600 |
| | | Casals Hall | Tokyo, Japan | 1987 | 511 |
| | | Kioi Hall | Tokyo, Japan | 1995 | 800 |
| | | Nara Centennial Hall | Nara, Japan | 1999 | 446 |
| | Music theatre | Generic | | | |

| | | | | | |
|---|---|---|---|---|---|
| Parliament | Opposition | United Kingdom | London, UK | 1876 | 650 |
| | | India | Chandigarh, India | 1964 | 108 |
| | Amphiteatre | France | Paris, France | 1728 | 577 |
| | | Sweden | Stockholm, Sweeden | 1905 | 349 |
| | | Germany | Berlin, Germany | 1894 (1999) | 709 |
| | | Netherlands | 1234 (1992) | 1999 | 150 |
| | Horseshoe | Bangladesh | Dhaka, Bangladesh | 1982 | 350 |
| | | South Africa | Cape Town, South Africa | 1884 | 490 |
| | | Italy | Rome, Italy | 1696 | 630 |
| | | European Union | Brussels, Belgium | 1995 | 705 |
| | Circle | Nordrhein-Westfalen | Düsseldorf, Germany | 1988 | 199 |
| | | European Union | Strasbourg, France | 1999 | 705 |
| | Block | Botswana | Gaborone, Botswana | 1965 | 61 |
| | | Brazil | Brasilia, Brazil | 1960 | 594 |
| | | Russia | Moscow, Russia | 1930s (1994) | 450 |
| | | United Nations | Geneva, Switzerland | 1938 | 2 000 |
| Sacred | Church, axial | Resurrection of Mary | Riola, Italy | 1978 | 240 |
| | | St Florian | Aigen im Ennstal | 1992 | 120 |
| | | Enghoj | Randers, Denmark | 1994 | 170 |
| | | Dunaujvaros | Dunaujvaros, Hungary | 1996 | 300 |
| | Church, centralised | St Maria Magdalena | Freiburg, Germany | 2004 | 650 |
| | | Glaubten Reformed Church | Zurich, Switzerland | 1972 | 450 |
| | | Our Lady of the Pentecost | Paris, France | 2001 | 300 |
| | | St Francis | Steyr, Austria | 2001 | 150 |
| | Church, large span | Korean Presbyterian Church | New York, USA | 1999 | 2 000 |
| | | Cathedral of Our Lady of the Angels | Los Angeles, USA | 2002 | 1 900 |
| | | Padre Pio Pilgrimage | San Giovanni, Italy | 2004 | 6 500 |
| | | Cathedral of Créteil Extension | Paris, France | 1979 (2015) | 2 000 |
| | Mosque | Mosque of Jondishapour University | Ahvas, Iran | 1975 | 180 |
| | | Dar Al Islam | Abiquiu, USA | 1981 | 80 |
| | | Al Furusia | Doha, Qatar | 1984 | 200 |
| | | Islamic Cultural Center | New York, USA | 1991 | 800 |
| | Synagogue | Gates of the Groves | New York, USA | 1989 | 250 |
| | | Cymbalista Synagogue | Tel Aviv, Israel | 1998 | 84 |
| | | Jewish Community Centre | Duisburg, Germany | 1999 | 150 |
| | | Dresden Synagogue | Dresden, Germany | 2001 | 236 |

| | | | | | |
|---|---|---|---|---|---|
| | Buddhist temple | Jetavana Buddhist Temple | Chuncheon-si, South Korea | 2018 | 30 |
| | | Kuhon-ji | Sasebo, Japan | 2003 | 50 |
| | | Bow-Yun Temple | Taiwan | 2001 | 30 |
| | | Ihaidō for Kōrin-ji | Matsuyama, Japan | 2017 | 30 |
| | Hindu temple | Tejorling Radiance Temple | Pune, India | 2018 | 5 |
| | | Temple in Stone and Light | Barmer, India | 2018 | 100 |
| | | Maruti Mandir | Nashik, India | 2018 | 50 |
| | | Shiv temple | Suppa, India | 2010 | 5 |
| Learning spaces | Large group discussion | Barcelona Botanical Institute | Barcelona, Spain | 2003 | |
| | | Engineering Research Center | Cincinnati, USA | 1995 | |
| | | Max Planck Institute for Molecular Cell Biology | Dresden, Germany | 2000 | |
| | | Faculty of Mechanical Engineering | Munich, Germany | 1997 | |
| | Small group learning | Barcelona Botanical Institute | Barcelona, Spain | 2003 | |
| | | Naito Chemistry Building and Bauer Laboratory | Cambridge, USA | 2002 | |
| | | Max Planck Institute for Molecular Cell Biology | Dresden, Germany | 2000 | |
| | | Exemplar School | London, UK | 2003 | |
| | Team teacher presentation | James H. Clark Center | Stanford, USA | 1923 | |
| | | Sciences Institute | Algiers, Algeria | 2005 | |
| | | Donald Danforth Plant Science Center | St. Louis, USA | 2001 | |
| | | Burr Elementary School | Fairfax, USA | 2006 | |
| | Collaborative learning | Donald Danforth Plant Science Center | St. Louis, USA | 2001 | |
| | | Gifu Research Laboratories of Amano Enzyme Inc. | Gifu, Japan | 1999 | |
| | | Faculty of Mechanical Engineering | Munich, Germany | 1997 | |
| | | Hachoresh School | Zichron, Israel | 1988 | |
| | One-on-one instruction | Naito Chemistry Building and Bauer | Cambridge, USA | 2002 | |
| | | Research and Laboratory | Hamburg, Germany | 2004 | |
| | | Burr Elementary School | Fairfax, USA | 2006 | |
| | | Ale Upper | Nodinge, Sweden | 1995 | |
| | Individual | Millennium Library | Norwich, UK | 2001 | |
| | | IKMZ | Cottbus, Germany | 2004 | |
| | | Biblioteca Pública | Ceuta, Spain | 2013 | |
| | | Burton Barr Central Library | Phoenix, Arizona | 1995 | |

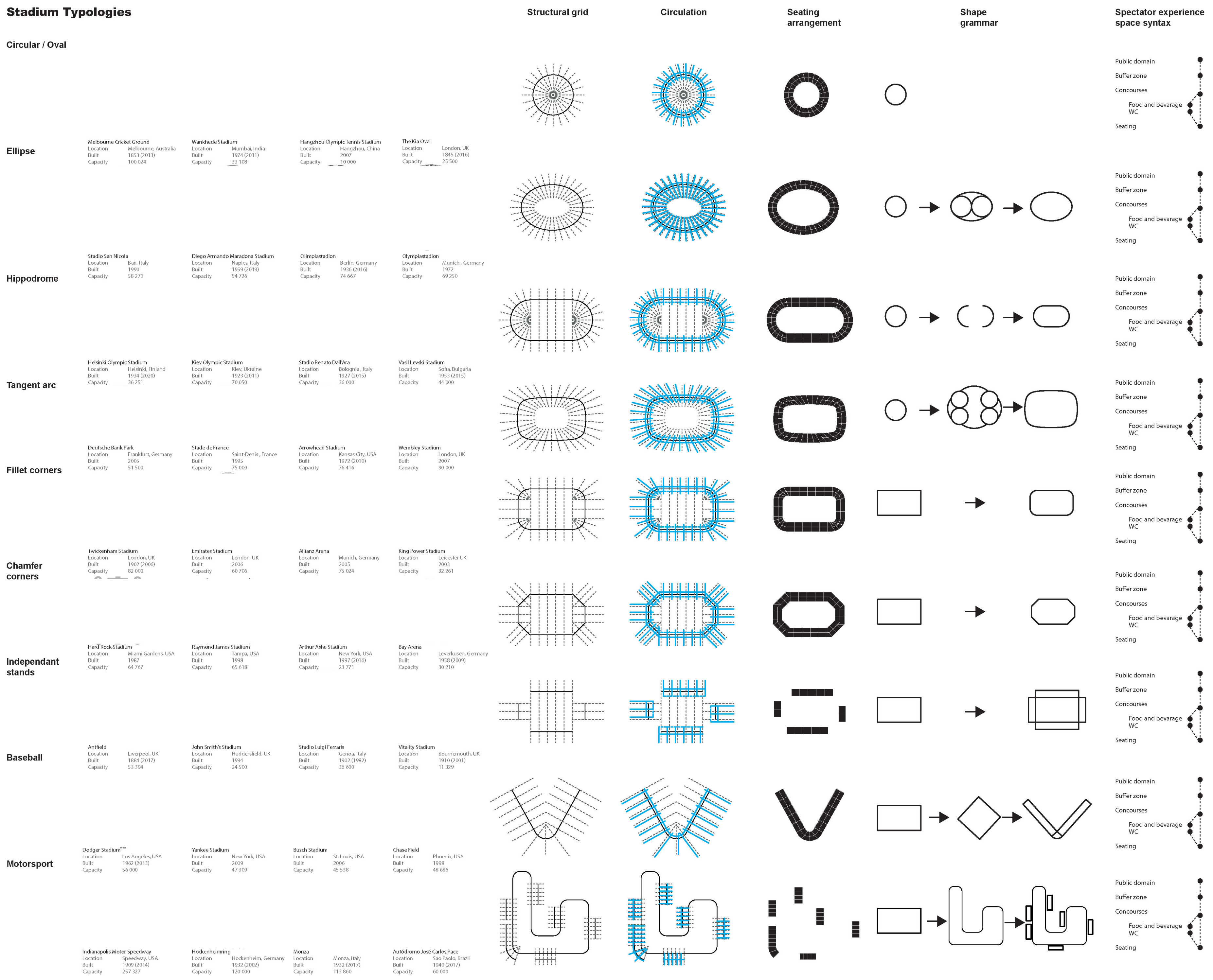



*Figure 2.9. Stadium types*

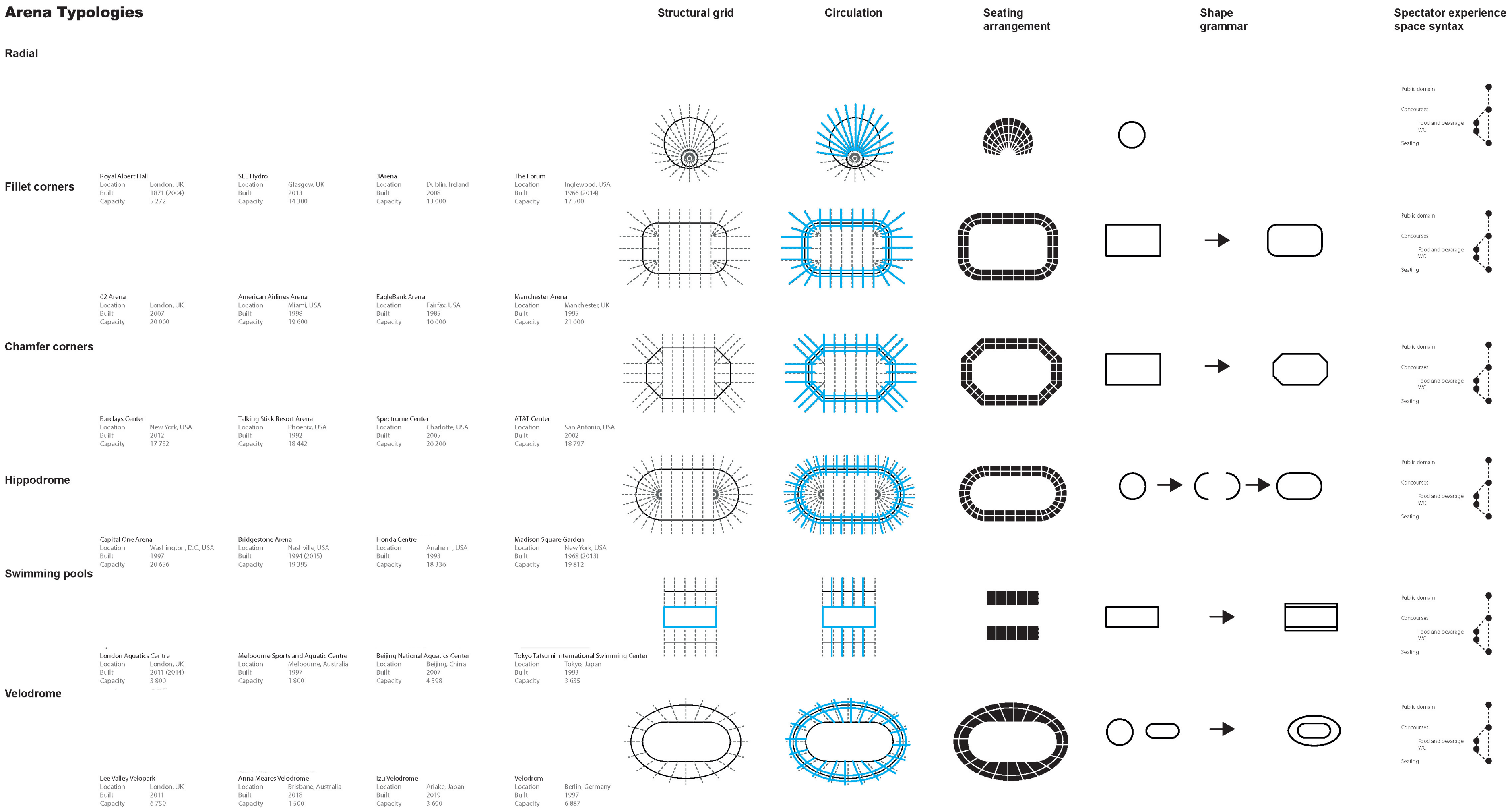



*Figure 2.10. Arena types*

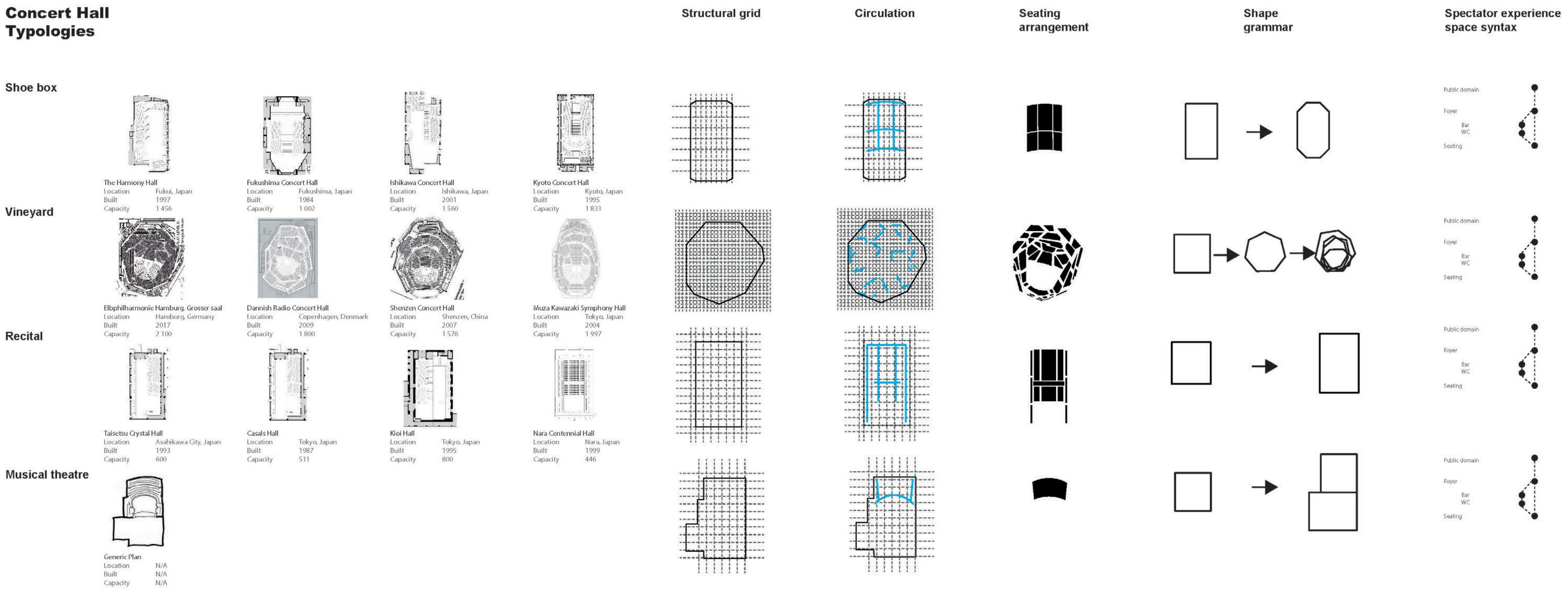



*Figure 2.11. Concert hall types*

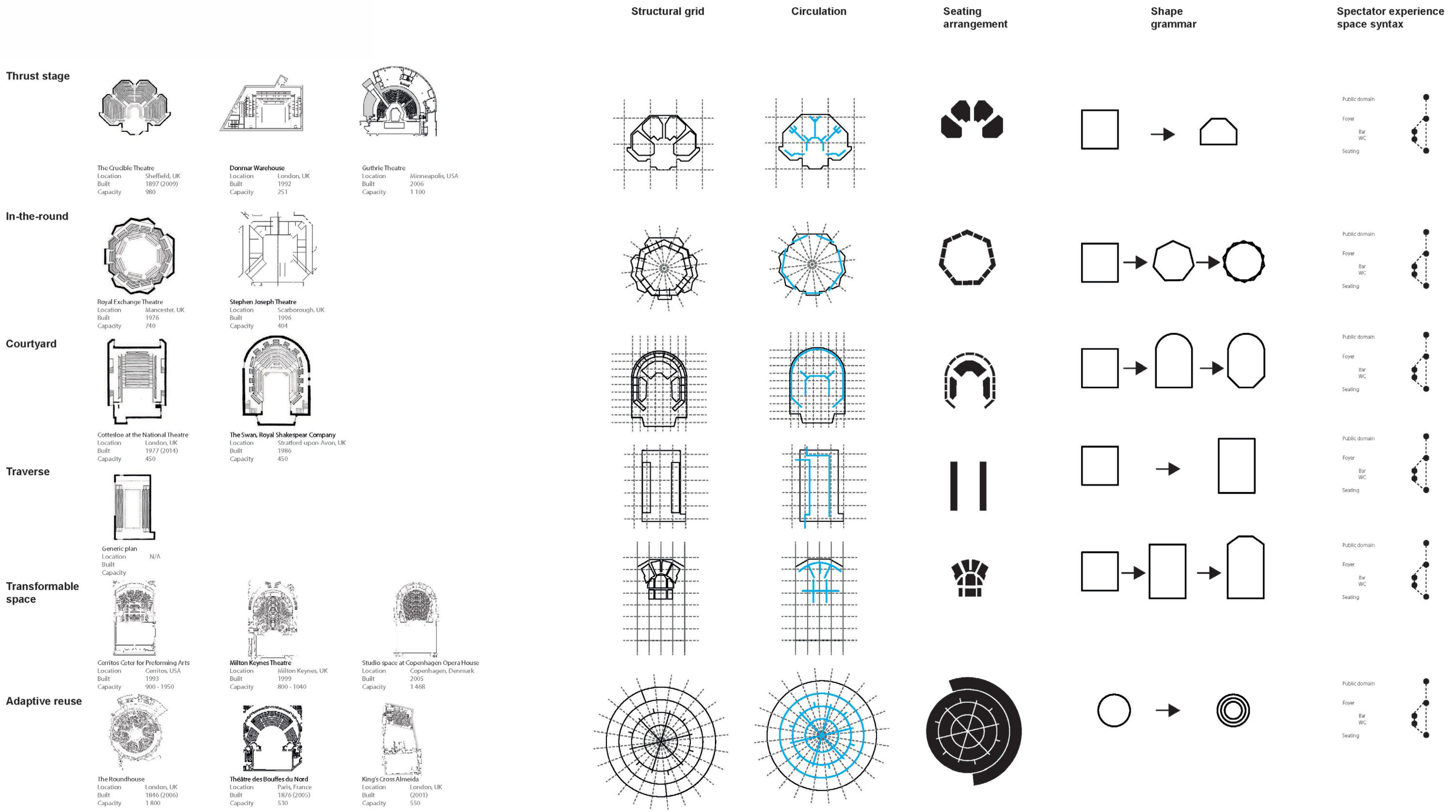



*Figure 2.12. Theatre types*

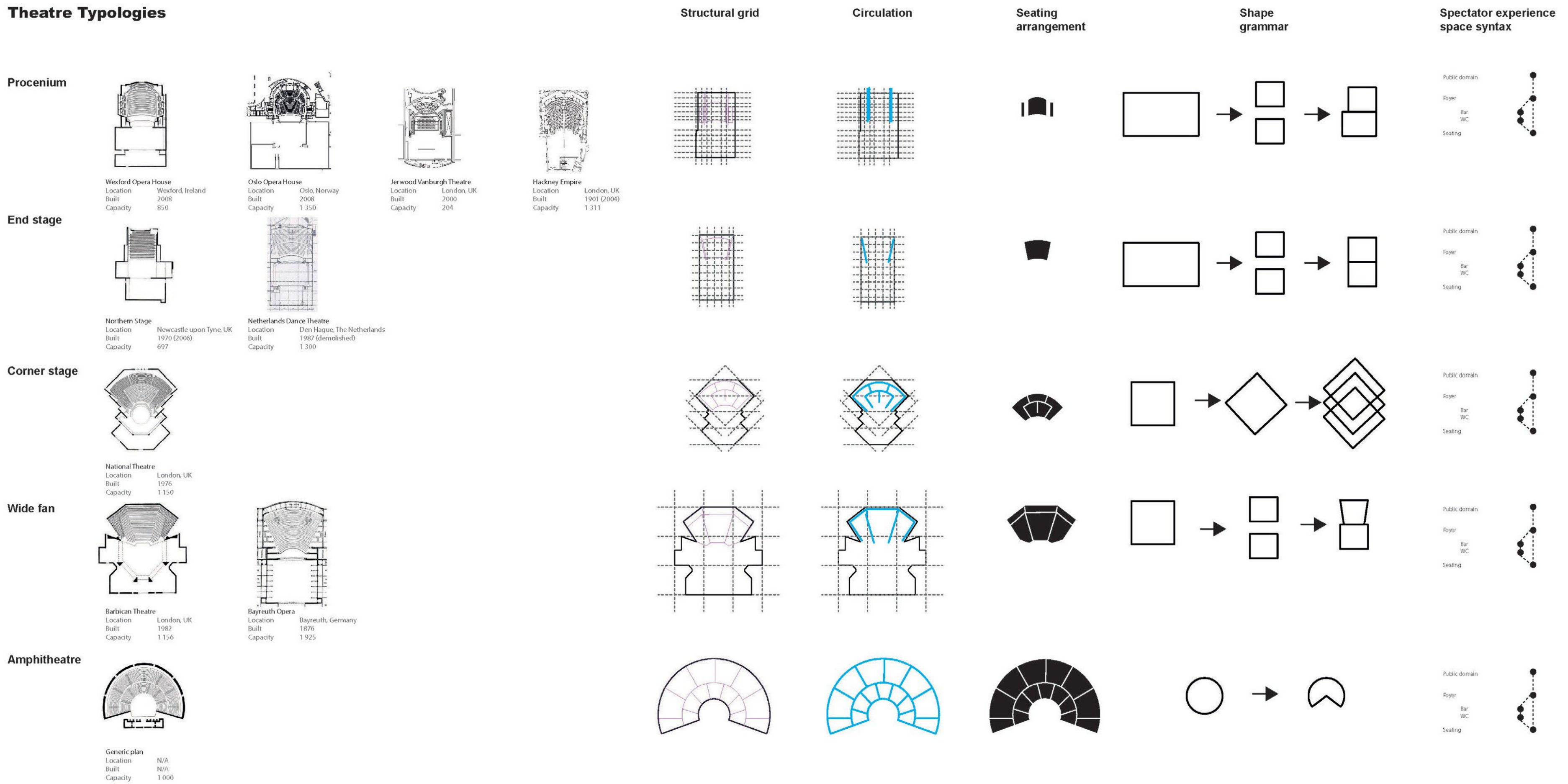



*Figure 2.13. Theatre types*

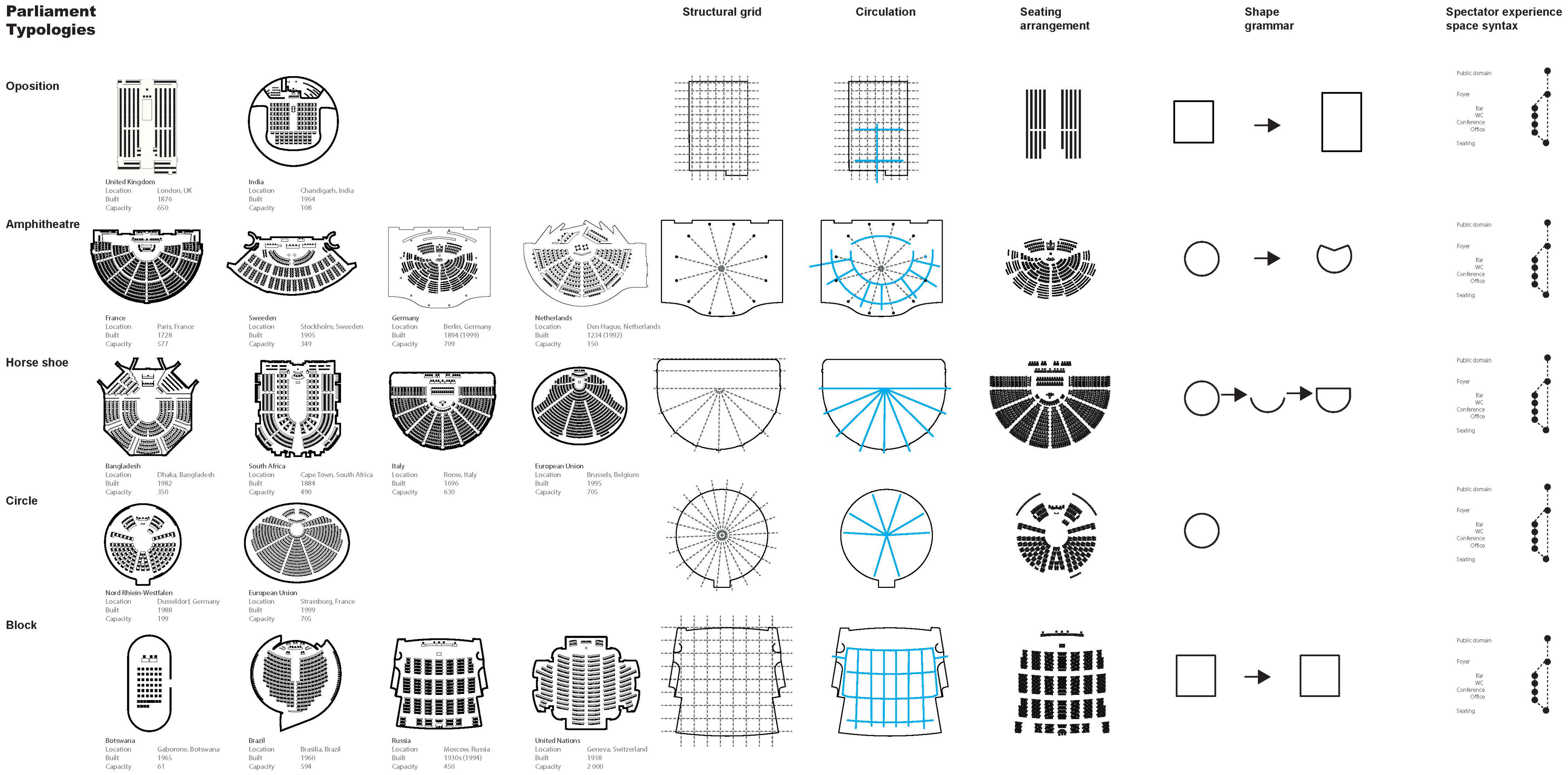



*Figure 2.14. Parliament types*

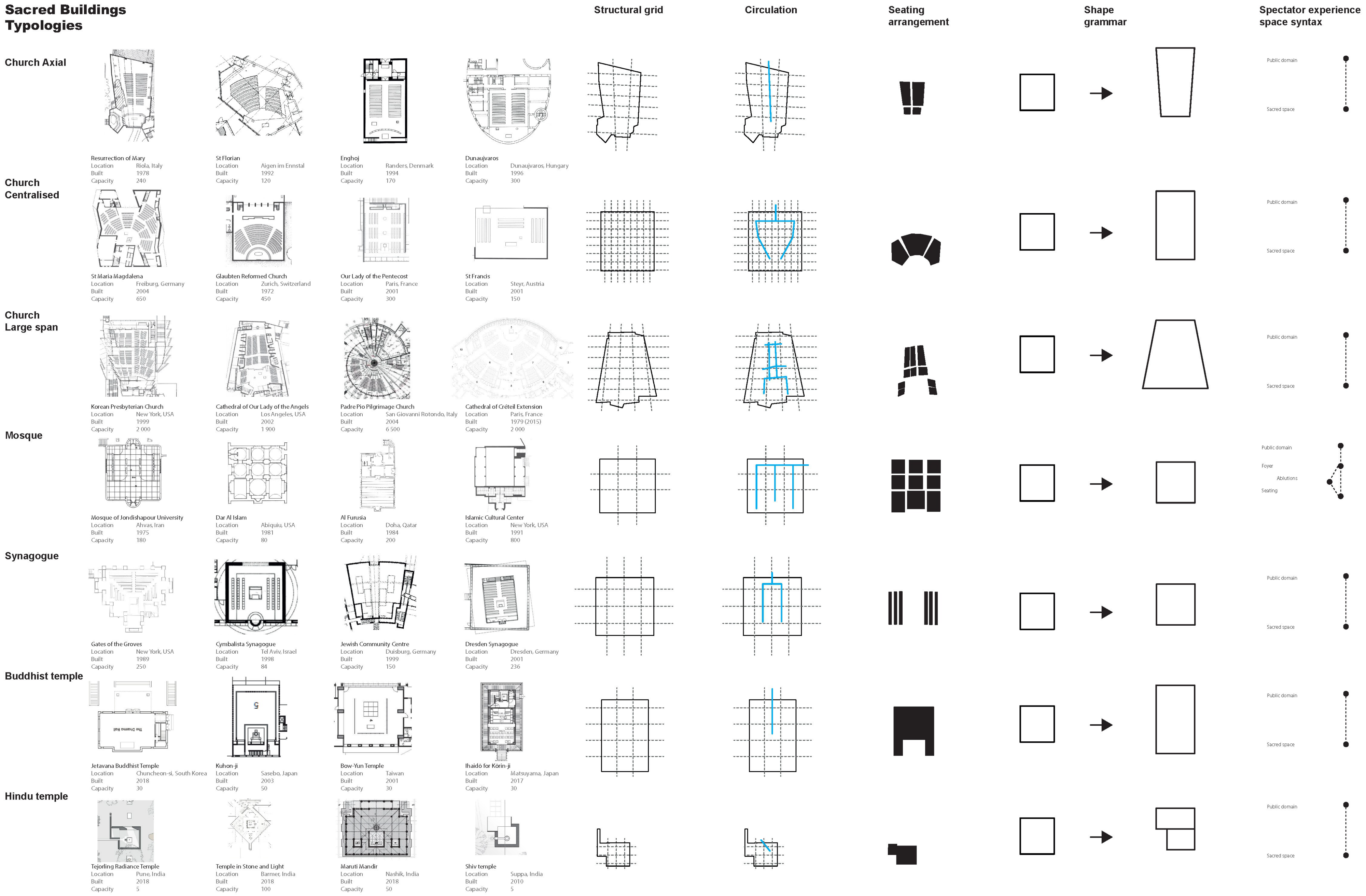



*Figure 2.15. Sacred buildings types*

## Learning spaces Typologies

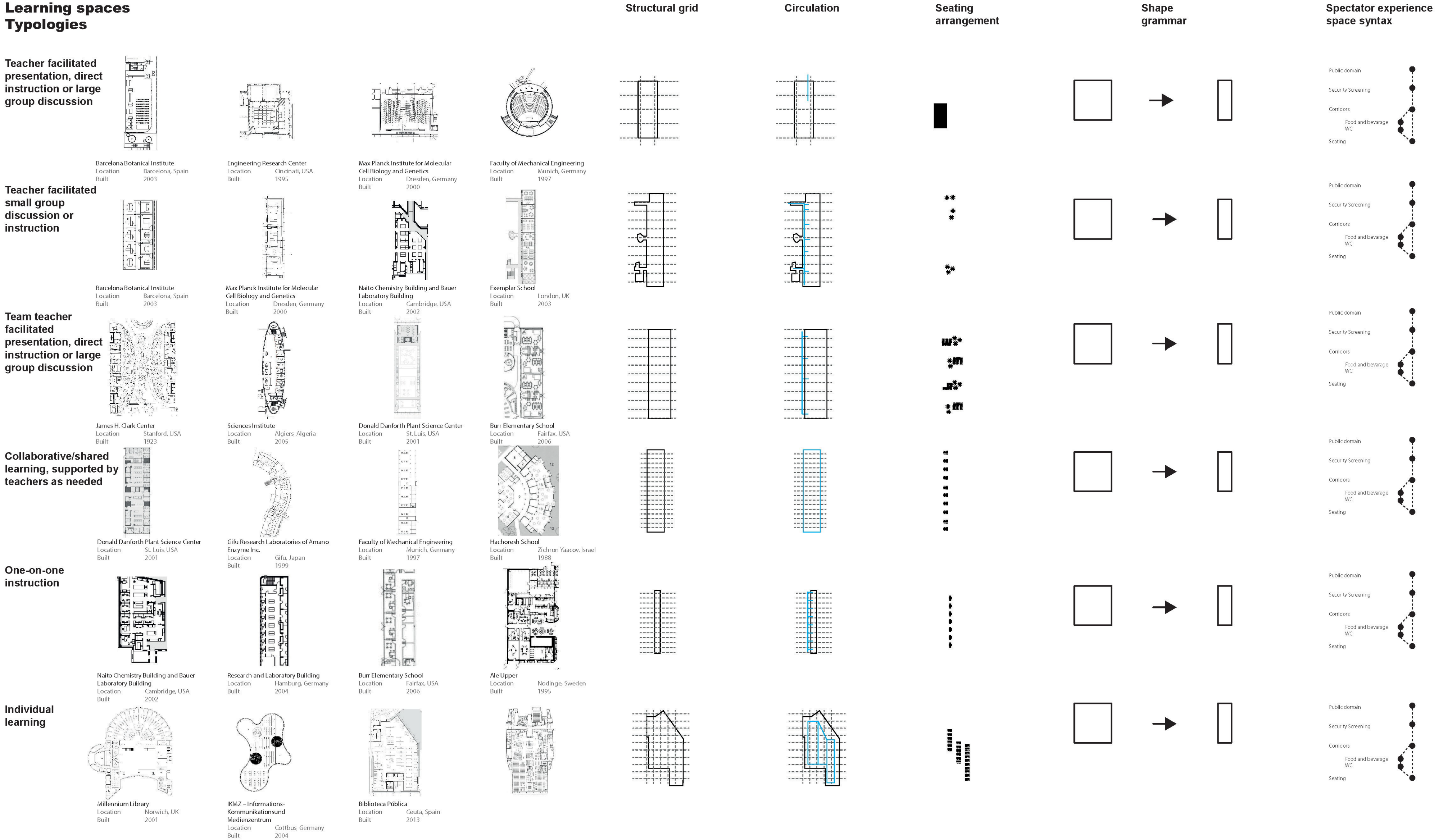



*Figure 2.16. Learning spaces types*

## 2.4 Type definitions through manual classification

Following the identification of the basic organisational and structural properties of the types, the next step is to define a set of analytical dimensions and map the way different types relate to each other through a manual typological study. The analytical dimensions are based on the literature review and the focus of study of circulation, layout, and quality of sightlines. Each of those themes is described and analysed through shared quantifiable properties and elements that were identified in the previous step. Each type is summarised as a simplified layout type drawing, and the stage is highlighted in the colour of their overarching type. The classification is based on data from the analysis phase and measurements from the available plans of the case studies. The ellipse and circular stadium morphologies have been studied together, as they share many properties with the tangent arc subtype.

Typological analysis allows for selective comparison of design features that can later serve as the basis for alternative grouping. The groupings are based on circulation, seating arrangement, viewing angles, acoustics, and their social perspective in relation to the social practices, procession and ceremonial movement that takes place in them. These categories are also performance criteria that are linked to structural categories such as modularity, type of structure, and impact on circulation and layout design. The identification of patterns and regularities from this manual analysis are then summarised in a numerical dataset. Additional descriptive information that covers more than one research category was included in a fourth group in the numerical dataset – building data.

| *Table 2.2. Initial analytical categories* | |
|---|---|
| **Analytical category** | **Manual classification** |
| Circulation | Circulation/Structural organisation |
| | Distance to exit |
| | Continuity |
| Layout | Backstage |
| | Ceremonial movement |
| | Group / Individual experience |
| | Structural grid by function |
| | Permanence / temporality |
| | Sound directed towards audience |
| | Structural grid stage orientation |
| Sightlines | Seating continuity |
| | Capacity |
| | Seat spacing |
| | Row depth |
| | Viewing platform slope |
| | Stage location |
| | Stage area |
| | Structural grid type |

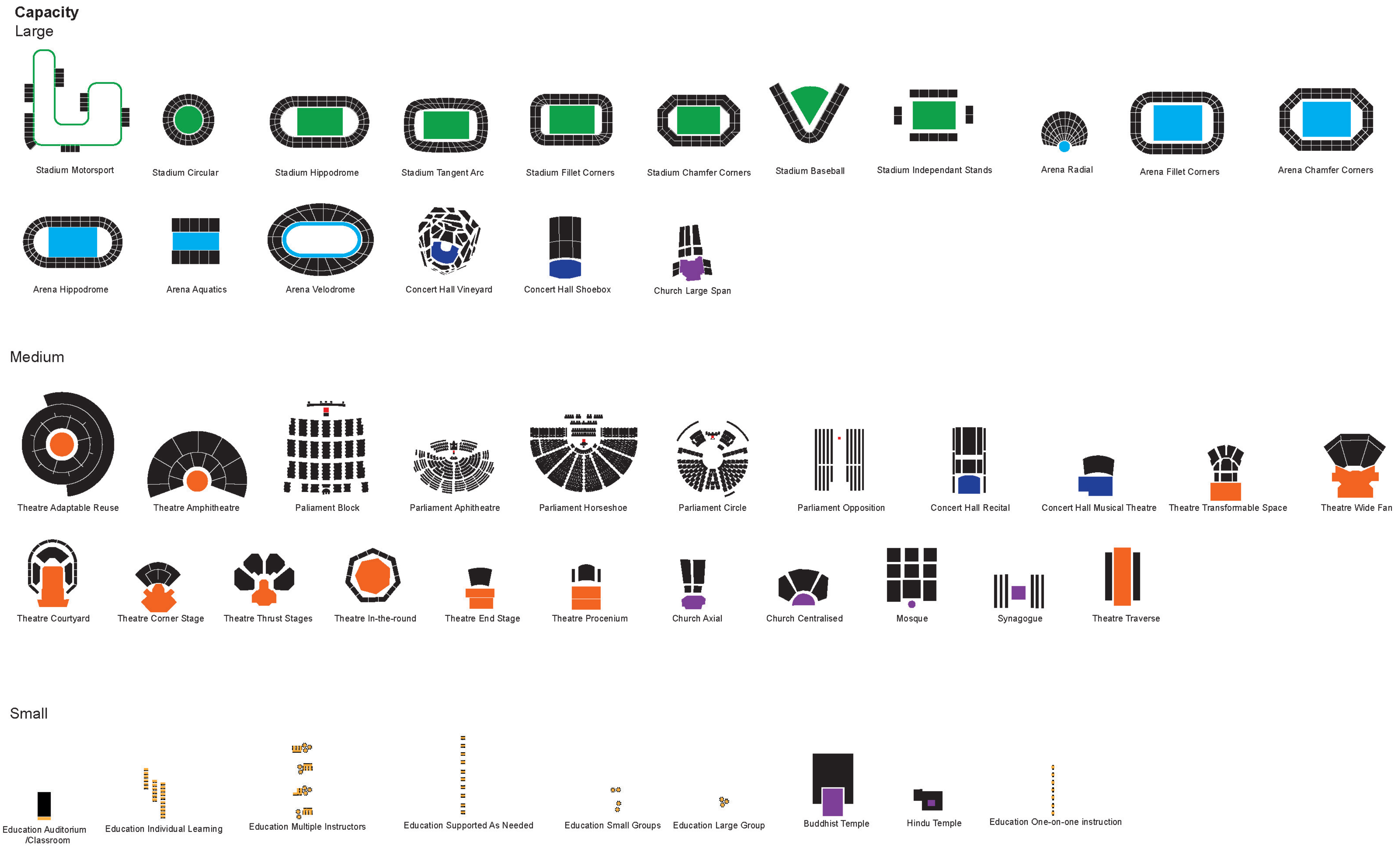



*Figure 2.17. Capacity – how many people can fit in the auditorium, which has implication in terms of every single architectural, structural, economic, experiential aspect*

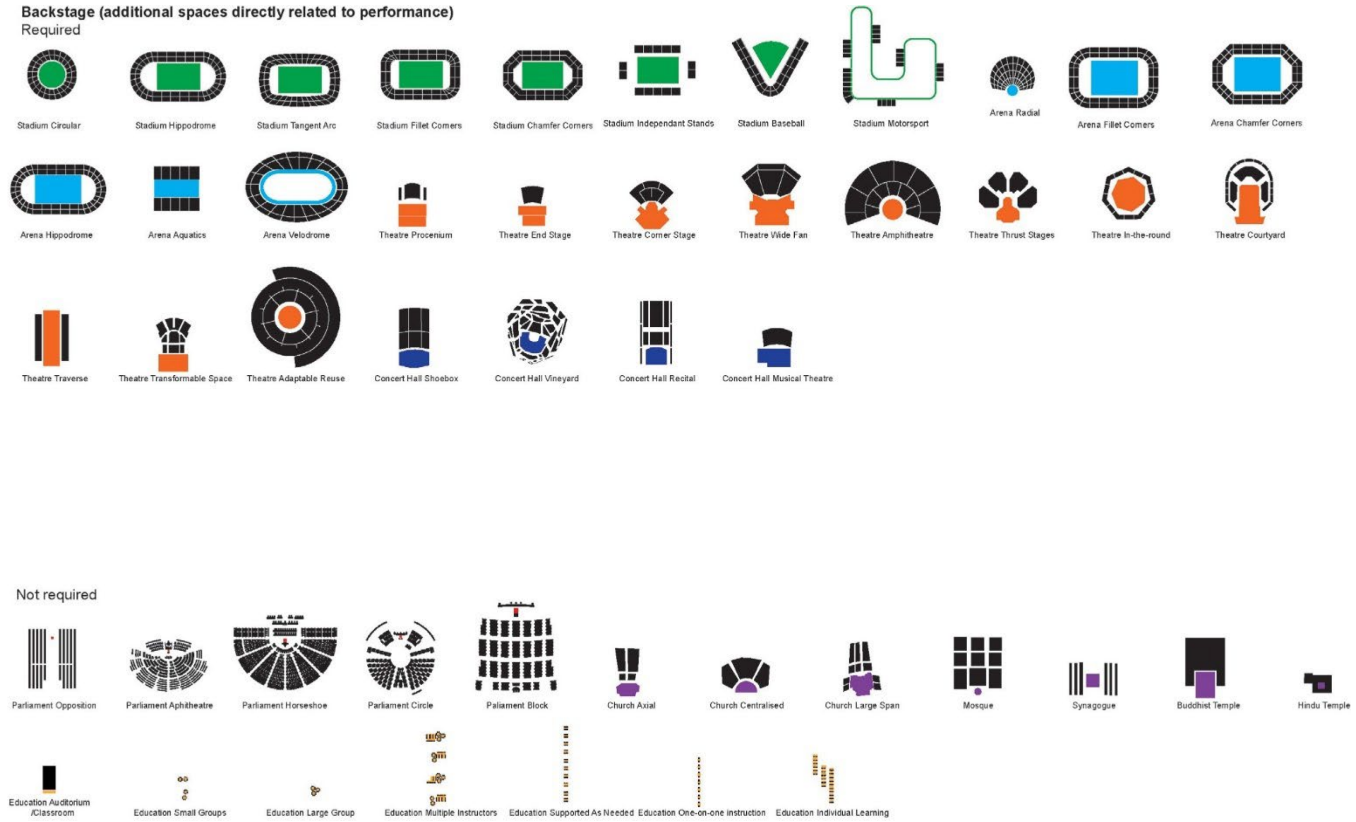



*Figure 2.18. Backstage – does the performance require additional infrastructure which results in a separate circulation routes for performers*

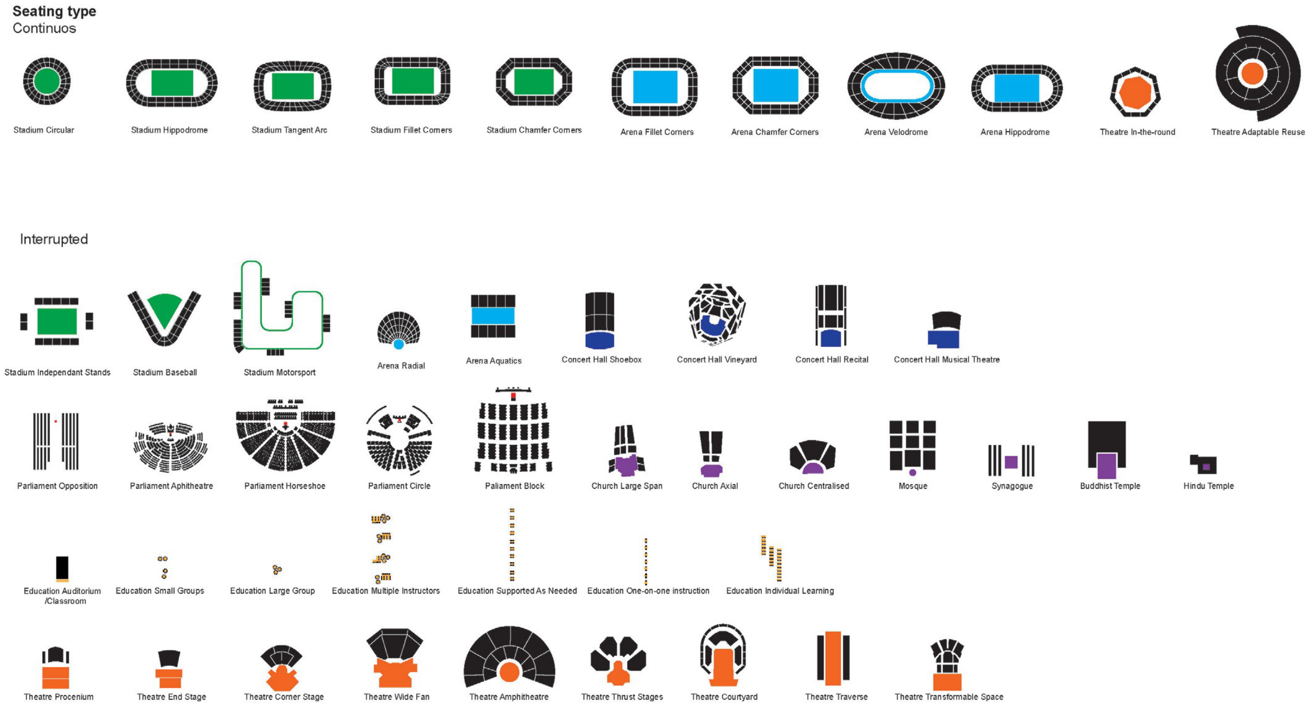



*Figure 2.19. Seating continuity - is the stage surrounded by seating*

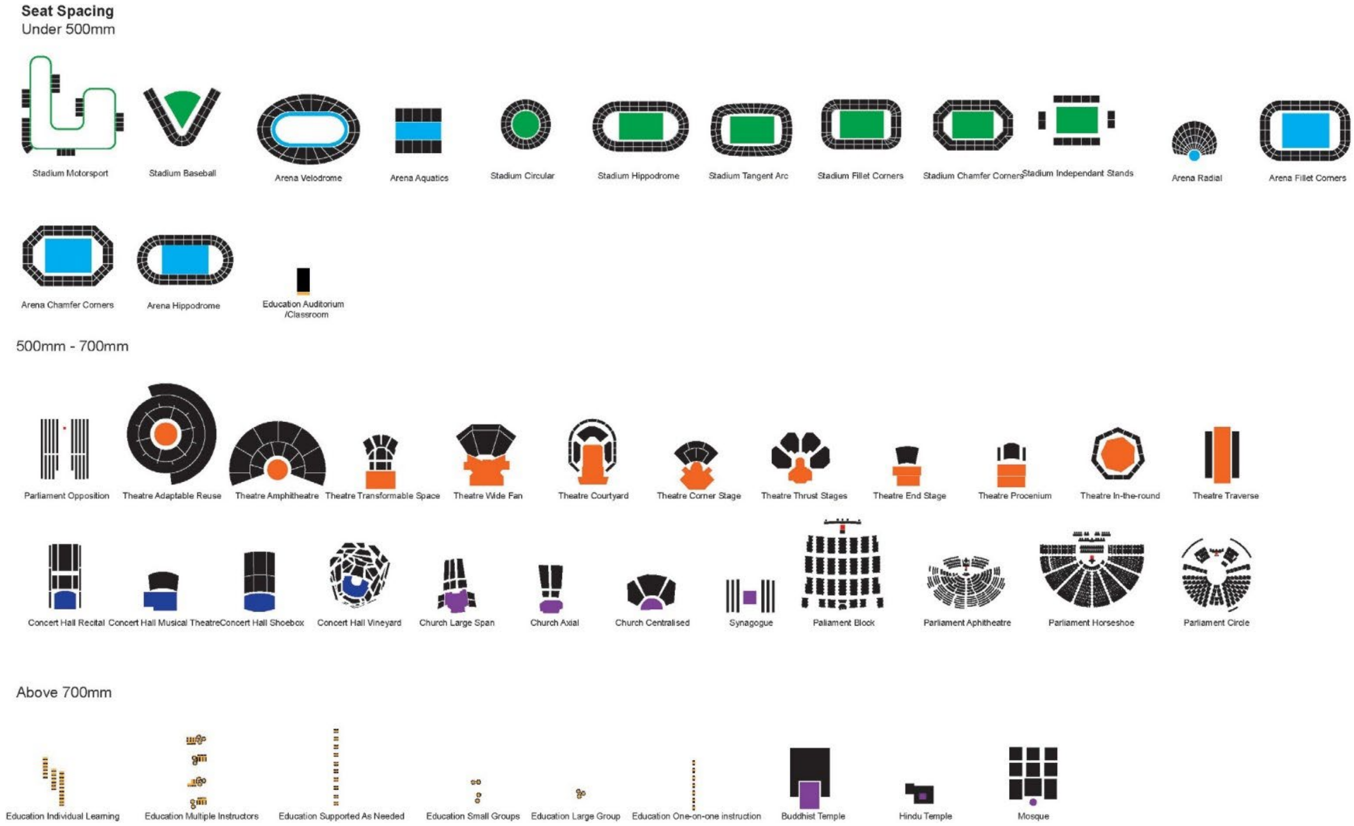



*Figure 2.20. Spacing between seats*

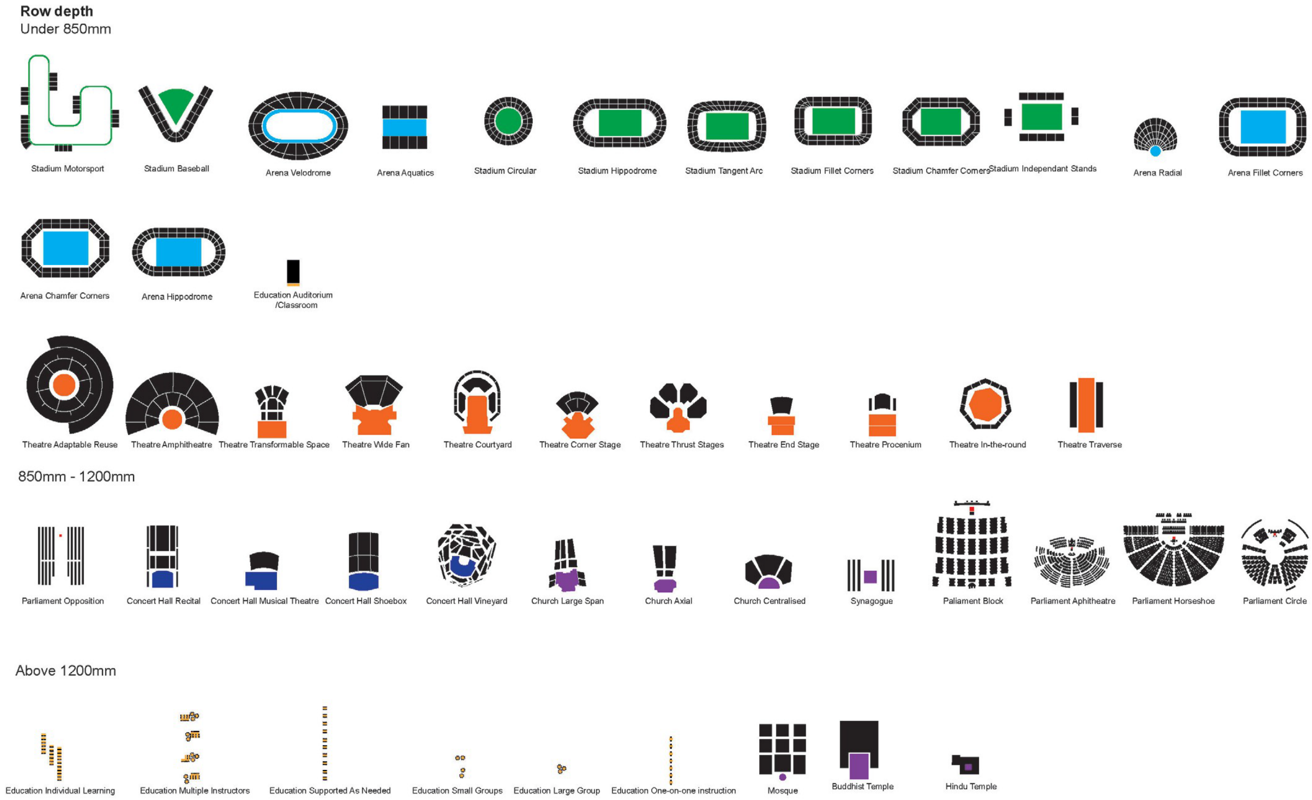



*Figure 2.21. Row depth – affects comfort, capacity and exit distances*

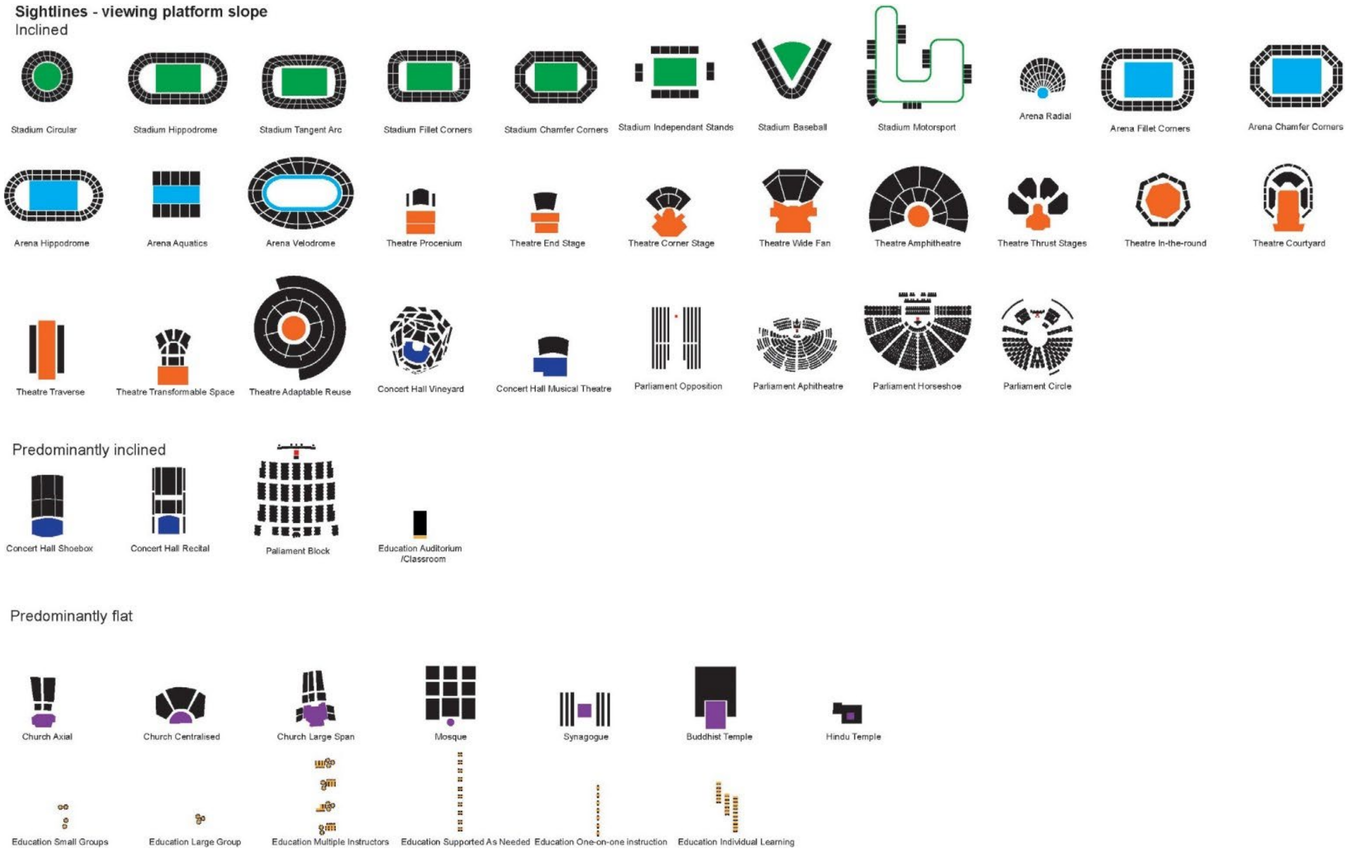



*Figure 2.22. Viewing platform inclination – whether the experience is primarily visual or audible, the larger the venue the steeper the seating*

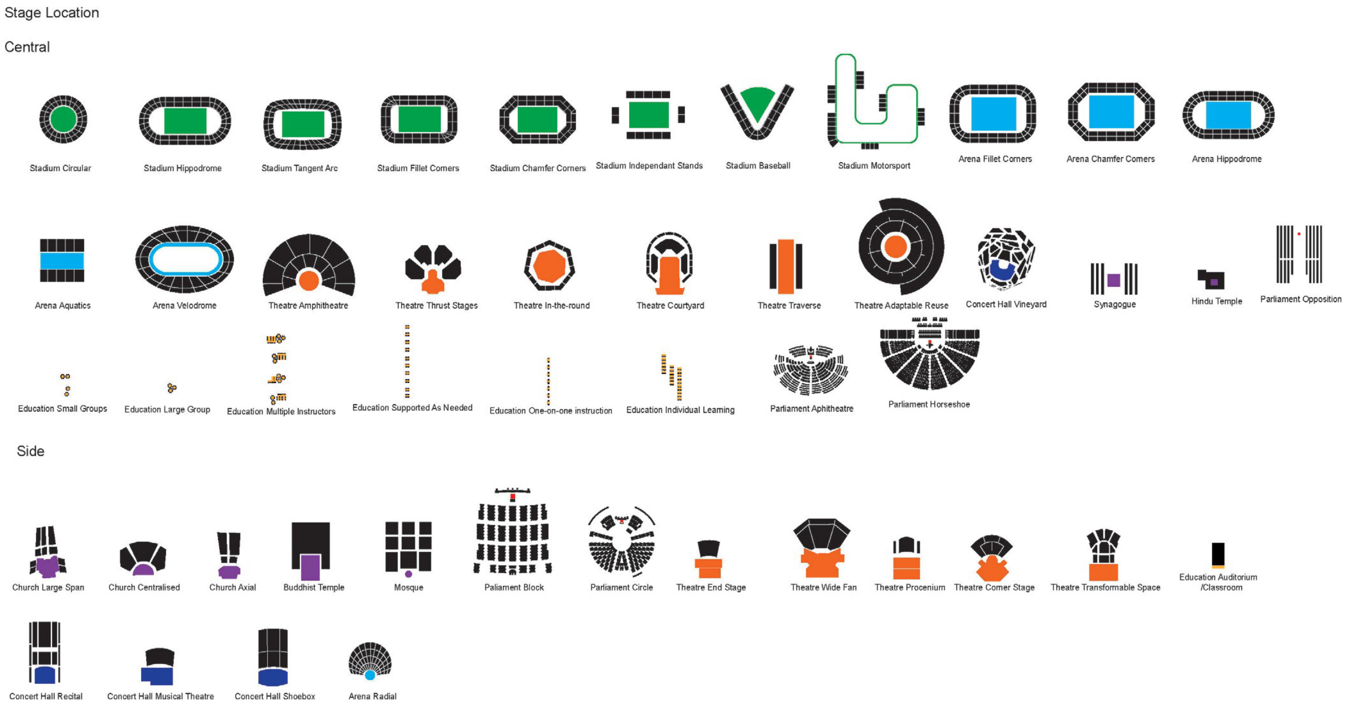



*Figure 2.23. Stage location –central or offset, affects circulation and seating arrangement*

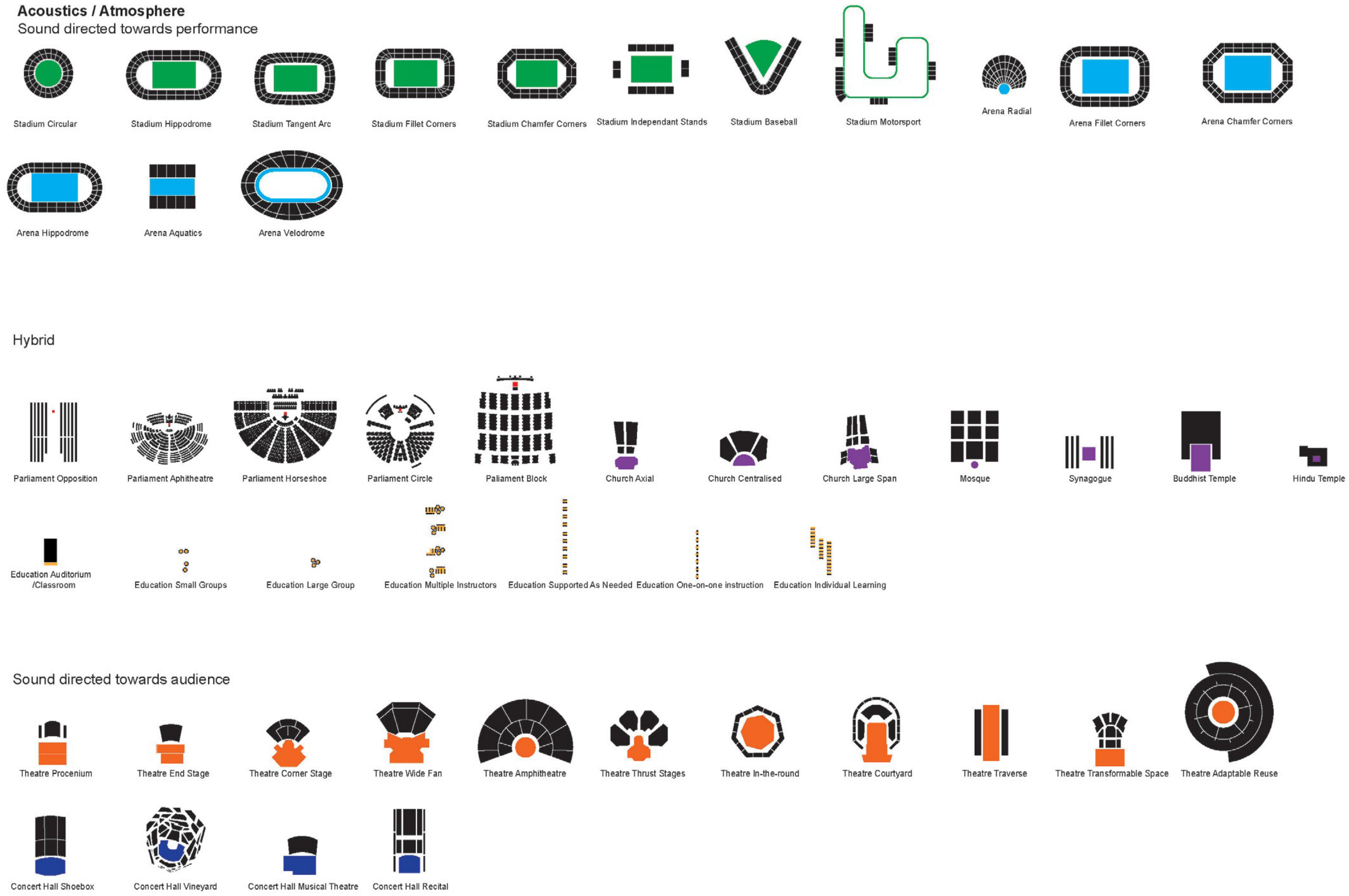



*Figure 2.24. Atmosphere –whether the audience creates the audible atmosphere or it is up to the performer to create it*

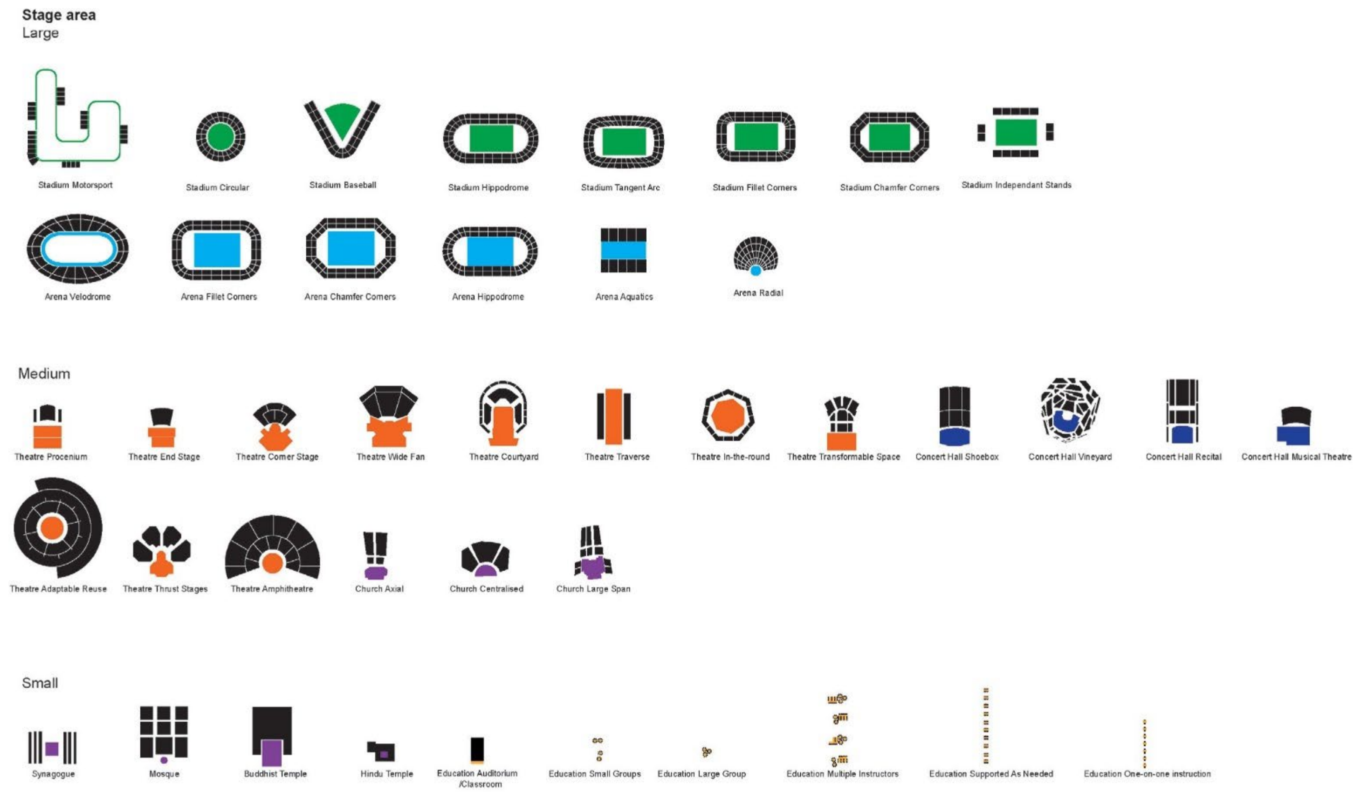



*Figure 2.25. Stage area - whether the circulation fits the structural grid  and whether the stage is enclosed*

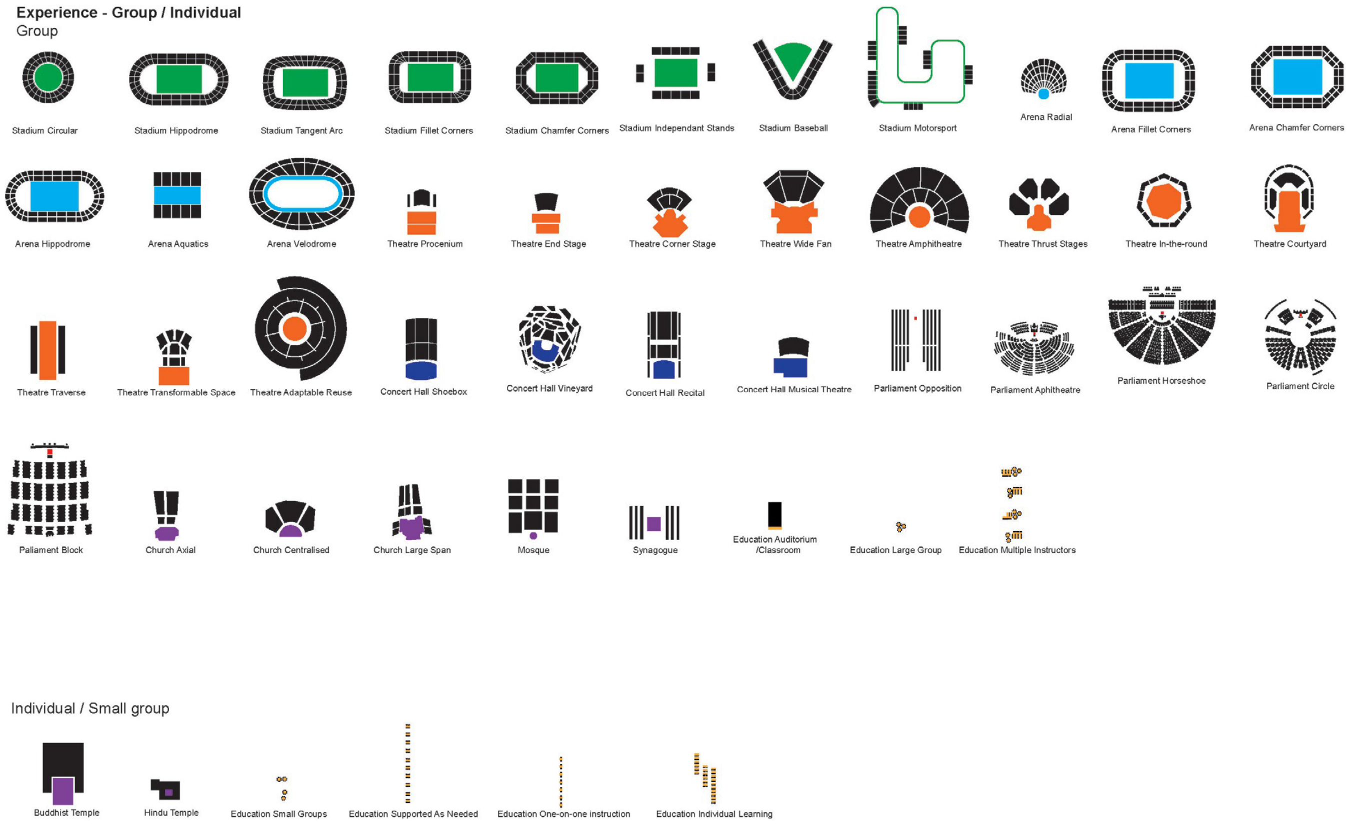



*Figure 2.26. Group / individual experience – highlights whether the spectator is part of a group, it is notable that there are some cases of a place for public assembly where the experience is individual*

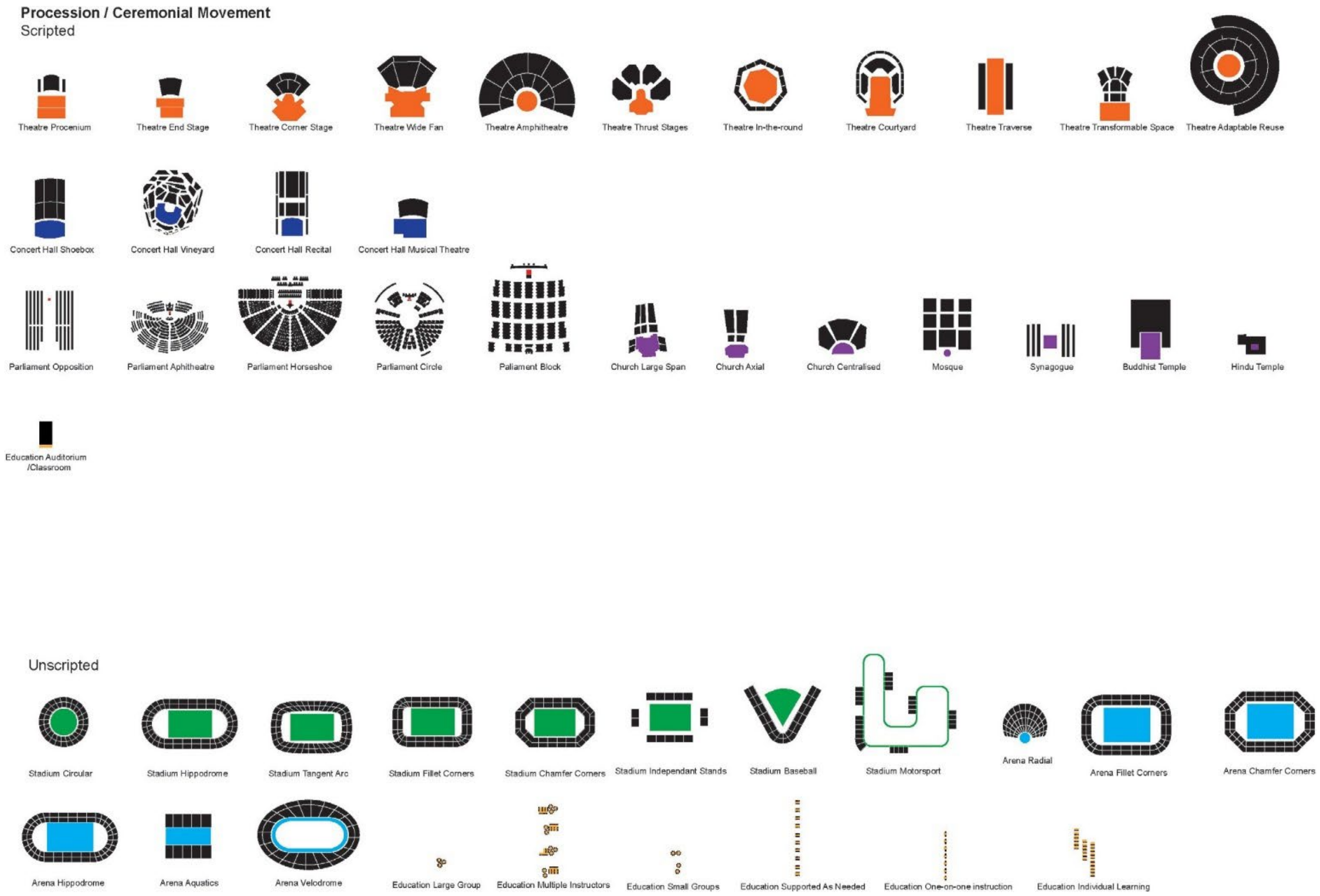



*Figure 2.27. By Procession / Ceremonial Movement - whether the performance relies on predeveloped script*

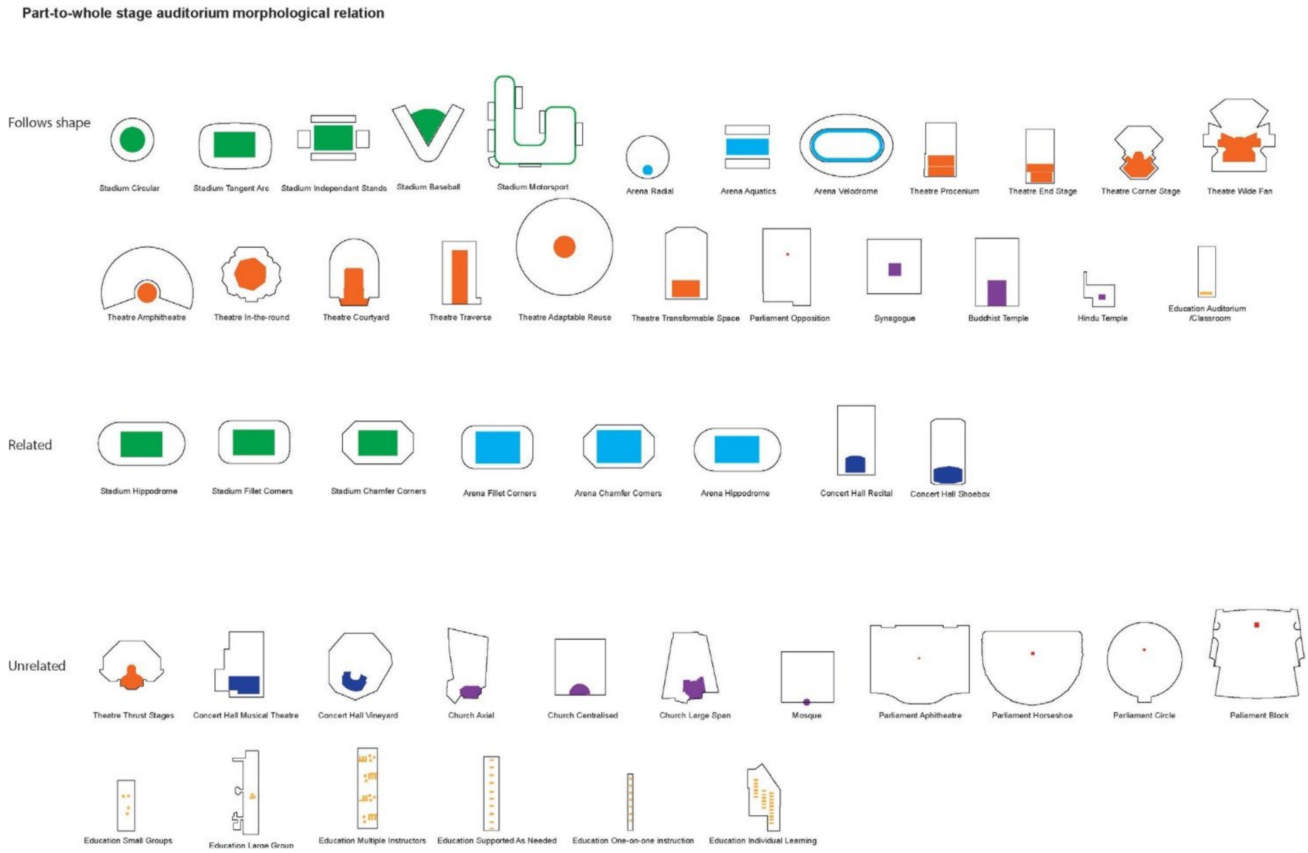



*Figure 2.28. Mapping highlighting types from different functional groups that share similarities in terms of organisation*

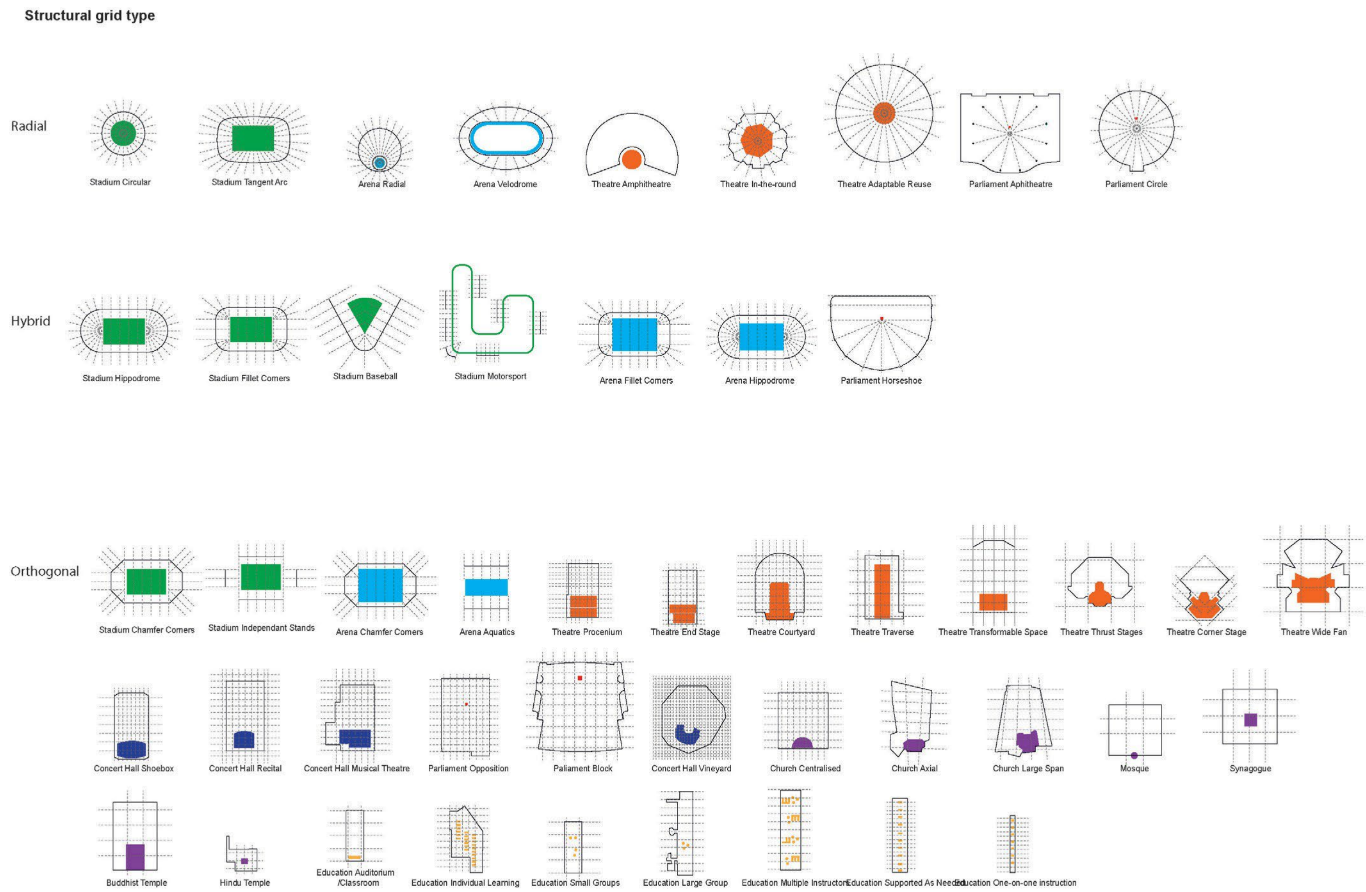



*Figure 2.29. Structural grid type – orthogonal, hybrid or radial*

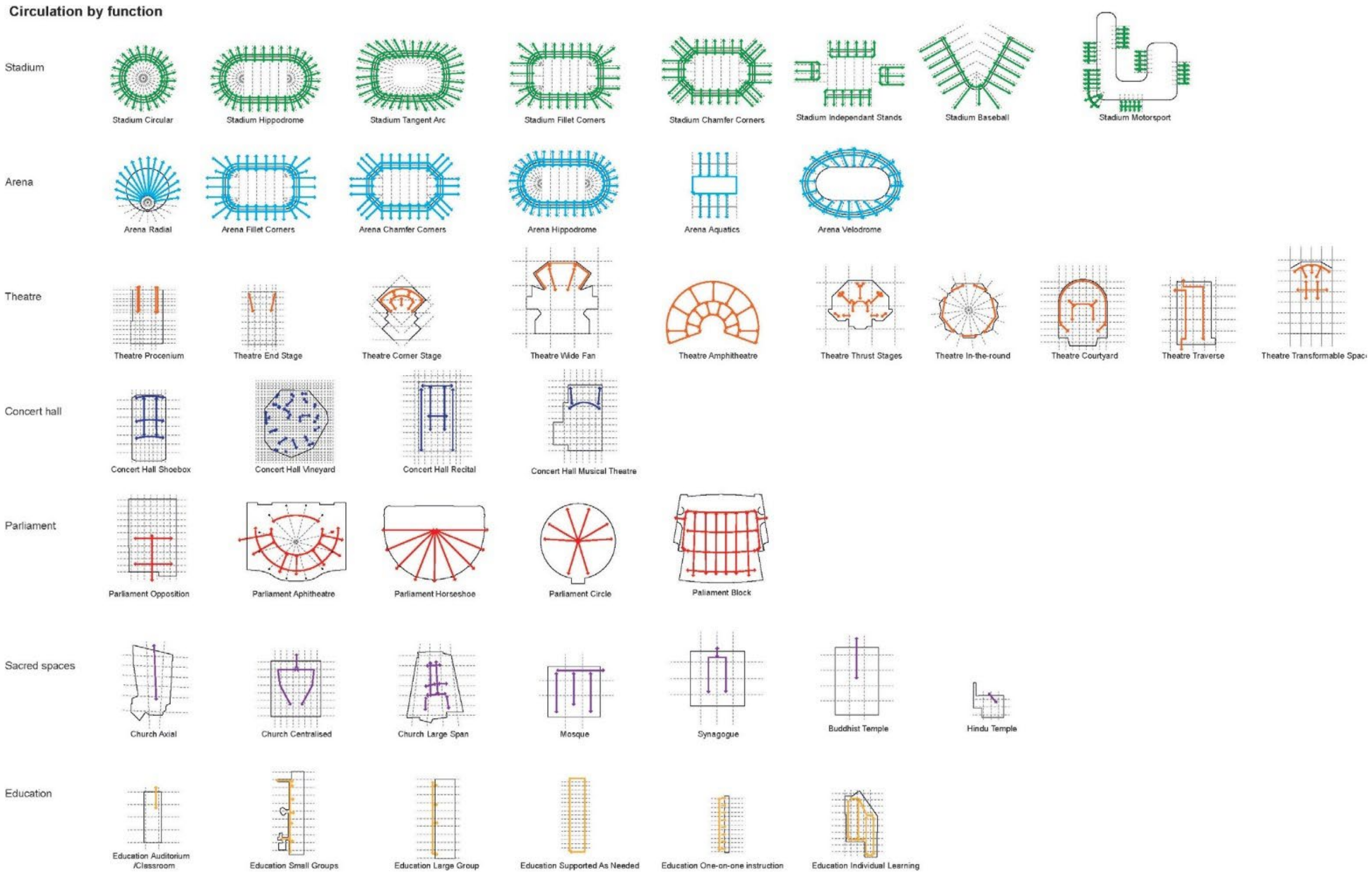



*Figure 2.30. Whether it is possible for the spectator to circumnavigate the stage*

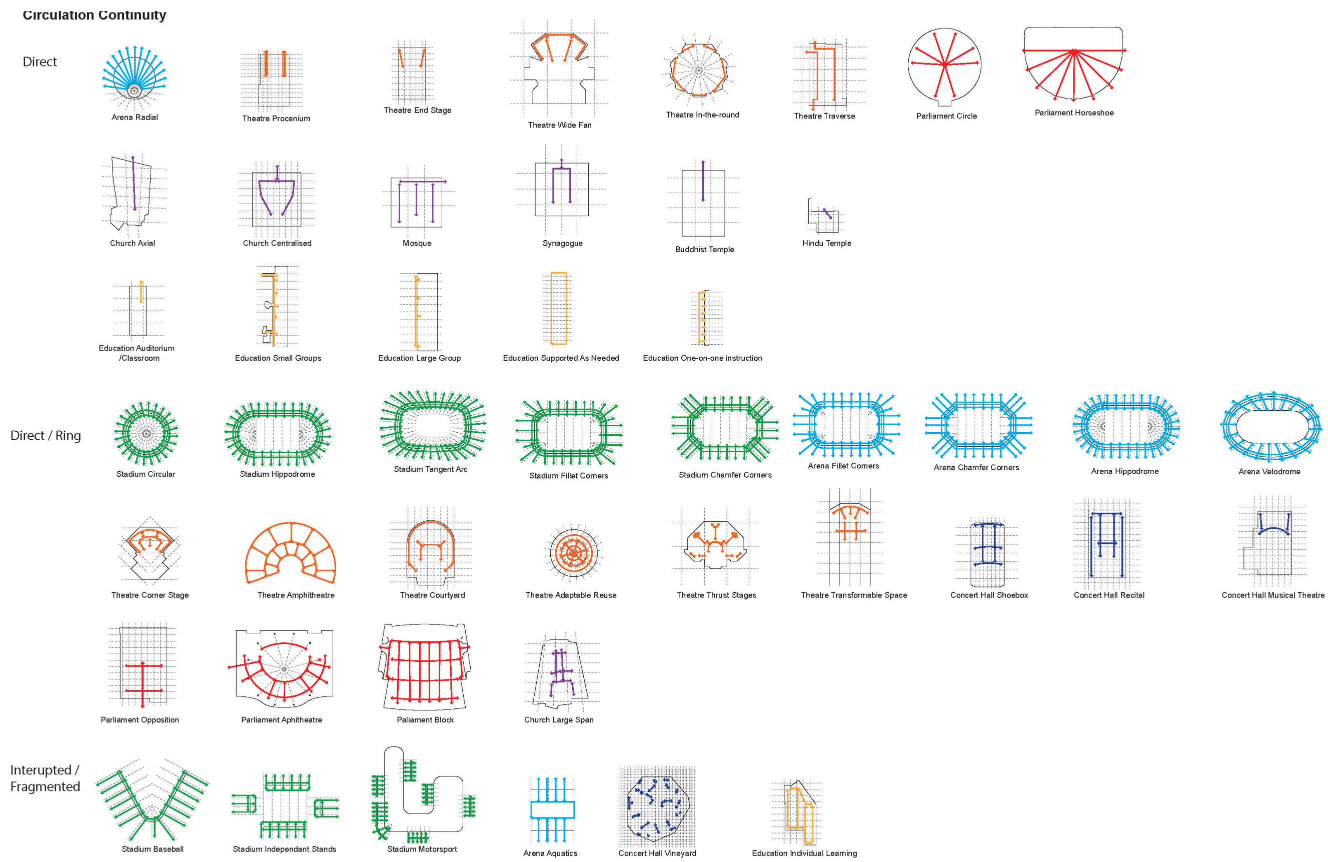



*Figure 2.31. Circulation continuity – groups the different categories based on whether the seating creates a full loop or not, which highlights whether the stage is surrounded by seating or not, which in turn highlights the direction of the ceremonial movement of the performers*

## 2.5 Defining typologies with machine learning

The construction of the numeric analytical machine learning model is aimed at producing a granular classification with a greater level of detail, establishing previously unattainable relationships, and evaluating the weight of the analytical categories to the overall classification. This dataset quantifies the various classifications from the manual typological analysis – in cases where classification is based on raw data (area, construction year, etc) the dataset includes the actual data; in the more complex cases (stage location, structural arrangement, processional movement, etc), where the value is a result from a number of parameters, the labelling is within the domain of 0 to 1.

### 2.5.1 Values for classification using numerical machine learning model

The data is sourced from the literature review and the analytical dimensions originate in the previous stage of the study. The selection of design driver categories for this phase of the analysis is based on the findings from the manual analysis. The features that produce the clearest classifications are taken forward and highlighted in green in the table below. Features that require spatial representation, such as part-to-part and part-to-whole analysis were omitted at this step but introduced in the following phases.

*Table 2.3. . Revised analytical categories following manual classification*

| Analytical category | Manual classification | Numerical machine learning model |
|---|---|---|
| Circulation | Circulation/Structure organisation | |
| | Distance to exit | Distance to exit |
| | Continuity | Continuity |
| Layout | Backstage | Backstage |
| | Ceremonial movement | Ceremonial movement |
| | Group / Individual experience | Group / Individual experience |
| | Structural grid by function | |
| | Permanence / temporality | Permanence / temporality |
| | Sound directed towards audience | Sound directed towards audience |
| | Structural grid stage orientation | Structural grid stage orientation |
| Sightlines | Seating continuity | Seating continuity |
| | Capacity | Capacity |
| | Seat spacing | Seat spacing |
| | Row depth | Row depth |
| | Viewing platform slope | Viewing platform slope |
| | Stage location | Stage location |

| | | |
|---|---|---|
| | Stage area* | |
| | Structural grid type | Structural grid type |
| Building data | | Completion year |
| | | Last refurbishment |
| | | Building footprint area |
| | | Auditorium area |
| | | Stage area |
| | | Auditorium capacity |
| | | Stage capacity |
| | | Roof |
| | | Cost |

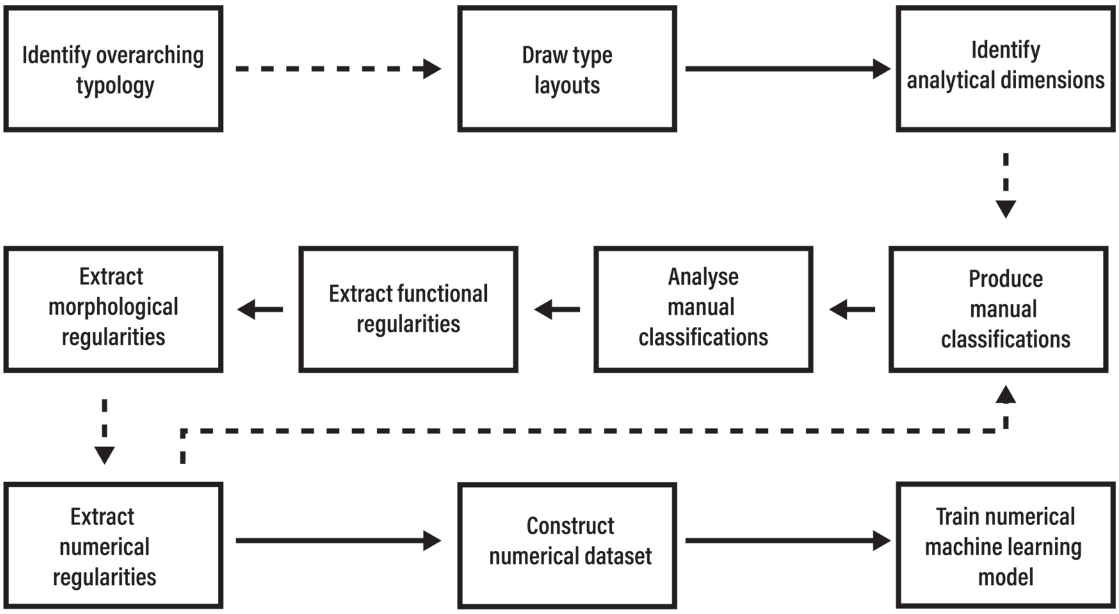



*Figure 2.32. Method for construction of numerical machine learning model for the classification of public assembly buildings*

## 2.5.2 Numerical classification

The aim of this phase of the research is to define groups, and therefore does not require identification of the best-performing case. As a result, the selected machine learning algorithm is the unsupervised k-means within Lunchbox in Grasshopper and Rhino 7. K-means clusters the subtypes based on an average mean value and the number of groups for subdivision. The classification is based on four groups, as in most of the cases there is a large main group, a smaller secondary group, and two small clusters with one or two elements. The extraction of regularities is based on the research themes and their subdivision into quantifiable features. The machine learning models are trained with a select number of inputs based on the research categories and combinations across categories. The findings in all the separate studies are clearly defined – based on their quantified properties, stadiums always form a separate group.

The Building data category affects the classification disproportionately – in all cases where this information was included, stadiums form three separate groups and all the other public assembly building types are grouped separately. To test whether this result was due to the differences in areas and capacity across cases, the research normalised the training inputs into the 0 to 1 range, but the classifications remained the same. The Sightlines and Circulation categories are not as influential as expected, but on the other hand confirmed the relationship between stadiums and arenas. This classification also highlighted the shared properties between stadiums and several subtypes of parliament buildings and theatres, with centrally organised layouts. This information was included in the chrono-morphological mapping of the development of public assembly buildings. The Layout data classification also highlights the difference between stadiums and arenas and the other case studies. This grouping also exposed the less obvious relationship between stadiums and educational spaces in terms of the performer/player-audience sound direction and ceremonial movement.

The advantages of the clustering approach in contrast to the manual classification are found in the ease of identification of the larger groups of analytical elements. This allows for comparative analysis and increase of the focus of the research towards a specific analytical feature. The utilisation of clustering also increases the speed of the analytical process and the identification of groups and similar performances across categories. In terms of the overall stadium design process, this approach allows for the identification of similar design solutions that could serve as basis for design revision.

**Dataset**

**CL** – Completion year **LR** - Last refurbishment **BF** – Building footprint in m$^2$
**AA** – Auditorium area **SA** – Stage area **AC** – Auditorium capacity
**SC** – Stage capacity **R** - Roof – 0 – no roof /0.1 – oculus/ 0.5 - roof with openings / 1 – fully covered interior **C** - Cost – 0 – cheap / 1- expensive
**O** – 0rganisation O -Radial/0.25 – Elliptic/0.5 - Hybrid/ 1 - Orthogonal
**V** – Viewing stand slope – 0 – flat / 1-steep **SS** – Seat spacing – 0 – close / 1-distant
**RD** – Row depth – 0 – narrow / 1 – wide **SL** – Stage location – 0 – side / 1 – centre
**E** – Expandability – 0- not expandable / 1 – expandable
**CC** – Circulation continuous / interrupted -0 – spectators cannot circumnavigate building / 1- spectators can circumnavigate building
**ED** – Escape distance – 0 -exits are close / 1 – exits are distant
**B** – Backstage – 0 – no backstage / 1 – backstage
**SC** - Seating continuity – 0 seating interrupted /1-seating continuous
**SD** – Sound direction – 0 – stage to audience / 1-audience to stage
**M** – Ceremonial movement – 0 – no staged performance /1 -staged performance
**E** - Group / Individual experience – 0 – individual / 1- group

*Table 2.4. Numerical dataset for k-means clustering*

| Type | Case Study | CL | LR | BF | AA | SA | AC | SC | R | C | O | V | SS | RD | SL | E | CC | ED | B | SC | SD | M | E |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Stadium - Circular | Melbourne Cricket Ground | 1853 | 2013 | 53160 | 54160 | 16 223 | 100 000 | 19 | 0.1 | 1 | 1 | 1 | 0.25 | 0.25 | 1 | 1 | 0.75 | 1 | 1 | 1 | 1 | 0.1 | 1 |
| Stadium - Hippodrome | Kyiv Olympic Stadium | 1923 | 2011 | 59600 | 52000 | 7140 | 70050 | 25 | 0.1 | 1 | 0.5 | 1 | 0.25 | 0.25 | 1 | 1 | 0.75 | 1 | 1 | 1 | 1 | 0.1 | 1 |
| Stadium - Tangent arc | Seoul Olympic Stadium | 1984 | 1984 | 52500 | 46085 | 7140 | 69950 | 25 | 0.1 | 1 | 1 | 1 | 0.25 | 0.25 | 1 | 1 | 0.75 | 1 | 1 | 1 | 1 | 0.1 | 1 |
| Stadium - Fillet | Allianz Arena Munich | 2005 | 2005 | 51000 | 45000 | 7140 | 75024 | 25 | 0.1 | 1 | 0.25 | 1 | 0.25 | 0.25 | 1 | 1 | 0.75 | 1 | 1 | 1 | 1 | 0.1 | 1 |
| Stadium - Chamfer | Raymond James | 1998 | 1998 | 57900 | 43178 | 7140 | 65618 | 25 | 0.1 | 1 | 0.1 | 1 | 0.25 | 0.25 | 1 | 1 | 0.75 | 1 | 1 | 1 | 1 | 0.1 | 1 |
| Stadium - Independent stands | Stade Velodrome Marseille | 1935 | 2014 | 51000 | 45454 | 7140 | 67394 | 25 | 0.1 | 1 | 0 | 1 | 0.25 | 0.25 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 0.1 | 1 |
| Stadium - Baseball | Washington Nationals | 2008 | 2008 | 63000 | 47700 | 9775 | 41313 | 17 | 0.1 | 1 | 0.5 | 1 | 0.25 | 0.25 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 0.1 | 1 |
| Stadium - Motorsport | Hockenheim ring | 1932 | 2002 | 614700 | 614700 | 679 000 | 120 000 | 24 | 0.05 | 1 | 0.5 | 1 | 0.25 | 0.25 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 0.1 | 1 |
| Arena - Radial | SSE Hydro Glasgow | 2013 | 2013 | 11000 | 9350 | 220 | 14300 | 20 | 1 | 1 | 1 | 1 | 0.25 | 0.25 | 1 | 0 | 0.75 | 1 | 1 | 0 | 1 | 0.1 | 1 |
| Arena - Fillet | O2 Arena London | 1999 | 2007 | 80176 | 10844 | 1200 | 20000 | 26 | 1 | 1 | 0.5 | 1 | 0.25 | 0.25 | 1 | 0 | 0.75 | 1 | 1 | 1 | 1 | 0.1 | 1 |
| Arena - Chamfer | Barclays Center New Jersey | 2012 | 2012 | 17421 | 10337 | 601 | 17732 | 13 | 1 | 1 | 0.1 | 1 | 0.25 | 0.25 | 1 | 0 | 0.75 | 1 | 1 | 1 | 1 | 0.1 | 1 |
| Arena - Hippodrome | T Mobile Las Vegas | 2016 | 2016 | 16900 | 14891 | 601 | 20000 | 13 | 1 | 1 | 0.5 | 1 | 0.25 | 0.25 | 1 | 0 | 0.75 | 1 | 1 | 1 | 1 | 0.1 | 1 |
| Arena - Aquatics | London Aquatics Centre | 2011 | 2014 | 11250 | 6146 | 2227 | 2500 | 8 | 0.5 | 1 | 0 | 1 | 0.25 | 0.25 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 0.1 | 1 |
| Arena - Velodrome | Velodrom, Berlin | 1997 | 1997 | 22213 | 18950 | 8715 | 6887 | 9 | 0.5 | 1 | 1 | 1 | 0.25 | 0.25 | 1 | 0 | 0.75 | 1 | 1 | 0 | 1 | 0.1 | 1 |
| Theatre - Proscenium | Wrexham Opera House | 2008 | 2008 | 2330 | 833 | 367 | 850 | 14 | 1 | 0.5 | 0 | 0.5 | 0.5 | 0.5 | 0 | 0 | 1 | 0.5 | 1 | 0 | 0 | 1 | 1 |

| | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Theatre - End stage | Nederlands DansTheatre | 1987 | 1987 | 3810 | 2510 | 1082 | 1300 | 40 | 1 | 0.5 | 0 | 0.5 | 0.5 | 0.5 | 0 | 0 | 1 | 0.5 | 1 | 0 | 0 | 1 | 1 |
| Theatre - Corner stage | National Theatre London | 1976 | 1976 | 11033 | 1380 | 574 | 1150 | 14 | 1 | 0.5 | 0 | 0.5 | 0.5 | 0.5 | 0 | 0 | 0.75 | 0.5 | 1 | 0 | 0 | 1 | 1 |
| Theatre - Wide fan | Barbican Arts Centre | 1982 | 1982 | 11771 | 979 | 642 | 1156 | 14 | 1 | 0.5 | 0 | 0.5 | 0.5 | 0.5 | 0 | 0 | 1 | 0.5 | 1 | 0 | 0 | 1 | 1 |
| Theatre - Amphitheatre | Generic | 300 | 300 | 1860 | 1860 | 60 | 1000 | 5 | 0.4 | 0.5 | 1 | 0.5 | 0.5 | 0.5 | 1 | 1 | 0.75 | 0.5 | 1 | 0 | 0 | 1 | 1 |
| Theatre - Thrust stage | The Crucible Theatre Sheffield | 1897 | 2009 | 2801 | 857 | 135 | 980 | 14 | 1 | 0.5 | 0 | 0.5 | 0.5 | 0.5 | 1 | 0 | 0.75 | 0.5 | 1 | 0 | 0 | 1 | 1 |
| Theatre - In- the-round | Royal Exchange Manchester | 1976 | 1976 | 3872 | 376 | 117 | 740 | 6 | 1 | 0.5 | 1 | 0.5 | 0.5 | 0.5 | 1 | 0 | 1 | 0.5 | 1 | 1 | 0 | 1 | 1 |
| Theatre - Courtyard | Shakespeare Company | 1986 | 1986 | 2218 | 714 | 230 | 450 | 14 | 1 | 0.5 | 0 | 0.5 | 0.5 | 0.5 | 1 | 0 | 0.75 | 0.5 | 1 | 0 | 0 | 1 | 1 |
| Theatre - Traverse | Generic | 1950 | 1950 | 778 | 778 | 614 | 400 | 14 | 1 | 0.5 | 0 | 0.5 | 0.5 | 0.5 | 1 | 0 | 1 | 0.5 | 1 | 0 | 0 | 1 | 1 |
| Theatre - Transformable | Cerritos Center for Performing Arts | 1993 | 1993 | 3667 | 1274 | 280 | 1950 | 14 | 1 | 0.5 | 0 | 0.5 | 0.5 | 0.5 | 0 | 0.5 | 0.75 | 0.5 | 1 | 0 | 0 | 1 | 1 |
| Theatre - Adaptable reuse | The Roundhouse | 1846 | 2006 | 3650 | 2610 | 26 | 1800 | 5 | 1 | 0.5 | 1 | 0.5 | 0.5 | 0.5 | 1 | 0.5 | 0.75 | 0.5 | 1 | 1 | 0 | 1 | 1 |
| Concert hall - Shoe box | Harmony Hall Fukui | 1997 | 1997 | 12415 | 1500 | 172 | 1456 | 100 | 1 | 0.5 | 0 | 0.5 | 0.5 | 0.5 | 0 | 0 | 0.75 | 0.5 | 1 | 0 | 0 | 1 | 1 |
| Concert hall - Vineyard | Elb philharmonie, Hamburg | 2017 | 2017 | 5857 | 1479 | 112 | 2100 | 100 | 1 | 1 | 0 | 0.5 | 0.5 | 0.5 | 1 | 0 | 0 | 0.5 | 1 | 0 | 0 | 1 | 1 |
| Concert hall - Recital | Taisetsu Crystal Hall | 1993 | 1993 | 8351 | 721 | 103 | 600 | 50 | 1 | 0.5 | 0 | 0.5 | 0.5 | 0.5 | 0 | 0 | 0.75 | 0.5 | 1 | 0 | 0 | 1 | 1 |
| Concert hall - Musical theatre | Generic | 1860 | 1860 | 1300 | 960 | 532 | 800 | 40 | 1 | 0.5 | 0 | 0.5 | 0.5 | 0.5 | 0 | 0 | 0.75 | 0.5 | 1 | 0 | 0 | 1 | 1 |
| Parliament - Opposition | Palace of Westminster | 1876 | 1955 | 19540 | 590 | 10 | 650 | 2 | 1 | 1 | 0 | 0.5 | 0.5 | 0.5 | 1 | 0.5 | 0.75 | 0.5 | 0 | 0 | 0.5 | 1 | 1 |
| Parliament - Amphitheatre | Reichstag | 1894 | 1999 | 13133 | 2000 | 10 | 598 | 2 | 1 | 1 | 1 | 0.5 | 0.75 | 0.75 | 1 | 0.5 | 0.75 | 0.5 | 0 | 0 | 0.5 | 1 | 1 |

| | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Parliament - Horseshoe | Palazzo Montecitorio | 1696 | 1918 | 16460 | 887 | 10 | 630 | 2 | 1 | 1 | 0.75 | 0.5 | 0.75 | 0.75 | 1 | 0.5 | 1 | 0.5 | 0 | 0 | 0.5 | 1 | 1 |
| Parliament - Circle | Nordrhein-Westfalen | 1988 | 1988 | 4577 | 640 | 10 | 181 | 2 | 1 | 1 | 1 | 0.5 | 0.75 | 0.75 | 1 | 0.5 | 1 | 0.5 | 0 | 0 | 0.5 | 1 | 1 |
| Parliament - Block | Brazil Congress | 1960 | 1960 | 8560 | 570 | 10 | 513 | 2 | 1 | 1 | 0 | 0.5 | 0.75 | 0.75 | 0 | 0.5 | 0.75 | 0.5 | 0 | 0 | 0.5 | 1 | 1 |
| Sacred - Church axial | Resurrection of Mary, Riola di Vergato | 1978 | 1978 | 1111 | 626 | 64 | 240 | 3 | 1 | 0.3 | 0 | 0 | 0.75 | 0.75 | 1 | 0.5 | 1 | 0.5 | 0 | 0 | 0.5 | 1 | 1 |
| Sacred - Church Centralised | Glaubten, Zurich | 1972 | 1972 | 1963 | 381 | 42 | 450 | 3 | 1 | 0.3 | 0 | 0 | 0.75 | 0.75 | 1 | 0.5 | 1 | 0.5 | 0 | 0 | 0.5 | 1 | 1 |
| Sacred - Church Large span | Cathedral of Our Lady of the Angels | 2002 | 2002 | 2604 | 1114 | 367 | 1900 | 27 | 1 | 1 | 0 | 0 | 0.75 | 0.75 | 1 | 0.5 | 1 | 1 | 0 | 0 | 0.5 | 1 | 1 |
| Sacred - Mosque | Dar al Islam, New Mexico | 1981 | 1981 | 164 | 164 | 2 | 80 | 1 | 1 | 0.3 | 0 | 0 | 1 | 1 | 1 | 0.5 | 1 | 0.1 | 0 | 0 | 0.5 | 1 | 1 |
| Sacred - Synagogue | Cymbalista, Tel Aviv | 1998 | 1998 | 707 | 127 | 6.3 | 84 | 1 | 1 | 0.3 | 0 | 0.5 | 1 | 1 | 0 | 0.5 | 1 | 0.1 | 0 | 0 | 0.5 | 1 | 1 |
| Sacred - Buddhist temple | Kuhon-ji, Japan | 2003 | 2003 | 244 | 244 | 15.6 | 50 | 1 | 1 | 0.3 | 0 | 0 | 1 | 1 | 1 | 0.5 | 1 | 0.1 | 0 | 0 | 0.5 | 1 | 0 |
| Sacred - Hindu temple | Tejorling Radiance Temple | 2018 | 2018 | 11 | 11 | 1 | 5 | 1 | 1 | 0.1 | 0 | 0 | 1 | 1 | 0 | 0.5 | 1 | 0.1 | 0 | 0 | 0.5 | 1 | 0 |
| Learning - Auditorium | Barcelona Botanical Ins | 2003 | 2003 | 1292 | 243 | 18 | 110 | 1 | 1 | 0.3 | 0 | 0.5 | 0.5 | 0.5 | 0 | 1 | 1 | 0.1 | 0 | 0 | 0.5 | 1 | 1 |
| Learning -S group | Exemplar School, London | 2003 | 2003 | 7545 | 174 | 1 | 18 | 1 | 1 | 0.5 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 0.1 | 0 | 0 | 0.5 | 0.1 | 0 |
| Learning - L group | Burr School, Fairfax | 2006 | 2006 | 3956 | 300 | 1 | 180 | 1 | 1 | 0.1 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 0.1 | 0 | 0 | 0.5 | 0.1 | 1 |
| Learning - Collaborative | Technical University of Munich | 1997 | 1997 | 12386 | 914 | 1 | 80 | 1 | 1 | 0.1 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 0.1 | 0 | 0 | 0.5 | 0.1 | 1 |
| Learning One on one | Beiersdorf Hamburg | 2004 | 2004 | 2788 | 5 | 1 | 2 | 1 | 1 | 0.1 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 0.1 | 0 | 0 | 0.5 | 0.1 | 0 |
| Learning - Individual | Biblioteca de Ceuta | 2013 | 2013 | 711 | 481 | 1 | 88 | 1 | 1 | 0.5 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 0.5 | 0 | 0 | 0.5 | 0 | 0 |

K-Means
ML clustering

Completion year
Last refurbishment
Footprint area
Auditorium Area
Stage Area
Auditorium Capacity
Stage Capacity
Roof
Cost
Radial/Hybrid/Ortho
Seating inclination
Seat spacing
Row depth
Stage location
Expandability
Circulation Direct/interupted
Escape Distance
Backstage
Seating continuity
Sound direction
Ceremonial movement
Group / individual experience

Building data
Organisational
Circulation
Experiential

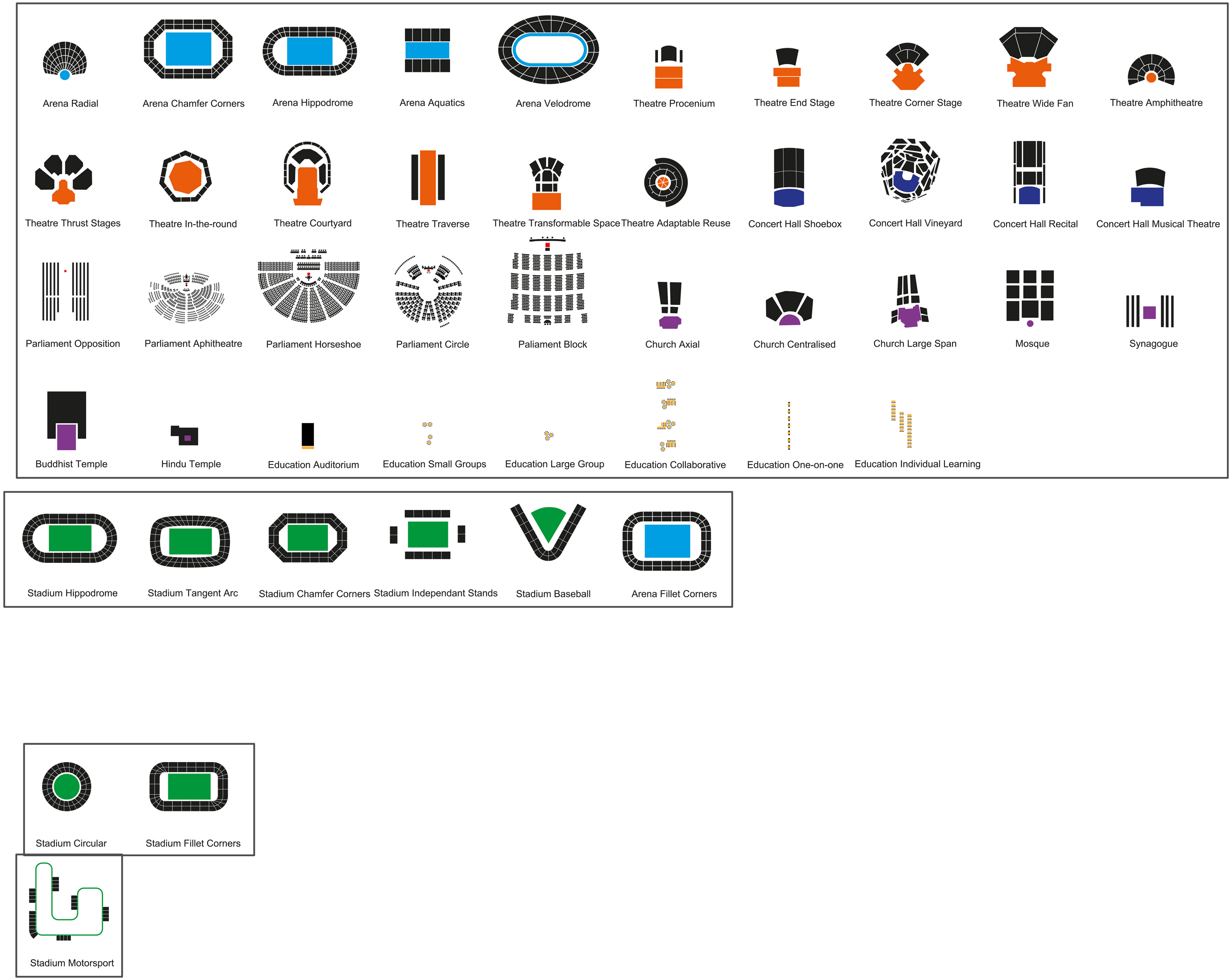



*Figure 2.33. Classification based on building data*

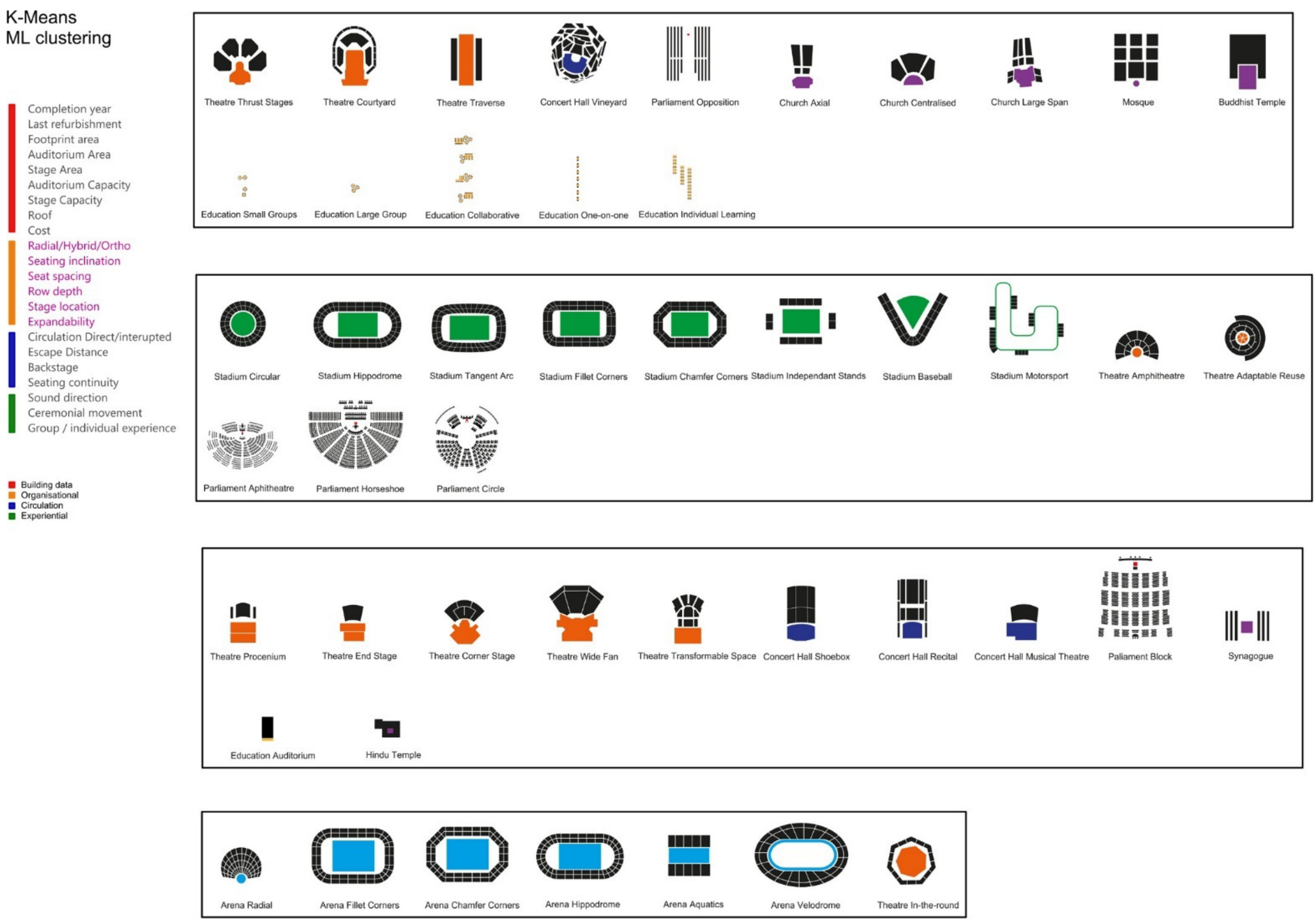



*Figure 2.34. Classification based on organisation data*

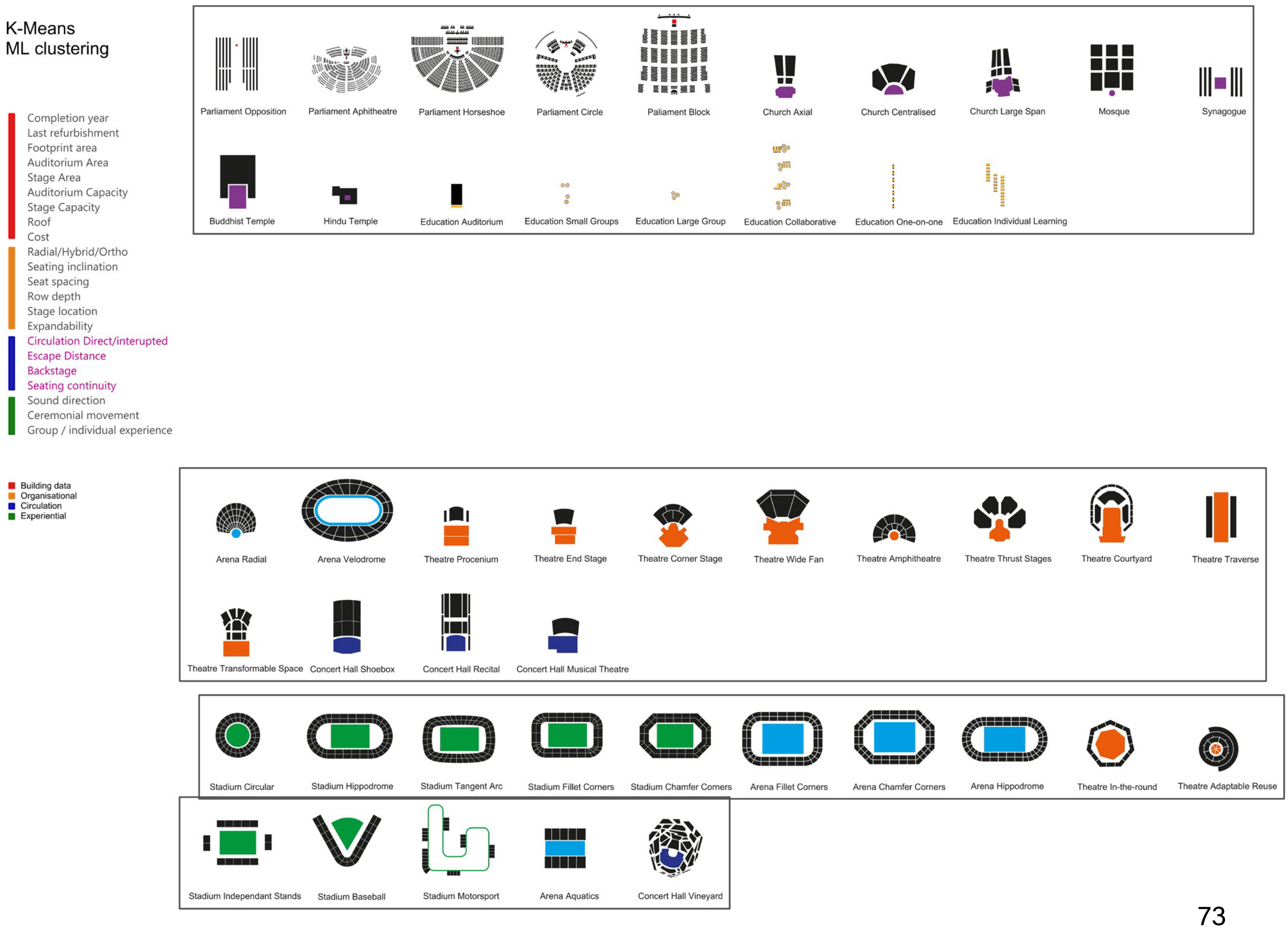



*Figure 2.35. Classification based on circulation data*

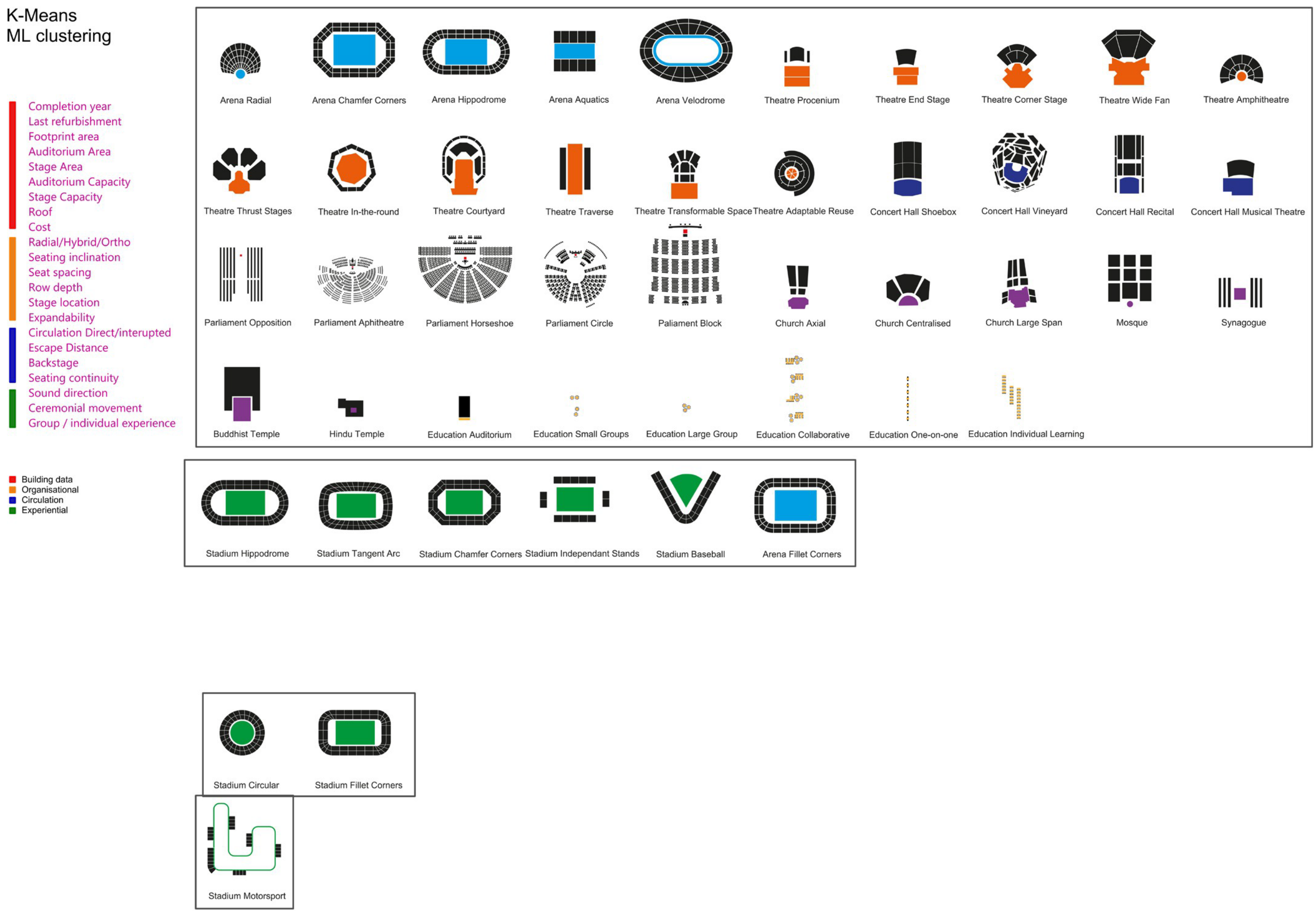



*Figure 2.36. Classification based on all data types*

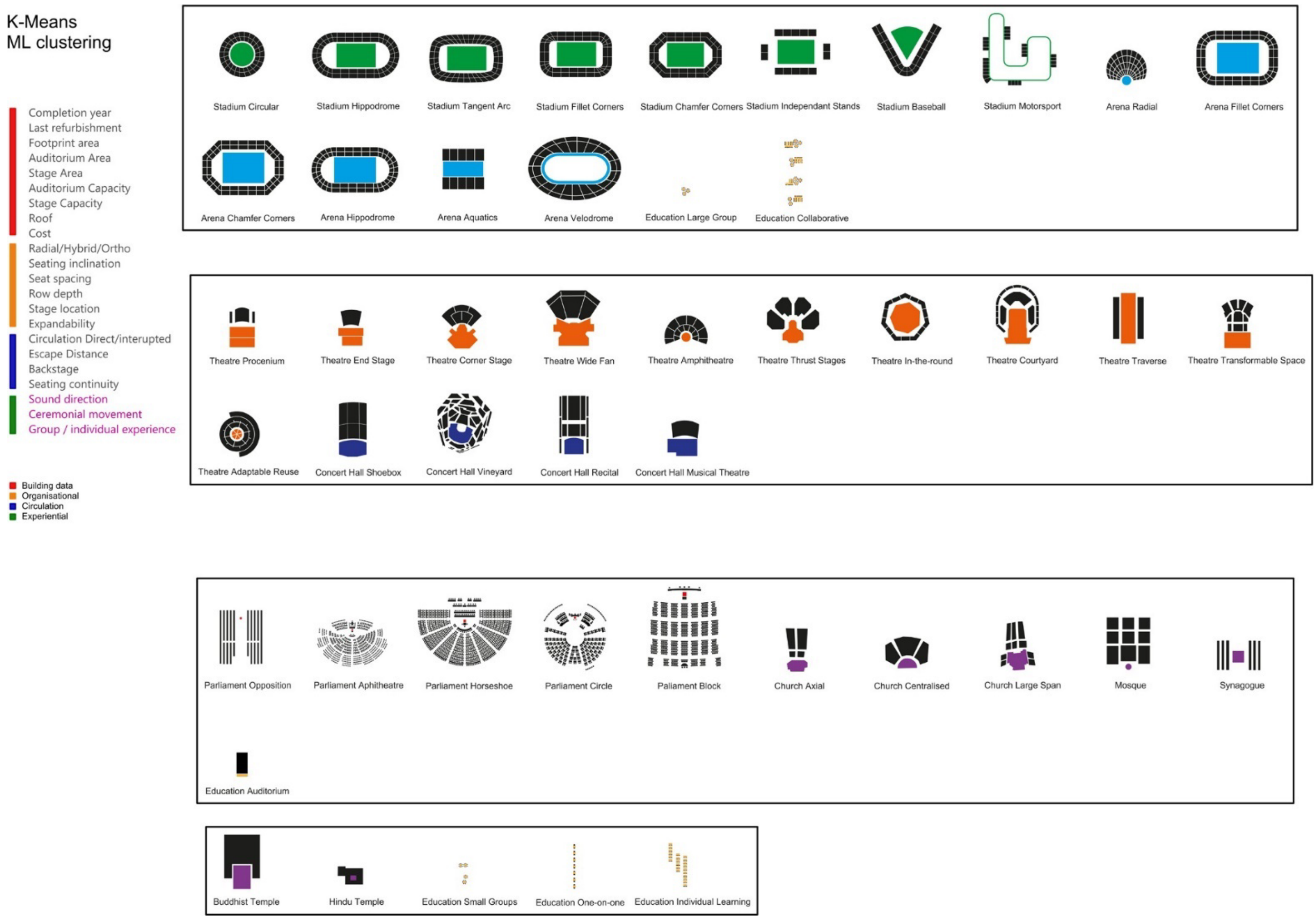



*Figure 2.37. Classification based on experiential data*

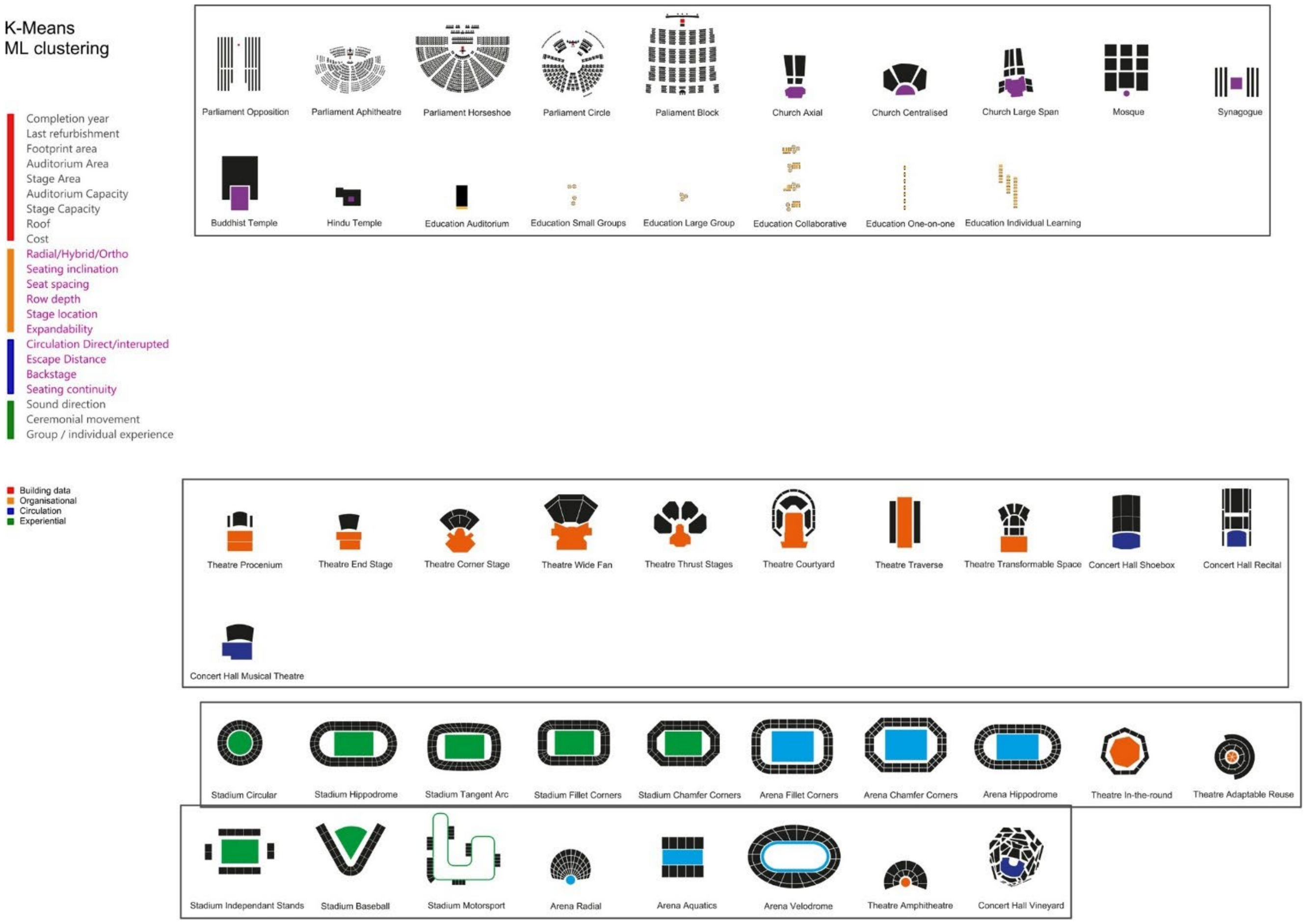



*Figure 2.38. Classification based on organisational and circulation data*

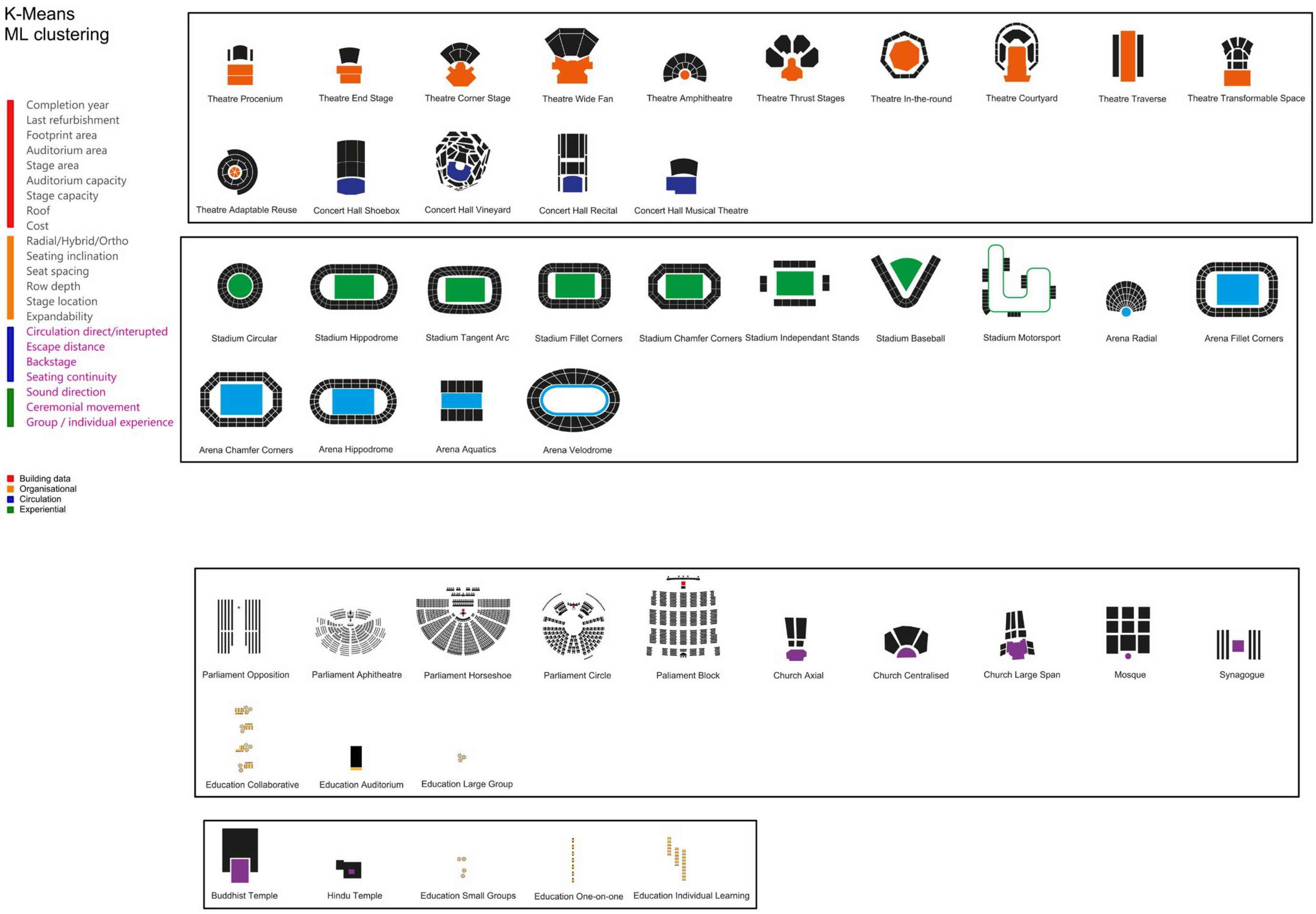



*Figure 2.39. Classification based on circulation and experiential data*

## 2.6 Spatial-numerical machine learning model

The next phase of the research identifies in more detail three areas of analysis of public assembly buildings – stage, auditorium, and building. A new machine learning model is constructed that utilises numerical building data, along with 2D and 3D morphological and functional data measured in Rhino 7. The new data is extracted from plans and 3D models of the case studies drawn by the author based on the literature review. This model enables a comprehensive analysis of part-to-part and part-to-whole relationships with machine learning. The results from this analysis are later summarised in a set of decision-making trees that classify each subtype based on an analytical category. The analytical categories are derived from the regularities identified in the previous phases but are adapted to the specifics of a more detailed representation based on data from a 3D model that is created through an arrangement of simplified layout drawings at the floor slab height of each individual case study.

### 2.6.1 Selection of machine learning algorithm

As with the numerical machine learning model, the analysis is conducted entirely with the k-means algorithm from the Accord machine learning framework and its implementation in LunchBox in Grasshopper and Rhino 7. This phase of the research is a direct development of the previous steps, but for the first time it combines spatial, structural, and other building data to construct a structured dataset. The primary difference with the previous step in terms of the data curation is the use of detailed architectural drawings which were developed within the same framework instead of using numerical data. This step allows for a much more detailed comparison of the layout in each case study. The limitation of the process can be found in the specific properties of each case study – these carry their own design specifics which can potentially differ from other examples within the specific subtype.

The detailed analysis of meaningful relationships and type construction are carried out after the completion of the detailed dataset. The primary aim of this phase is to identify the morphological design drivers and classify the case studies, based on each property. At this stage the research takes a more empirical approach, based on the updated dataset. It is important to note that again, even when the quantified values are normalised within the domain 0 to 1, the case study stadiums and arenas form a distinct group, while the other case study buildings are in different groups. The table

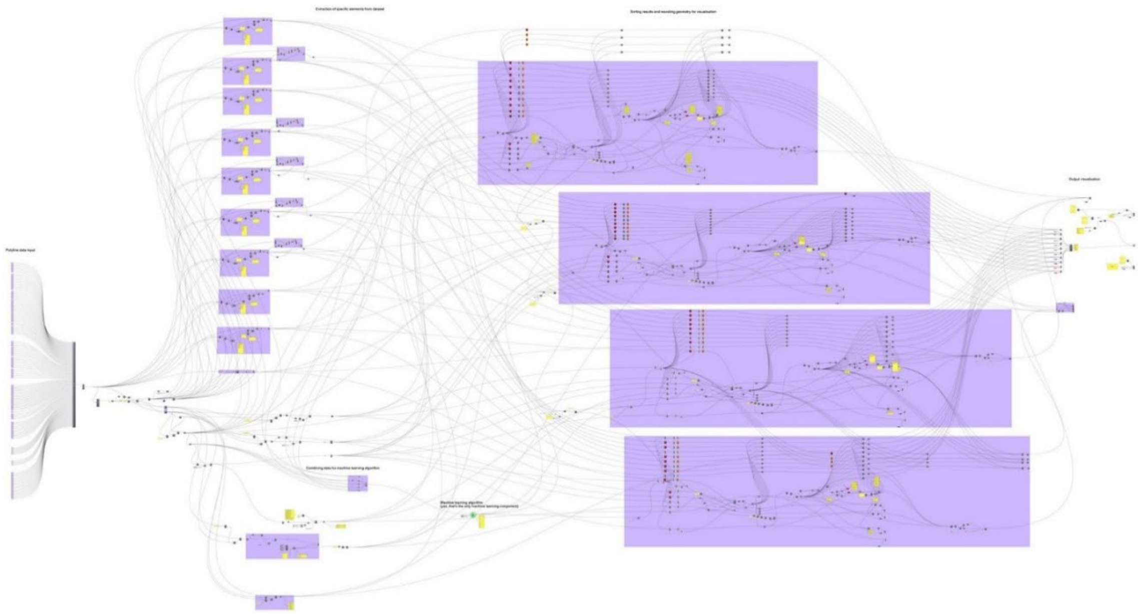


Figure 2.40. Grasshopper script utilising K-means machine learning algorithm for spatial-numerical classification

on the following page summarises the design drivers taken from the numerical model to the spatial-numerical model. The selection is based on the effect of each feature on the classification of the subtypes – if the analytical dimension allows the machine learning algorithm to classify all the stadium subtypes within the same group, the feature is regarded as a dominant typological characteristic. Those dominant categories are then taken forward and are highlighted in green in the table below. The new analytical features introduced at this stage are based on the additional data that can be extracted from drawings, as opposed to the numerical inputs of the previous phase.

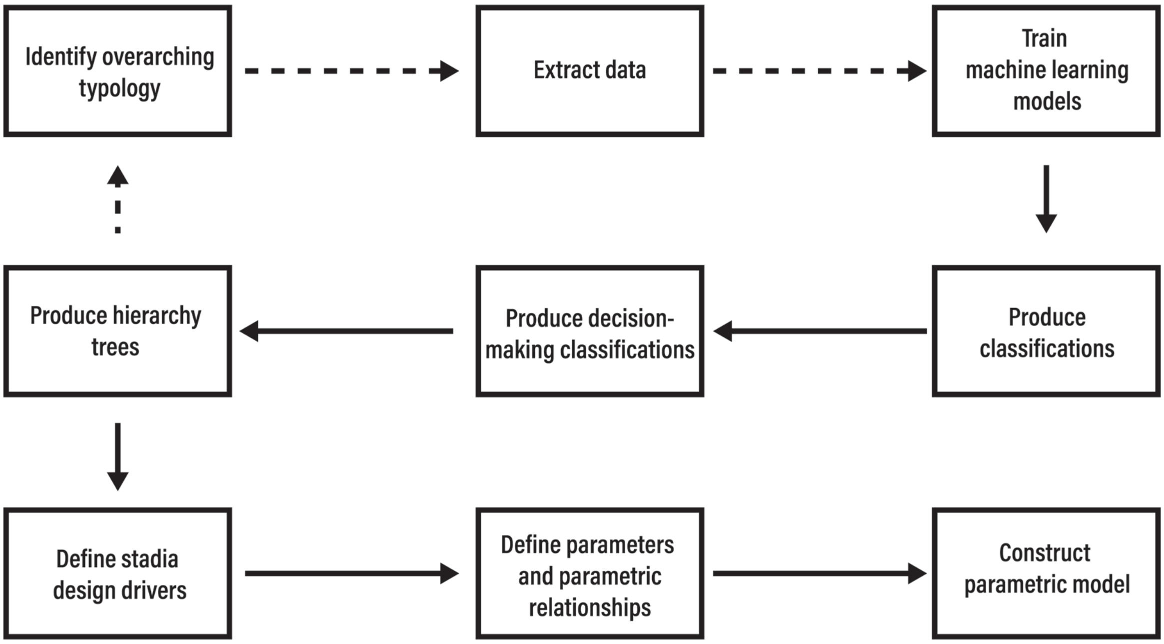



Figure 2.41. Development of spatial-numerical machine learning model

*Table 2.5. Revised analytical categories following numerical analysis*

| Analytical category | Numerical model | Spatial-numerical model |
|---|---|---|
| Circulation | Circulation/Structure organisation | |
| | | Access |
| | Distance to exit | Level 1 - General admission access to main building, Level 2 - GA movement inside building, Level 3 - GA access to auditorium (main access floor) |
| | Continuity | Classification based on fragmentation of crowd flow (main access floor) |
| | | Relationship between access routes and GA concourse (main access floor) |
| | | Circulation areas other than concourse (main access floor) |
| | | Organisational patterns of areas other than concourse (main access floor) |
| | Backstage | Backstage |
| Layout | Ceremonial movement | Ceremonial movement |
| | Group / Individual experience | Group/individual experience |
| | Structural grid by function | |
| | | GA Concourse to service areas relationships (main access floor) |
| | | GA Concourse to all other areas relationships (main access floor) |
| | | GA Concourse to commercial and toilets areas (main access floor, GA concourse scale) |
| | | Services and utilities (main access floor) |
| | | Commercial spaces (main access floor) |
| | | Performance-related spaces (main access floor) |
| | | Non-performance-related spaces (main access floor) |
| | | Concourse - relationship with other functions |
| | | GA Concourse to level footprint relationship (main access floor) |
| | | Auditorium classification based on GA concourse and services areas |
| | | Basement - building support relationships (in the case studies that have basements with publicly available plans) |
| | | Parking and service areas |
| | | All support functions |
| | Permanence / temporality | |

| | | |
|---|---|---|
| | Sound directed towards audience | |
| | Structural grid stage orientation | |
| Sightlines | Seating continuity | Auditorium - seating arrangement and other relationships |
| | | Stage to auditorium relationship |
| | | Auditorium classification based on seating fragmentation |
| | Seat spacing | Seat spacing |
| | Row depth | Row depth |
| | Viewing platform slope | Seating inclination |
| | Stage location | Stage location |
| | Structural grid type | Structure type |
| | Part-to-whole Stage/ Auditorium/Building scale | Part-to-whole Stage/Auditorium/Building scale |
| | Part-to-whole Auditorium to building footprint | Part-to-whole Auditorium to building footprint |
| | Part-to-whole stage to building footprint morphology | Part-to-whole stage to building footprint morphology |
| Building data | Completion year | Completion year |
| | Last refurbishment | Last refurbishment |
| | Building footprint area | Building footprint area |
| | Auditorium area | Auditorium area |
| | Stage area | Stage area |
| | Auditorium capacity | Auditorium capacity |
| | Stage capacity | |
| | Roof | Roof |
| | Cost | |

*Table 2.6. Spatial-numerical dataset case studies*

| **Type** | **Case study** | **Location** | **Built** (renovated) |
|---|---|---|---|
| Stadium Circle | Melbourne Cricket Ground | Melbourne, Australia | 1853 (2013) |
| Stadium Hippodrome | Kyiv Olympic Stadium | Kiev, Ukraine | 1923 (2011) |
| Stadium Tangent Arc / Elliptic | Seoul Olympic Stadium | Seoul, South Korea | 1984 |
| Stadium Chamfer Corner | Raymond James Stadium | Tampa, USA | 1998 |
| Stadium Fillet Corners | Allianz Arena Munich | Munich, Germany | 2005 |
| Stadium Independent Stands | Stade Velodrome Marseille | Marseille, France | 1935 (2014) |

| | | | |
|---|---|---|---|
| Stadium Baseball | Washington Nationals | Washington DC, USA | 2008 |
| Arena Radial | SSE Hydro Glasgow | Glasgow, UK | 2013 |
| Arena Hippodrome | T-Mobile Arena | Las Vegas, USA | 2016 |
| Arena Chamfer | Barclays Center | New York, USA | 2012 |
| Arena Fillet Corners | O2 Arena London | London, UK | 2007 |
| Theatre Proscenium | Wrexham Opera House | Wrexham, UK | 2008 |
| Theatre End Stage | Nederlands Dans Theatre | Den Hague, NL | 1987 |
| Theatre Corner Stage | National Theatre London | London, UK | 1976 |
| Theatre Wide Fan | Barbican Arts Centre | London, UK | 1982 |
| Theatre Amphitheatre | Generic | | |
| Theatre Thrust Stage | The Crucible Theatre | Sheffield, UK | 1897 (2009) |
| Theatre In-the-round | Royal Exchange | Manchester, UK | 1867 (1998) |
| Theatre Courtyard | Royal Shakespeare Comp. | London, UK | 1986 |
| Theatre Traverse | Generic | | |
| Theatre Transformable | Center for Performing Arts | Cerritos, USA | 1993 |
| Theatre Adaptable Reuse | The Roundhouse | London, UK | 1846 (2006) |
| Concert Hall Recital | Taisetsu Crystal Hall | Asahikawa City, Japan | 1993 |
| Concert Hall Vineyard | Elbphilharmonie | Hamburg, Germany | 2017 |
| Concert Hall Shoe Box | Harmony Hall | Fukui, Japan | 1997 |
| Concert Hall Music Theatre | Generic | | |
| Parliaments Opposition | Palace of Westminster | London, UK | 1876 |
| Parliaments Amphitheatre | Reichstag | Berlin, Germany | 1894 (1999) |
| Parliaments Horseshoe | Palazzo Montecitorio | Rome, Italy | 1673 |
| Parliaments Circle | Nordrhein-Westfalen | Dusseldorf, Germany | 1988 |
| Parliaments Block | Brazil National Congress | Brasilia, Brazil | 1960 |
| Sacred Spaces Church Axial | Resurrection of Mary | Riola di Vergato, Italy | 1978 |
| Sacred Spaces Church Centralized | Glaubten Reformed Church | Zurich, Switzerland | 1972 |
| Sacred Spaces Church Large Span | Cathedral of Our Lady of the Angels | Los Angeles, USA | 2002 |
| Sacred Spaces Mosque | Dar al Islam | Abiquiu, USA | 1981 |
| Sacred Spaces Synagogue | Cymbalista | Tel Aviv, Israel | 1998 |
| Sacred Spaces Buddhist Temple | Kuhon-ji | Natan City, Japan | 2003 |
| Sacred Spaces Hindu Temple | Tejorling Radiance Temple | Pune, India | 2018 |
| Classroom / Auditorium | Botanical Institute | Barcelona, Spain | 2003 |
| Educational Small Groups | Exemplar School | London, UK | 2003 |
| Educational Large Groups | Burr School | Fairfax, USA | 2006 |
| Educational Collaborative | Technical University | Munich, Germany | 1997 |
| Educational One-on-one | Beiersdorf | Hamburg, Germany | 2004 |
| Educational Individual Learning | Biblioteca Pública Ceuta | Ceuta, Spain | 2013 |

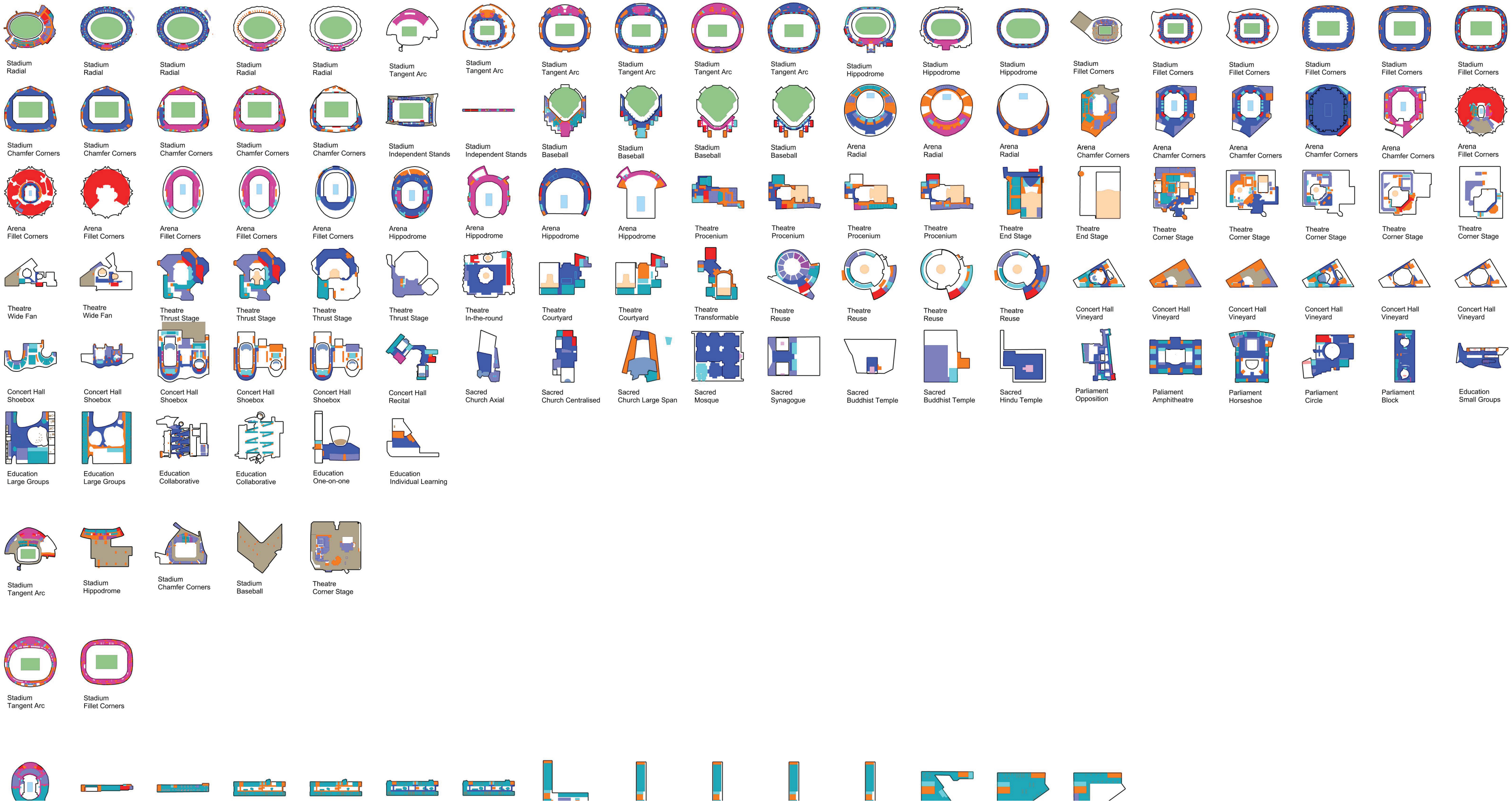



*Figure 2.42. Places for assembly and recreation layouts full dataset*

# Dataset elements

## Stadium Tangent Arc

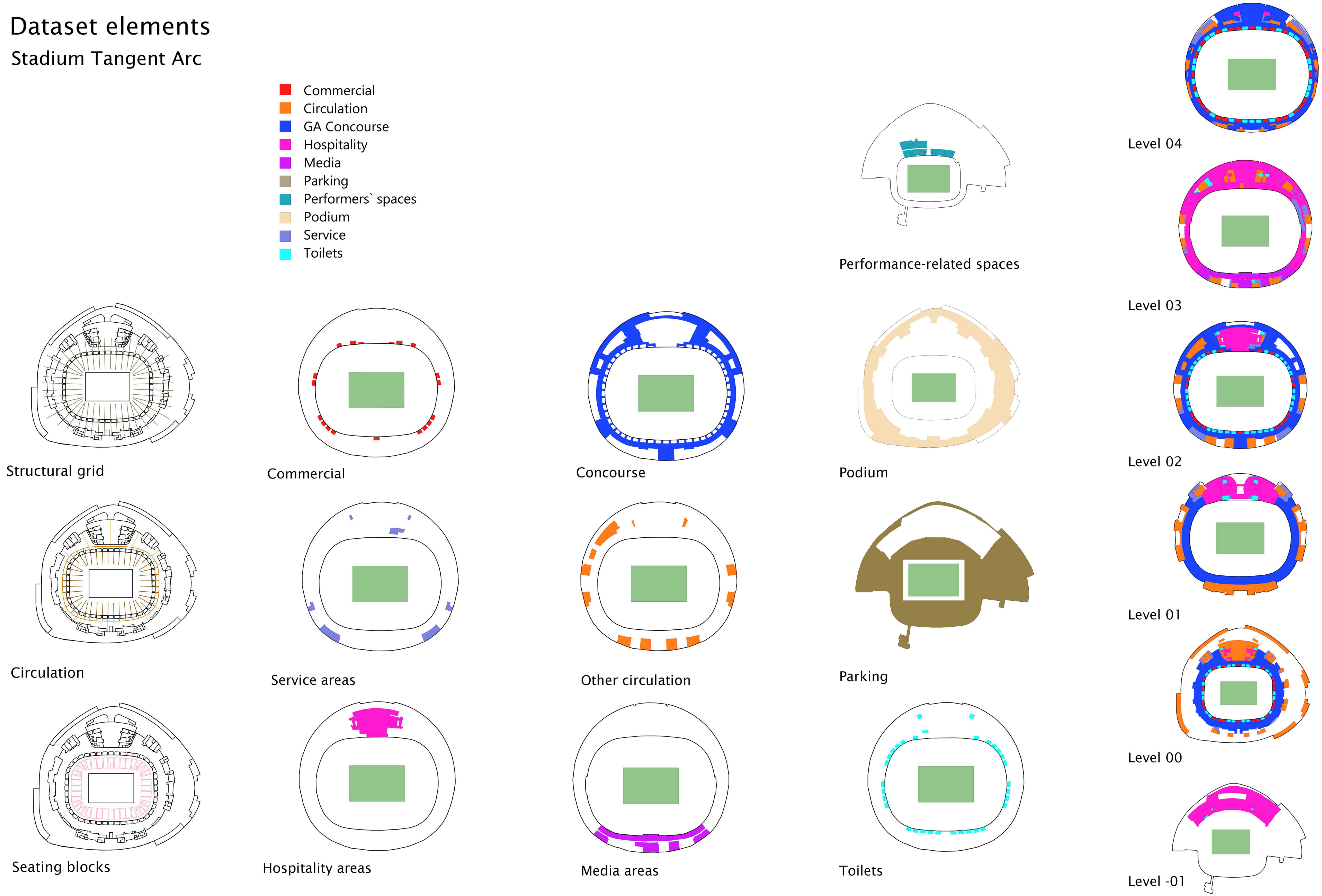



*Figure 2.43. Places for assembly and recreation dataset elements based on Wembley National Stadium / Foster + Partners ArchDaily (2017)*

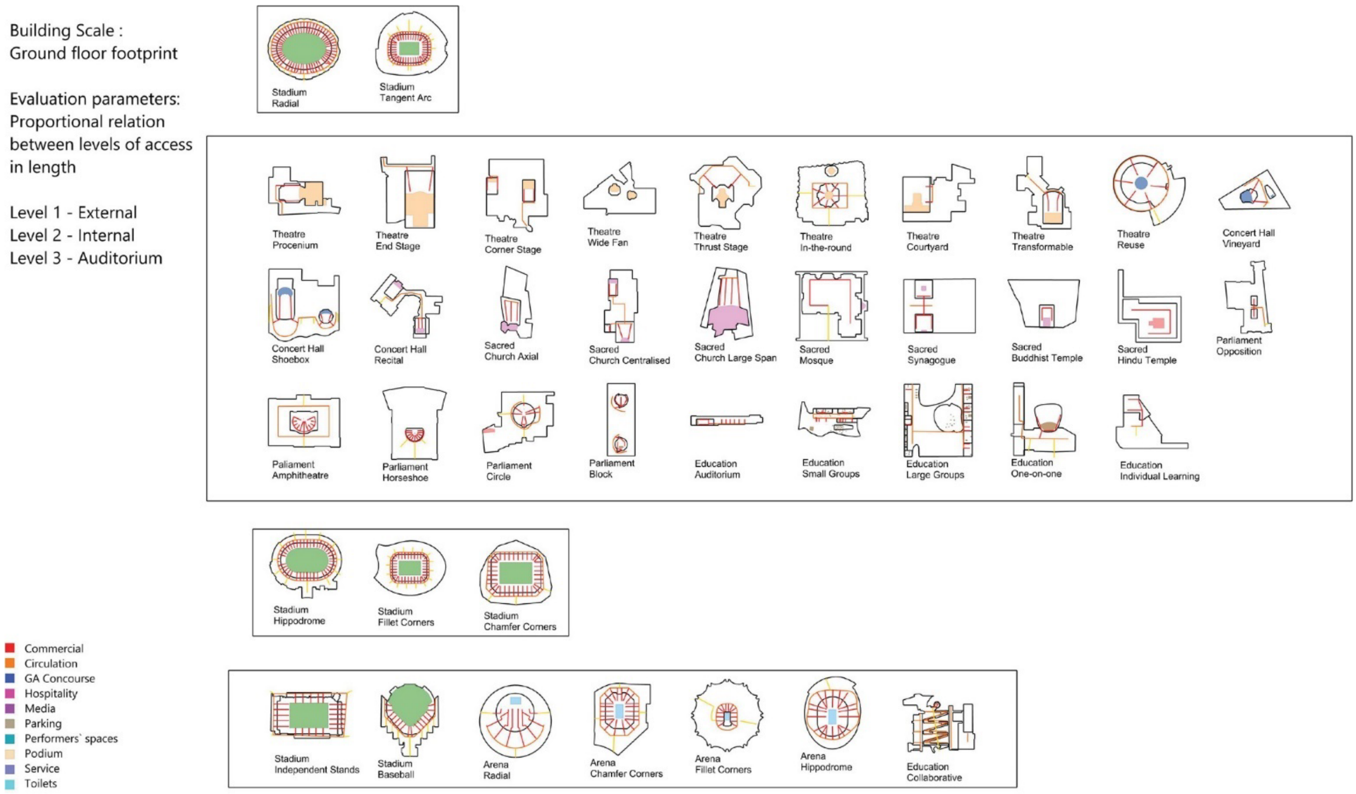



*Figure 2.44. Classification based on Level 1 - General admission access to main building, Level 2 - GA movement inside building, Level 3*

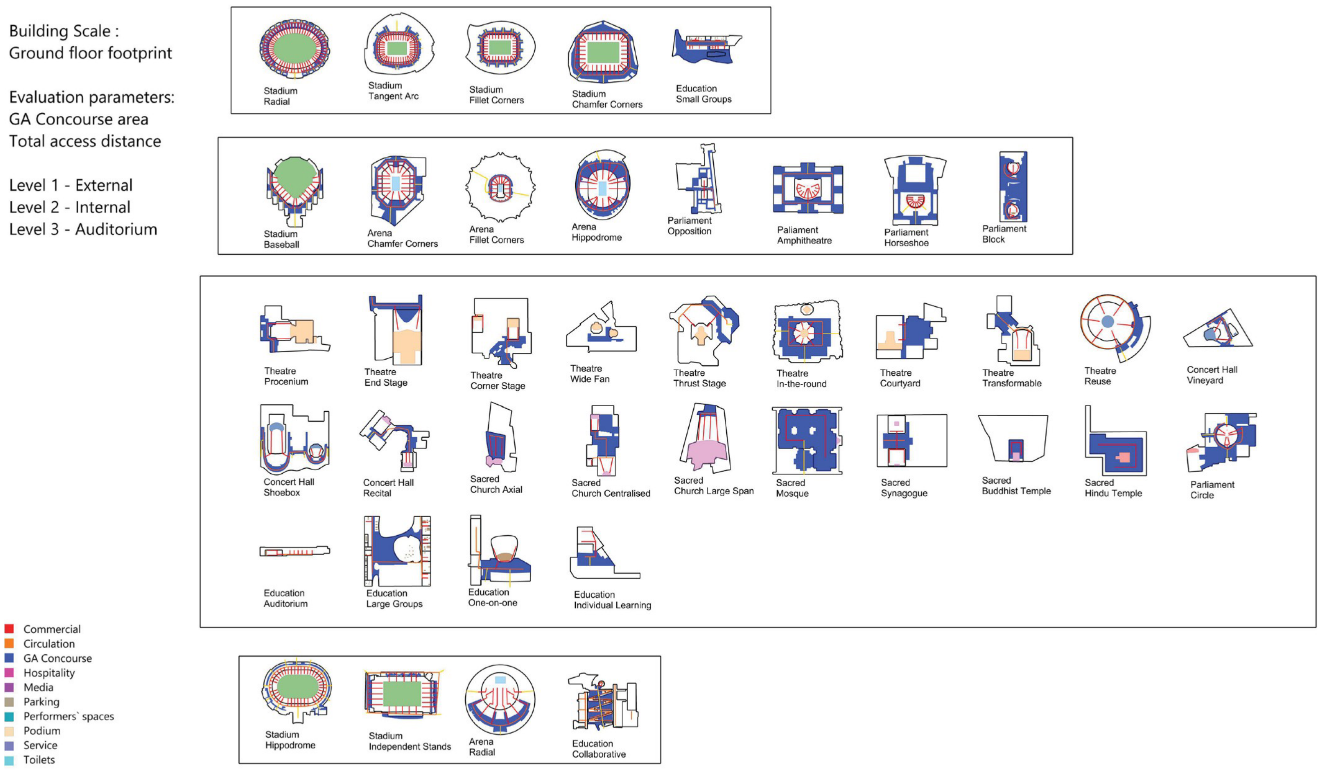
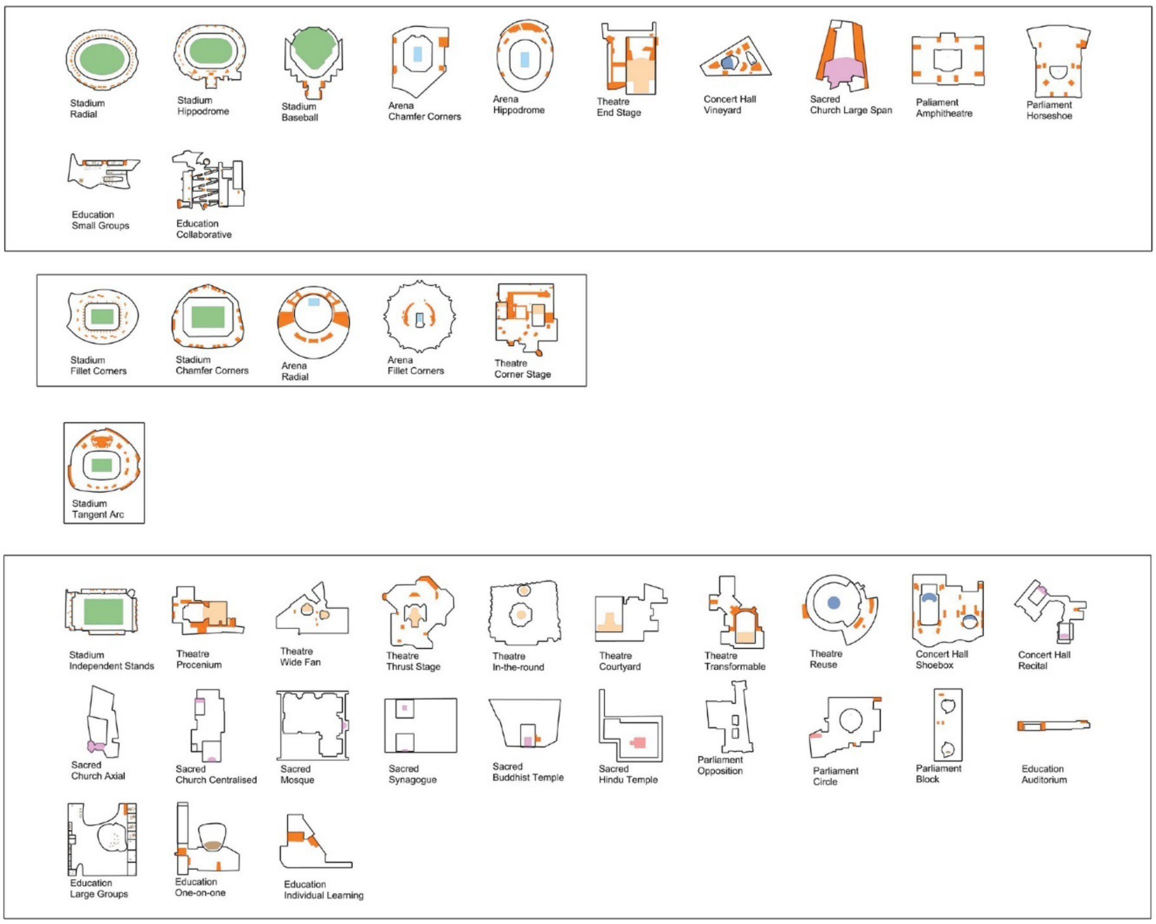



*Figure 2.45. Classification based on relationship between access routes and GA concourse (main access floor)*

Building Scale :
Ground floor footprint

Evaluation parameters:
Level footprint
Circulation area

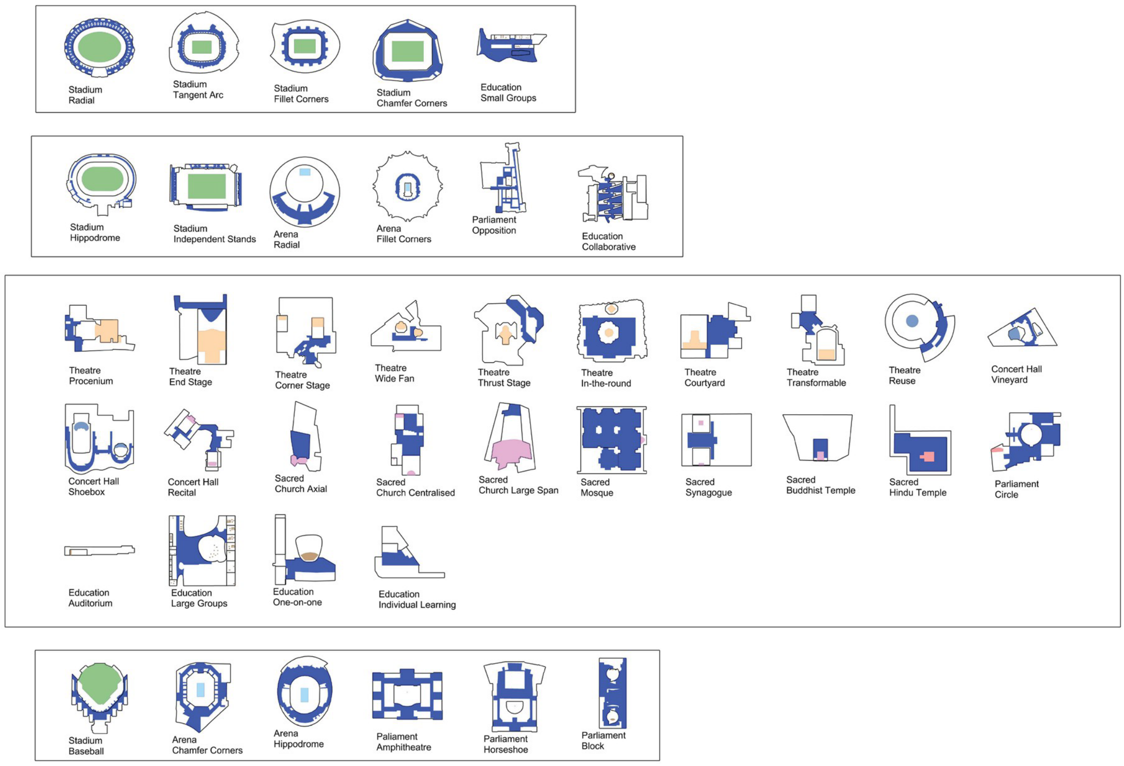



- Commercial
- Circulation
- GA Concourse
- Hospitality
- Media
- Parking
- Performers` spaces
- Podium
- Service
- Toilets

*Figure 2.46. Classification based on circulation areas other than concourse (main access floor)*

Building Scale :
Ground floor footprint

Evaluation parameters:
GA Concourse area
Level footprint area




- Commercial
- Circulation
- GA Concourse
- Hospitality
- Media
- Parking
- Performers` spaces
- Podium
- Service
- Toilets

*Figure 2.47. Classification based on GA Concourse to level footprint relationship (main access floor)*

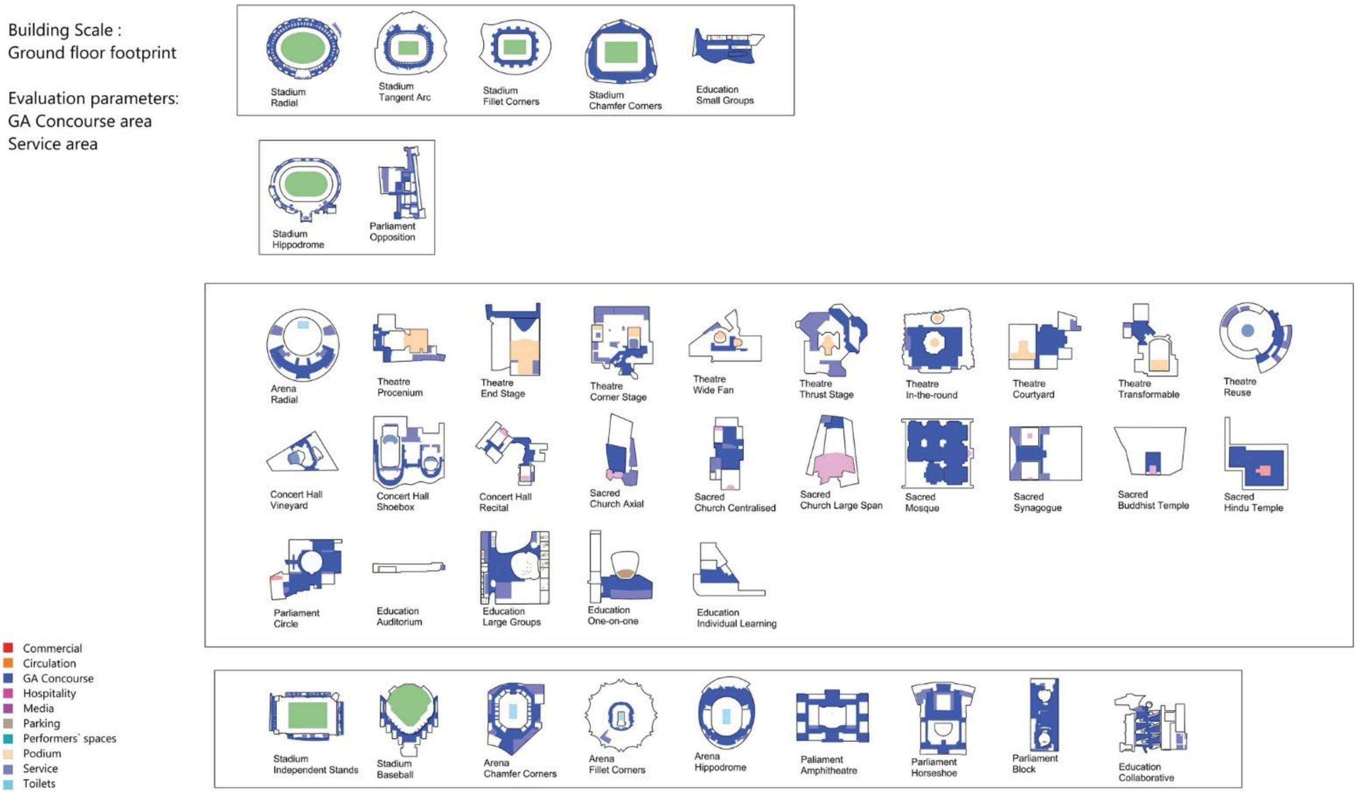



*Figure 2.48. Classification based on GA Concourse to service areas relationships (main access floor)*

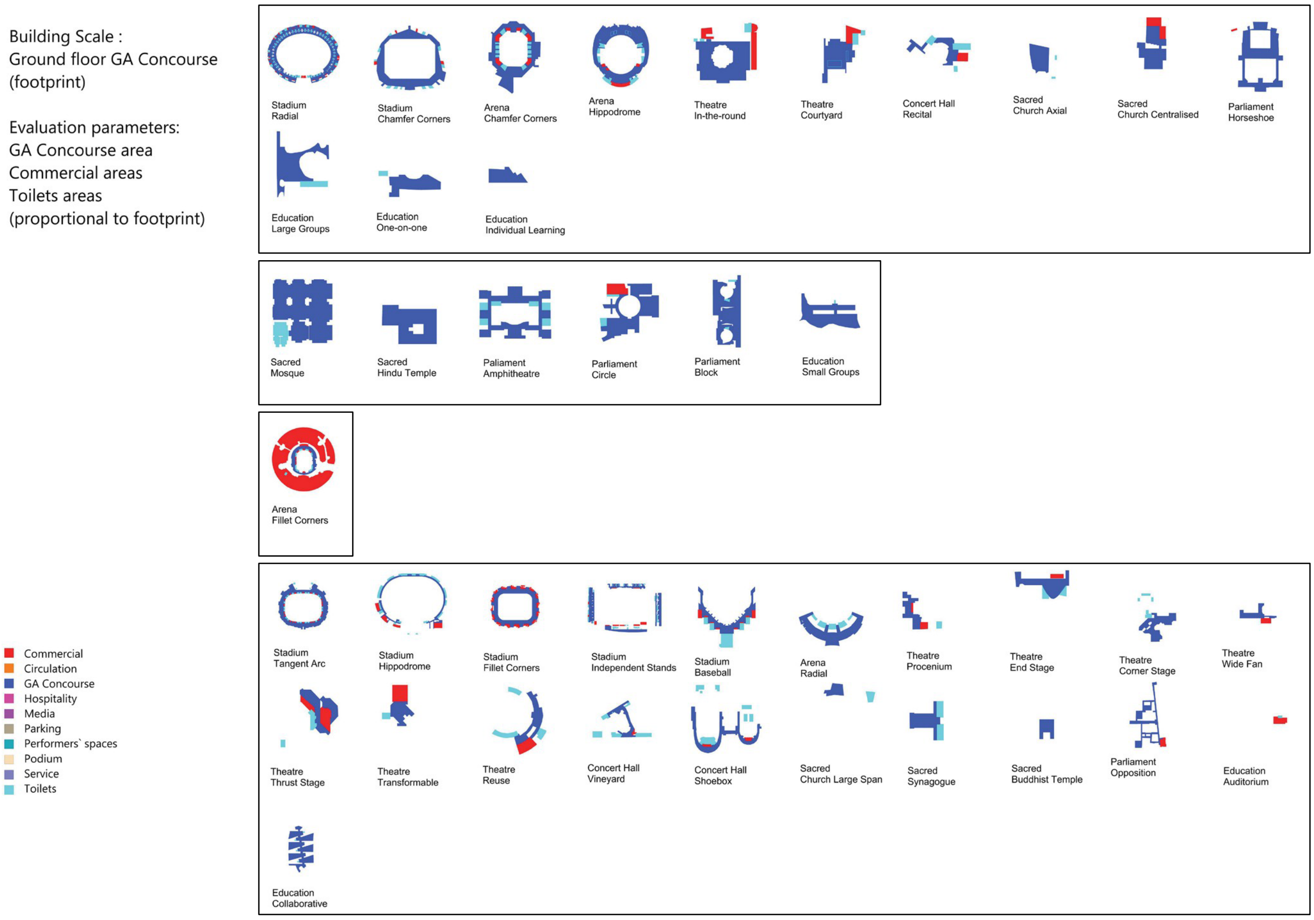



*Figure 2.49. Classification based on GA Concourse to commercial and toilets areas (main access floor, GA concourse scale)*

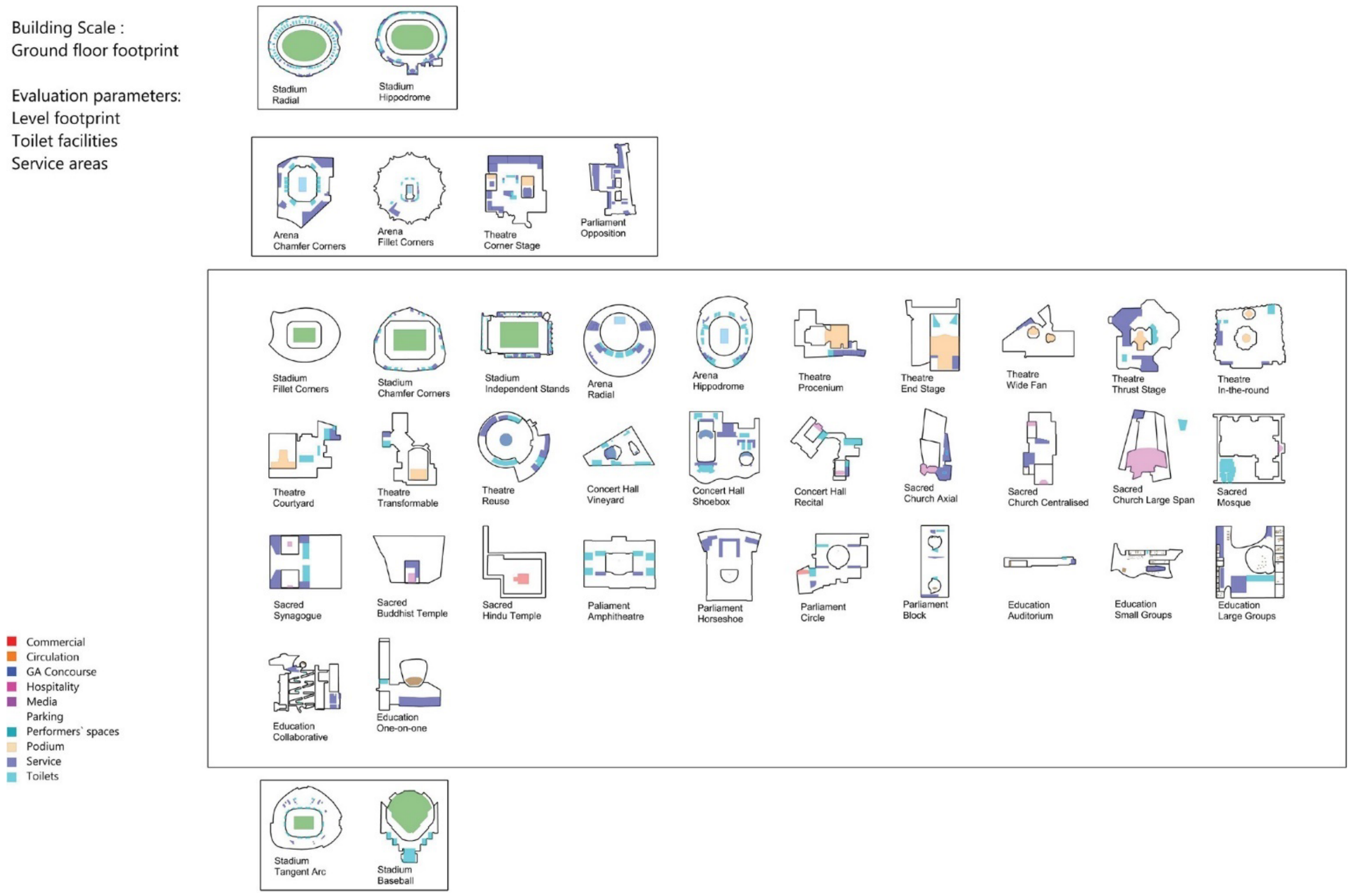



*Figure 2.50. Classification based on services and utilities (main access floor)*

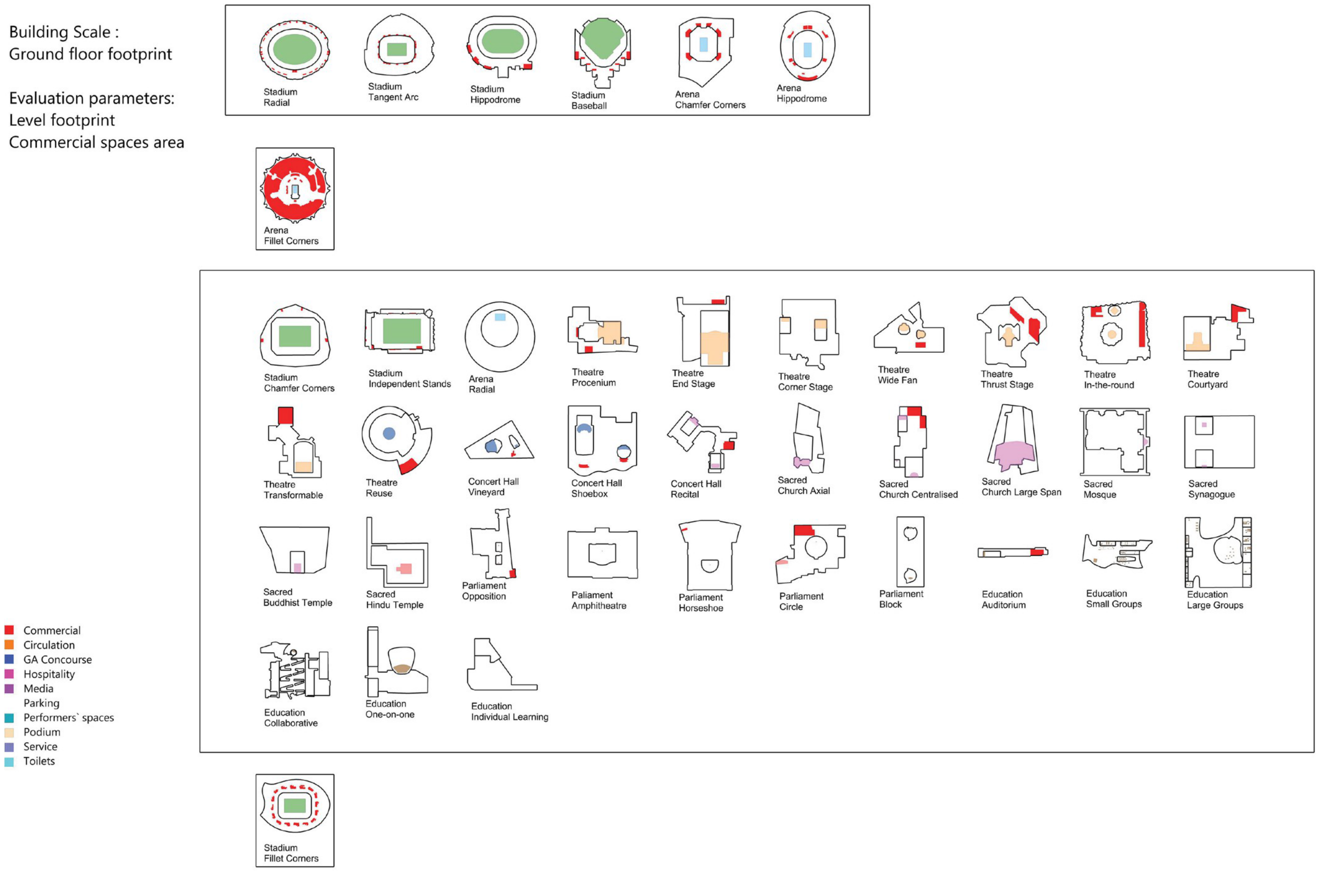



*Figure 2.51. Classification based on commercial spaces (main access floor)*

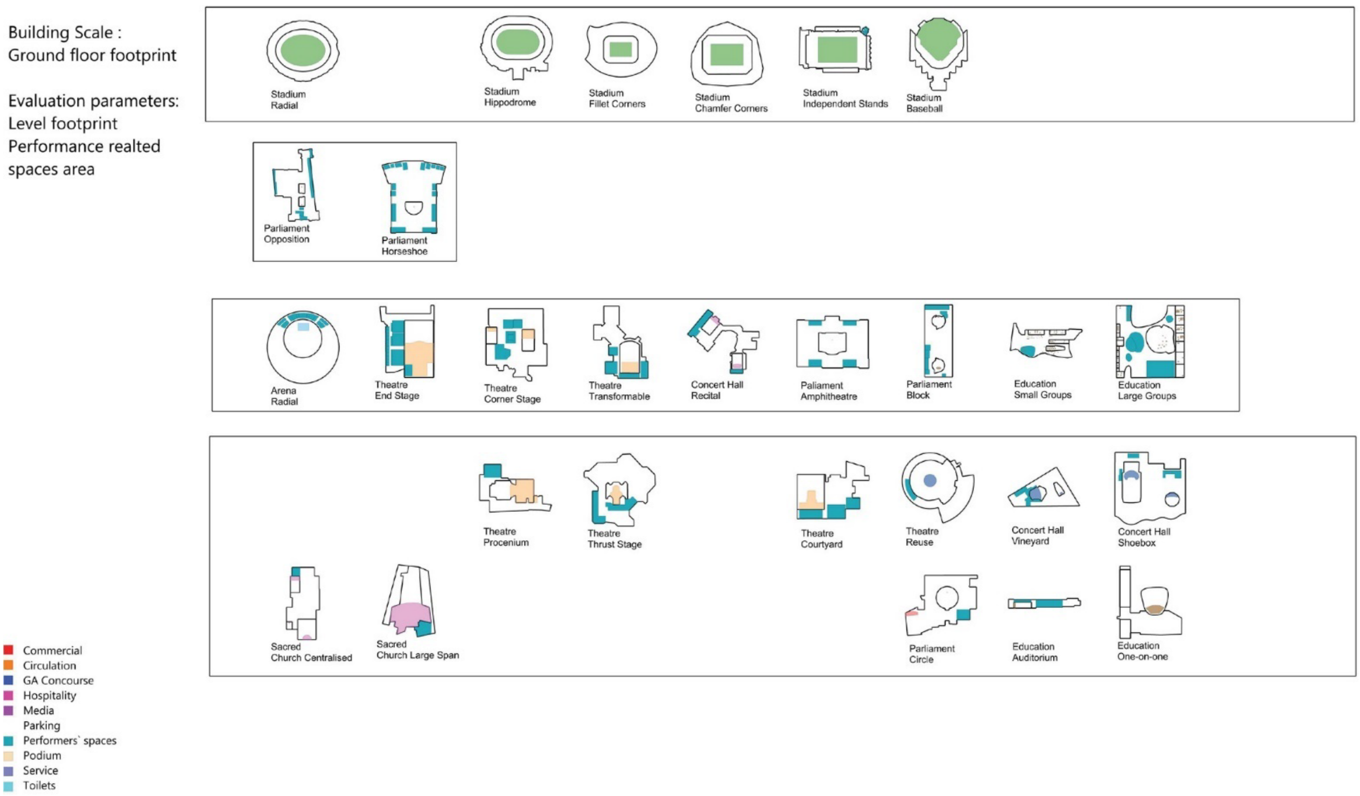



*Figure 2.52. Classification based on performance-related spaces (main access floor)*

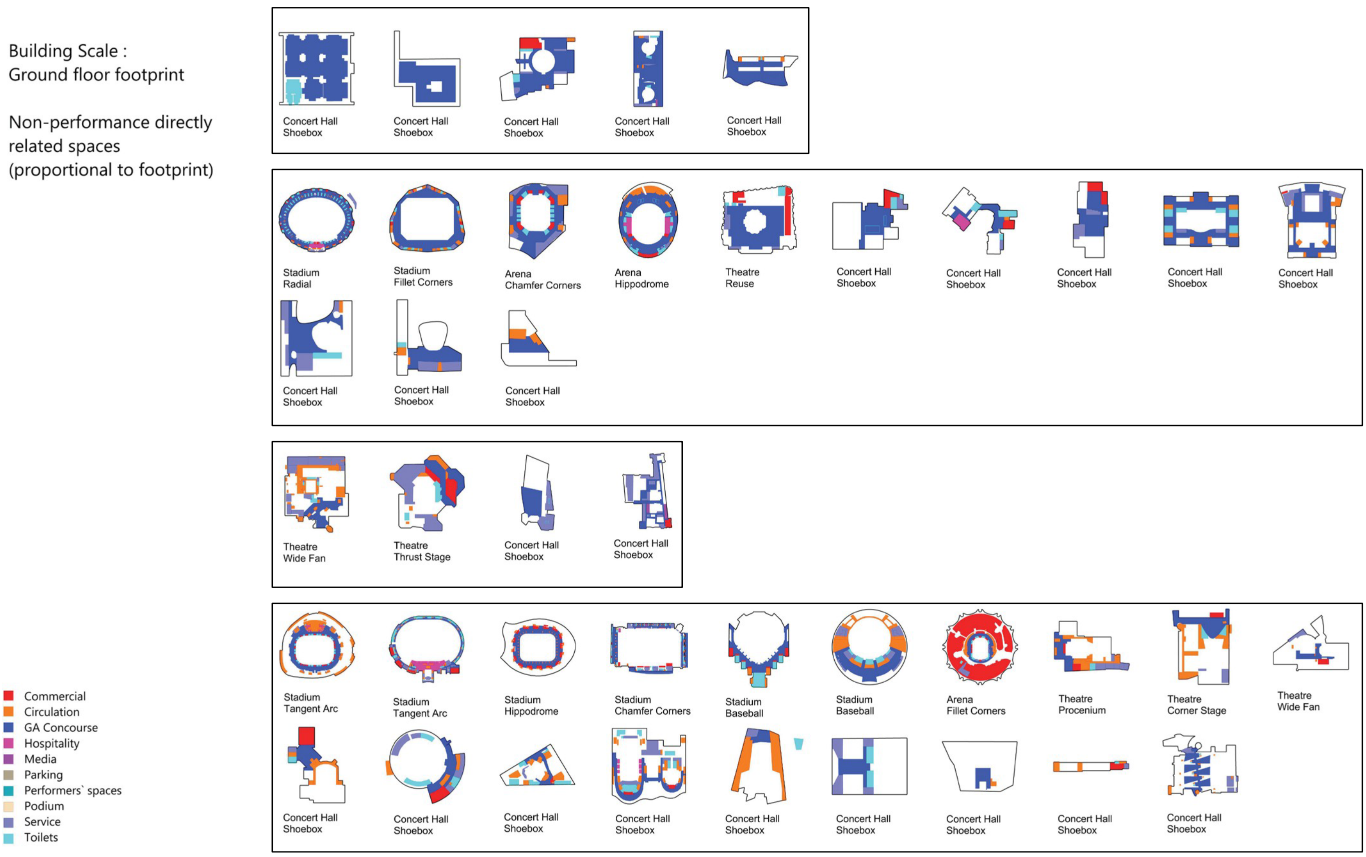



*Figure 2.53. Classification based on non-performance-related spaces (main access floor)*

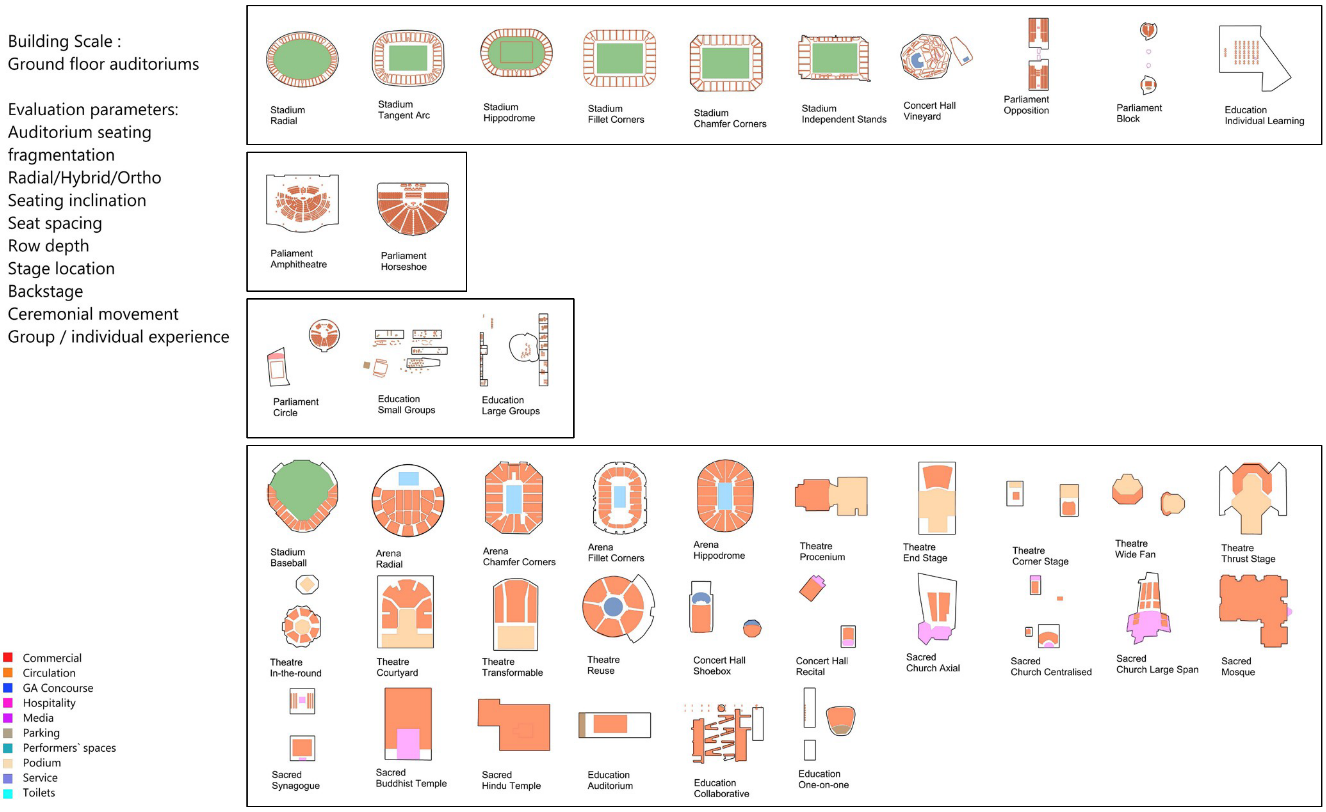



*Figure 2.54. Classification based on auditorium properties*

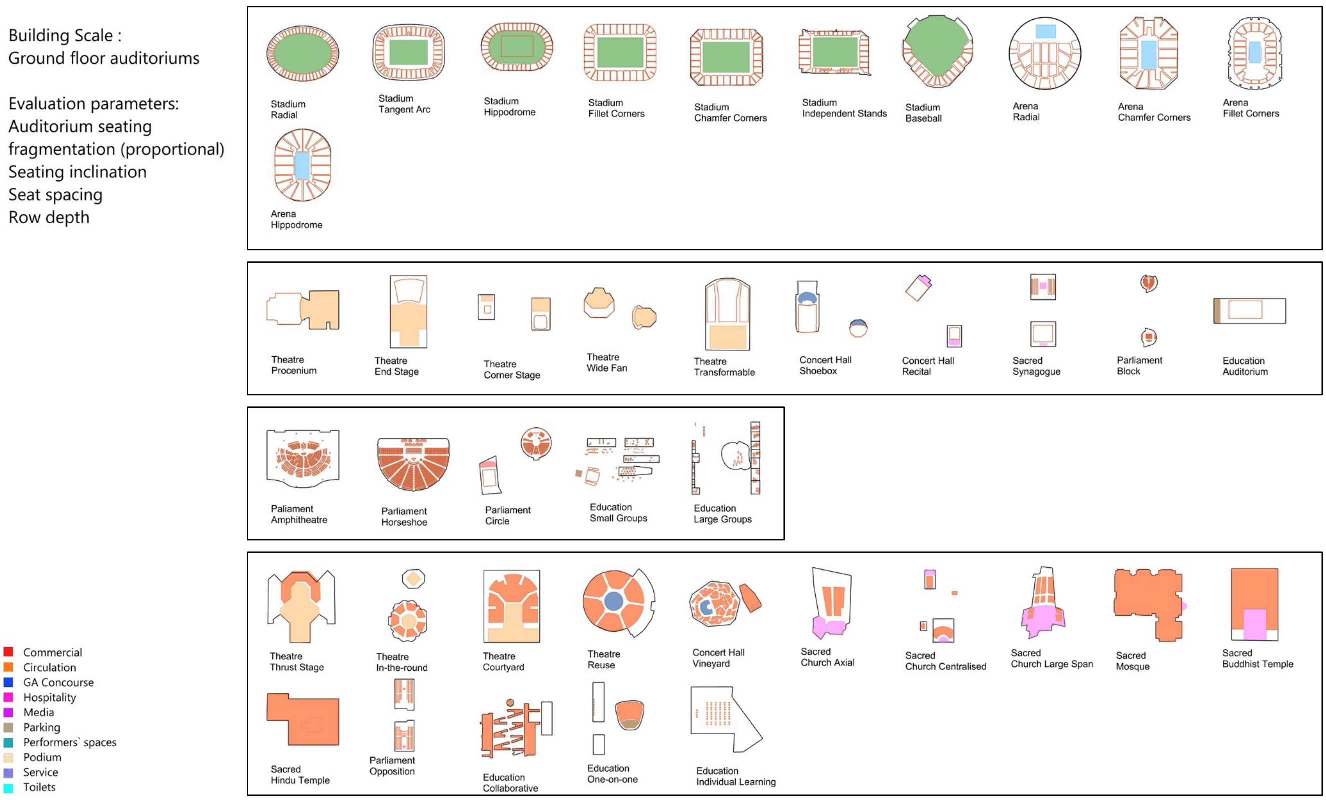
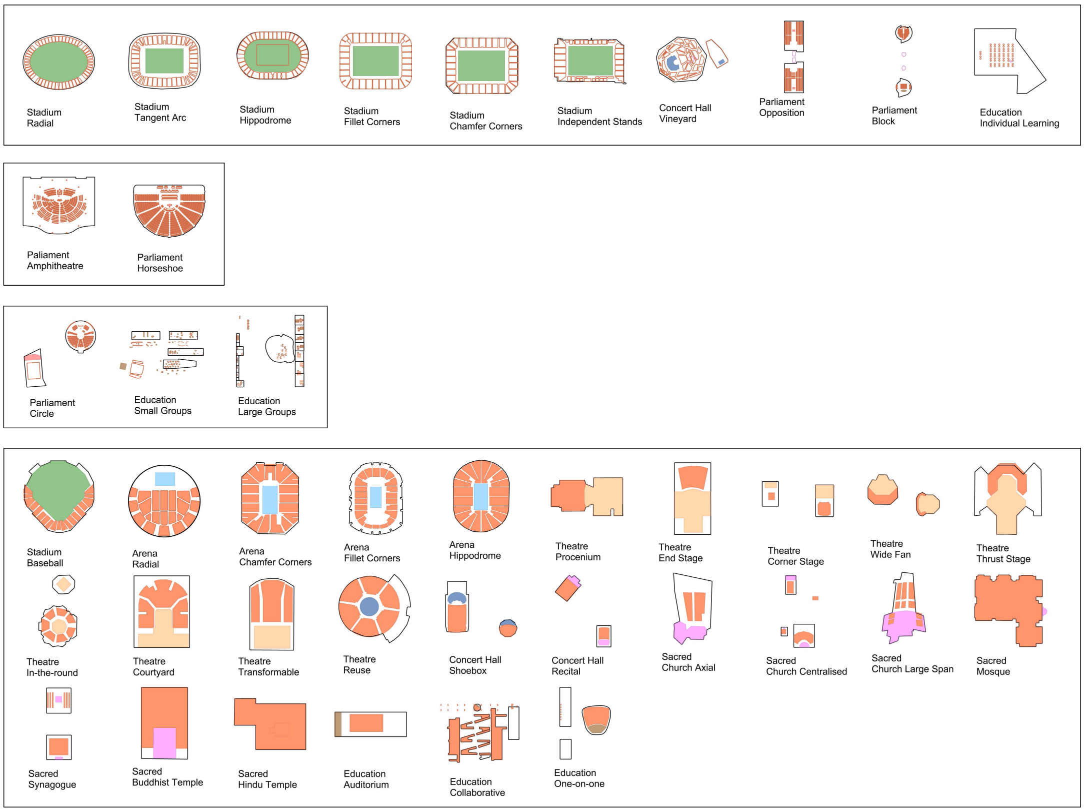



*Figure 2.55. Classification based on auditorium properties*

Building Scale :
Ground floor auditoriums

Evaluation parameters:
Auditorium seating
fragmentation
Radial/Hybrid/Ortho
Seating inclination
Seat spacing
Row depth
Stage location
Backstage
Ceremonial movement
Group / individual experience

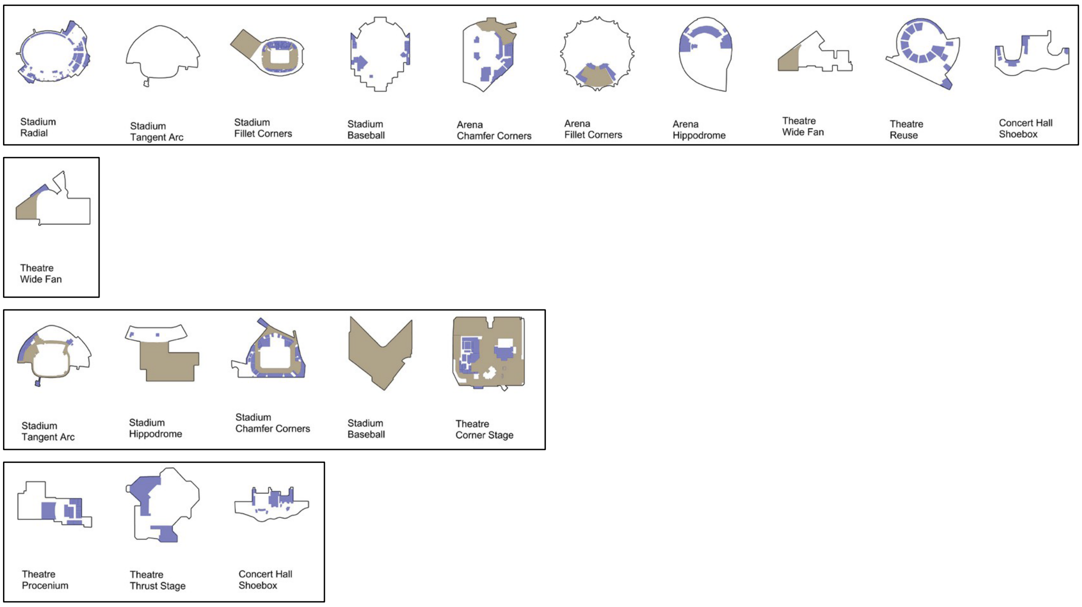



Commercial
Circulation
GA Concourse
Hospitality
Media
Parking
Performers` spaces
Podium
Service
Toilets

Figure 2.56. Classification based on auditorium properties in relation to concourses and services

Building Scale :
Basement - Parking and service

Evaluation parameters:
Parking areas
Service areas
(proportional to footprint)




Commercial
Circulation
GA Concourse
Hospitality
Media
Parking
Performers` spaces
Podium
Service
Toilets

Figure 2.57. Classification based on basement properties in relation to parking and services

## 2.7 Translation of typological characteristics into structured relationships

### 2.7.1 Design driver classification

The next methodological challenge faced by these approaches to design is the question 'How can this new information be structured?' Digital representation enables the creation of a dataset and groupings, but conclusions are yet to be reached. This research approaches this problem by bringing all the analysis features from the previous phases together and evaluating the weight of each feature on the overall classification.

The findings from the spatial-numerical machine learning analysis are summarised in a set of decision-making hierarchy trees which highlight the different classifications based on the properties of public assembly buildings. There are two trees – orthogonal and radial – for each analytical category, based on the organisation of the specific case study. There are three sets of classifications based on the three primary zones of each of the buildings – footprint, auditorium, stage. Each layer is based on a design driver and the internal hierarchies are based on the design criteria that differentiates the specific branch. The characteristics that were most distinct became the base identifiers for the next phase of the project.

| Table 2.7. Revised analytical categories following spatial-numerical analysis | | |
|---|---|---|
| **Analytical category** | **Spatial-numerical model** | **Decision-making trees** |
| Circulation | Number of external access points | Access |
| | Level 1 - General admission access to main building, Level 2 - GA movement inside building, Level 3 - General admission access to auditorium (main access floor) | Circulation continuity |
| | Classification based on fragmentation of crowd flow (main access floor) | Circulation continuity |
| | Relationship between access routes and general admission concourse (main access floor) | Circulation continuity |
| | Circulation areas different than concourse (main access floor) | Circulation continuity |
| | Ceremonial movement | |
| Layout | Group/individual experience | |
| | General admission concourse to service areas relationships (main access floor) | |
| | General admission concourse to all other area relationships(main access floor) | |
| | General admission concourse to commercial and toilets areas (main access floor, GA concourse scale) | |
| | Services and utilities (main access floor) | Services and utilities (main access floor) |
| | Commercial spaces (main access floor) | Commercial spaces (main access floor) |
| | Performance-related spaces (main access floor) | Performance-related spaces (main access floor) |
| | Non-performance-related spaces (main access floor) | Non-performance-related spaces (main access floor) |
| | Concourse - relationship with other functions | Concourse - relationship with other functions |
| | General admission concourse to level footprint relationship (main access floor) | |
| | Auditorium classification based on general admission concourse and services areas | |
| | Basement - building support relationships (in the case studies that have basements with publicly available plans) | |
| | Parking and service areas | Parking and service areas |
| | All support functions | Non-performance-related spaces (main access floor) |
| | Organisational patterns of areas other than concourse (main access floor) | |

| | | |
|---|---|---|
| | Backstage | |
| | Building footprint area | |
| | Auditorium area | |
| | | Multiple auditoria |
| | Stage area | Stage area |
| | Auditorium capacity | Auditorium capacity |
| | Roof | Roof |
| | Part-to-whole stage/auditorium/building scale | Part-to-whole stage to building footprint morphology |
| | Part-to-whole auditorium to building footprint | Part-to-whole auditorium to building footprint |
| | Part-to-whole stage to building footprint morphology | Part-to-whole stage to building footprint morphology |
| Sightlines | Auditorium - seating arrangement and other relationships | Auditorium seating continuity |
| | Stage to auditorium relationship | Auditorium airflow |
| | Stage to auditorium relationship | Auditorium lighting |
| | Stage to auditorium relationship | Auditorium acoustics |
| | Auditorium classification based on seating fragmentation | |
| | Seat spacing | Seat spacing |
| | Row depth | Row depth |
| | Seating inclination | Auditorium slope |
| | Stage location | Stage materiality |
| | Stage location | Stage mechanics |
| | Stage location | Stage multifunctionality |
| | Structure type | Structural grid type |
| | | Stage circulation |
| | | Stage alternative uses |
| Building data | Completion year | |
| | Last refurbishment | |

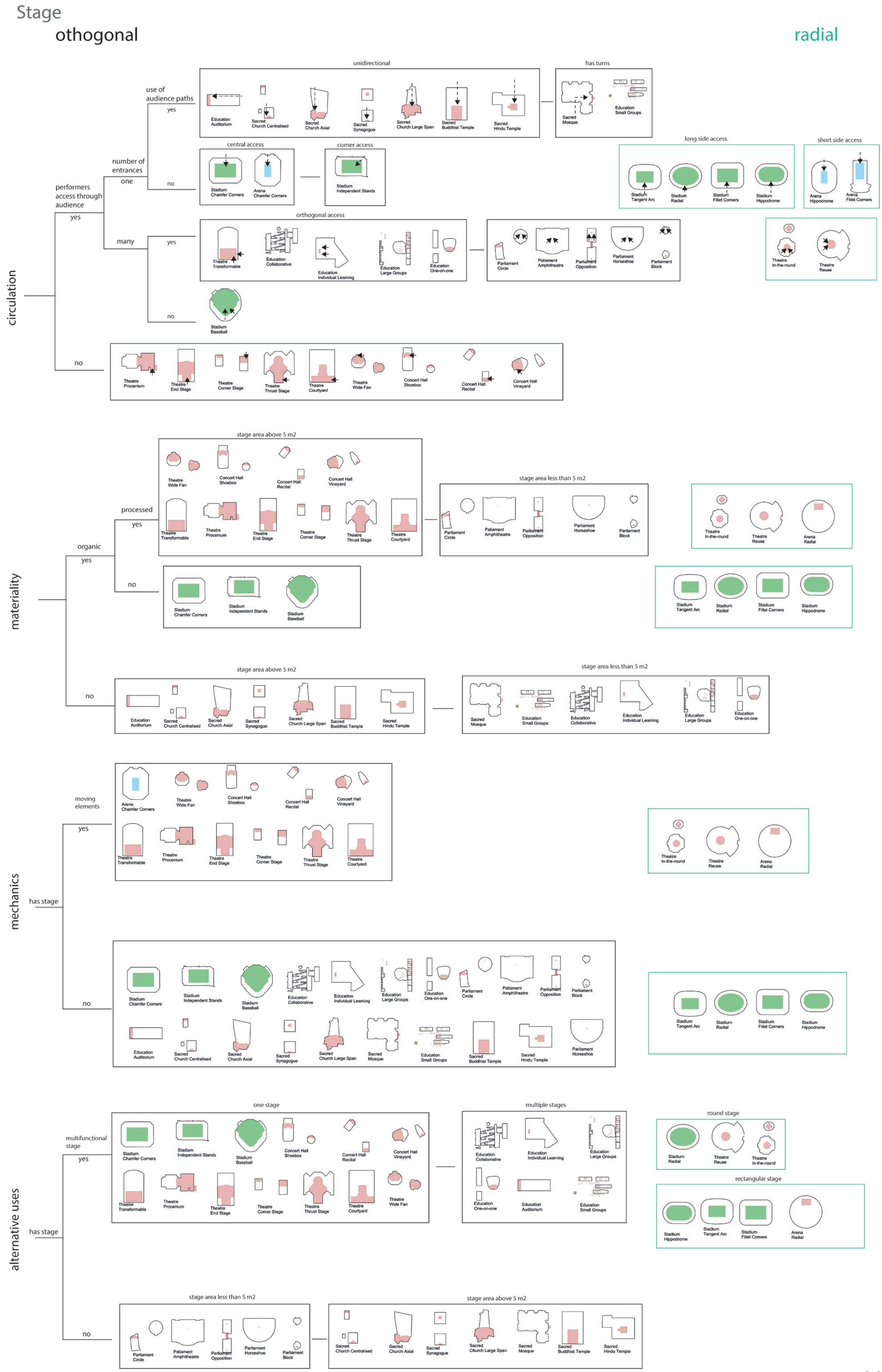





*Figure 2.58. Decision-making trees based on auditorium properties (high resolution image)*

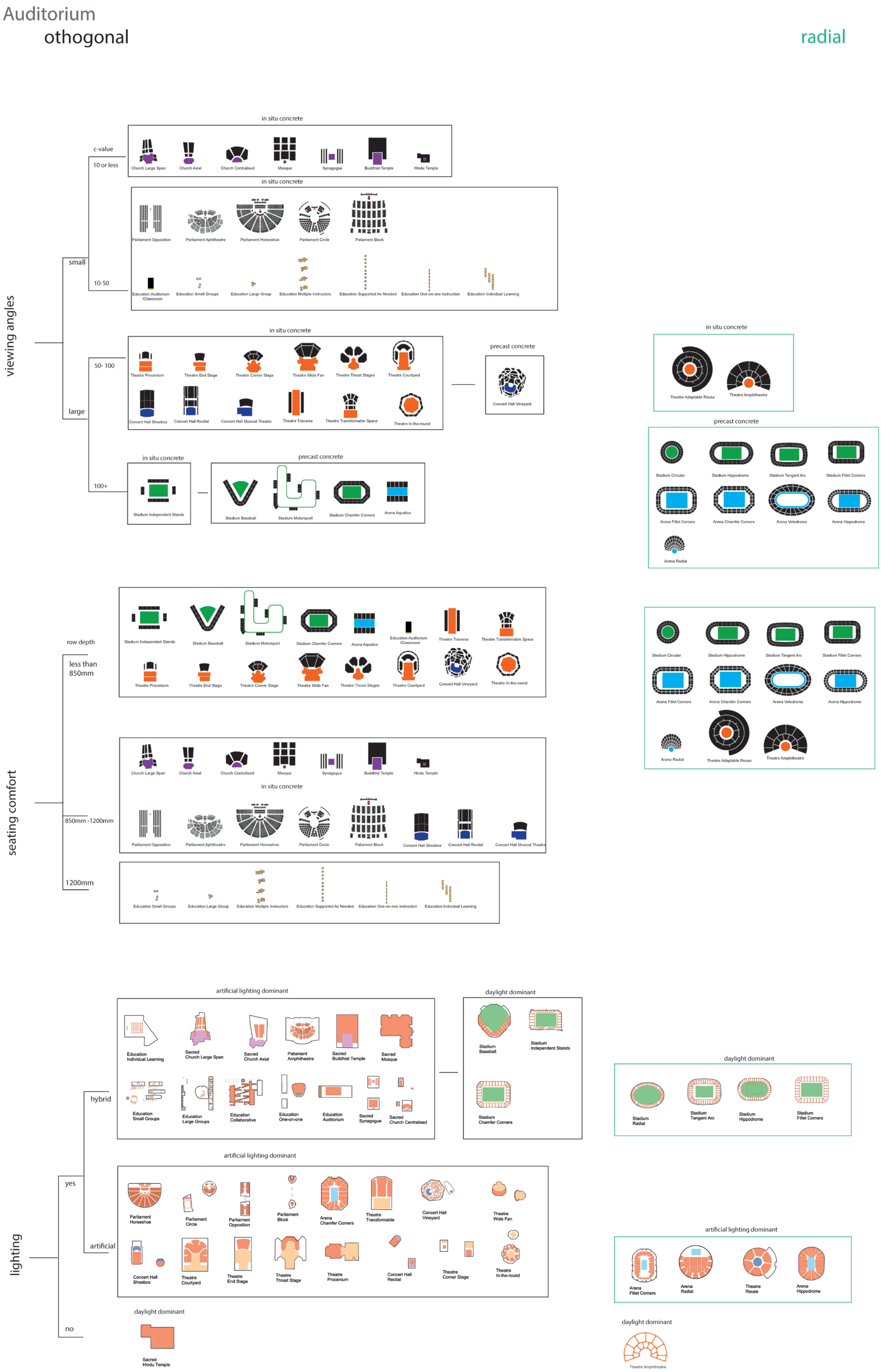



*Figure 2.59. Decision-making trees based on auditorium properties (high resolution image)*

Auditorium
othogonal

radial

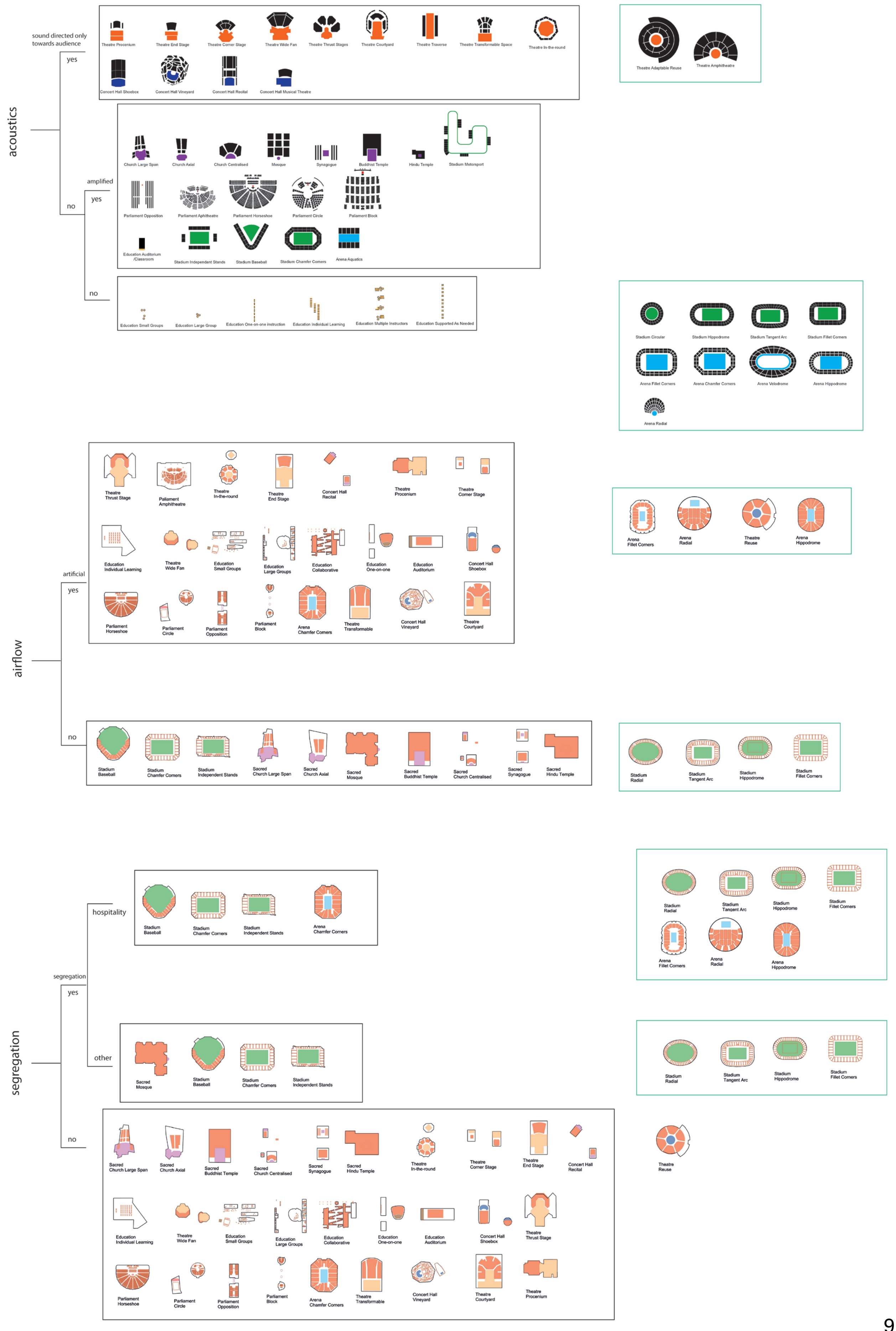



Figure 2.60. Decision-making trees based on auditorium properties (high resolution image)

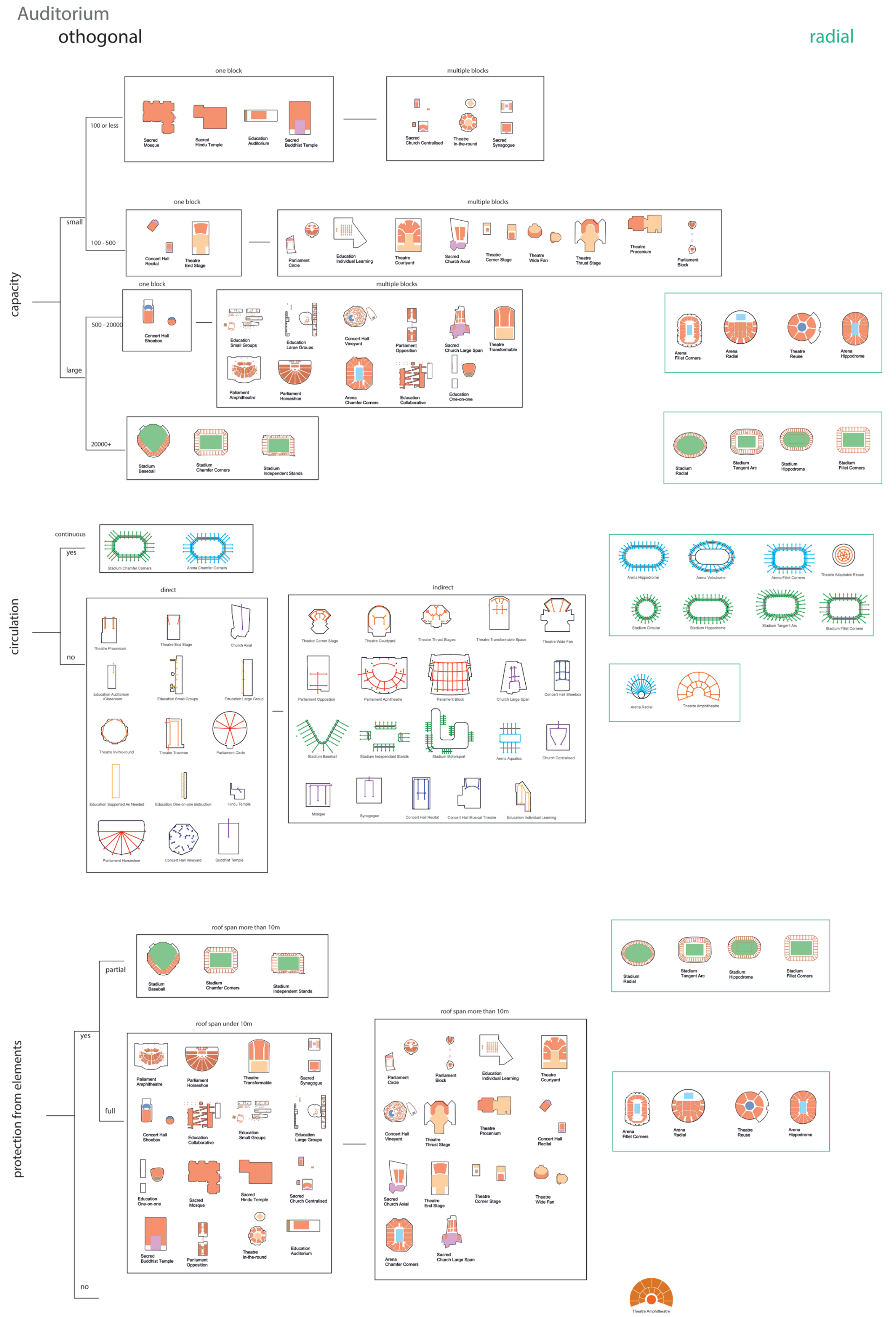



*Figure 2.61. Decision-making trees based on auditorium properties (high resolution image)*

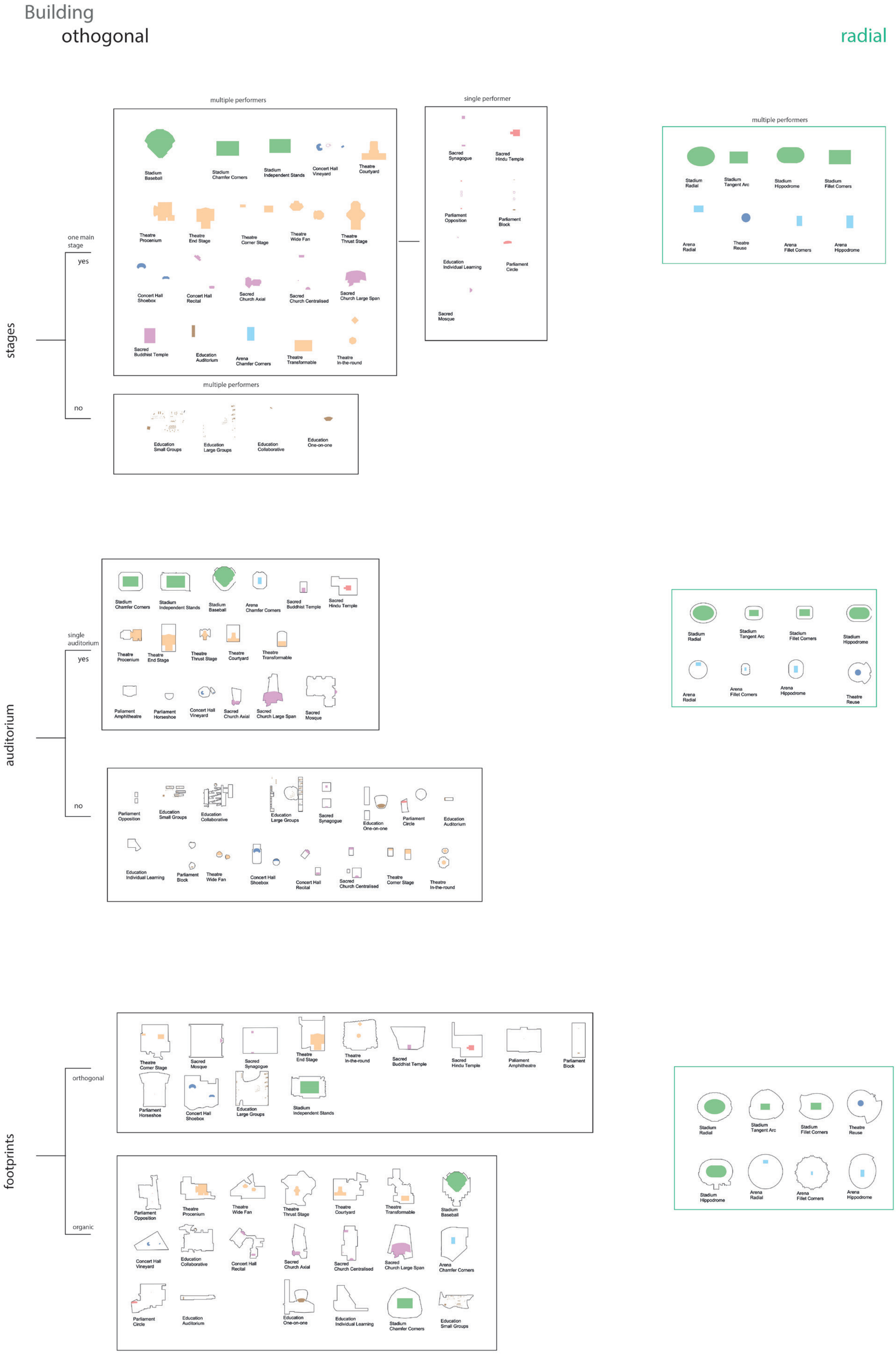



*Figure 2.62. Decision-making trees based on building properties (high resolution image)*

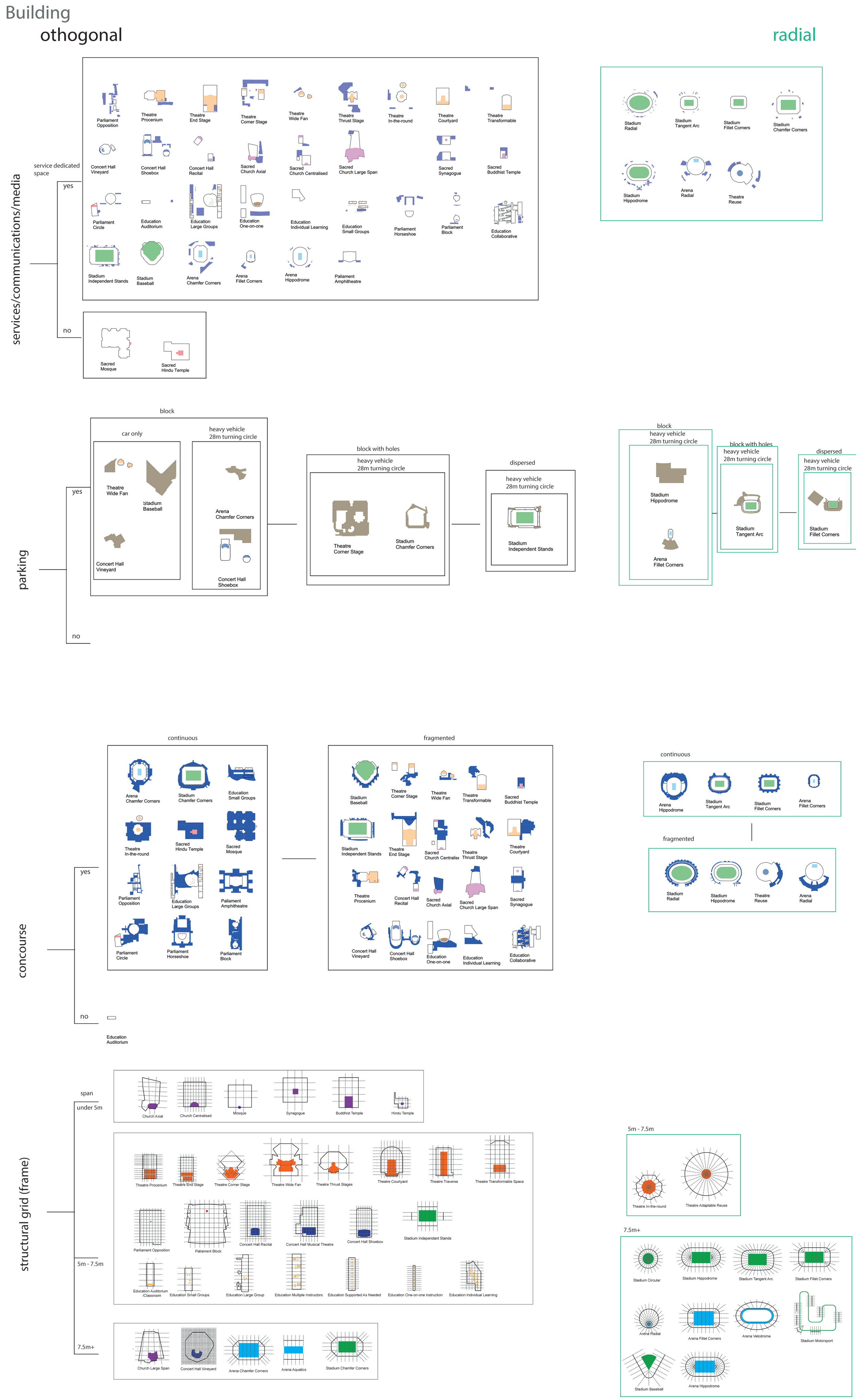



*Figure 2.63. Decision-making tree based on building properties (high resolution image)*

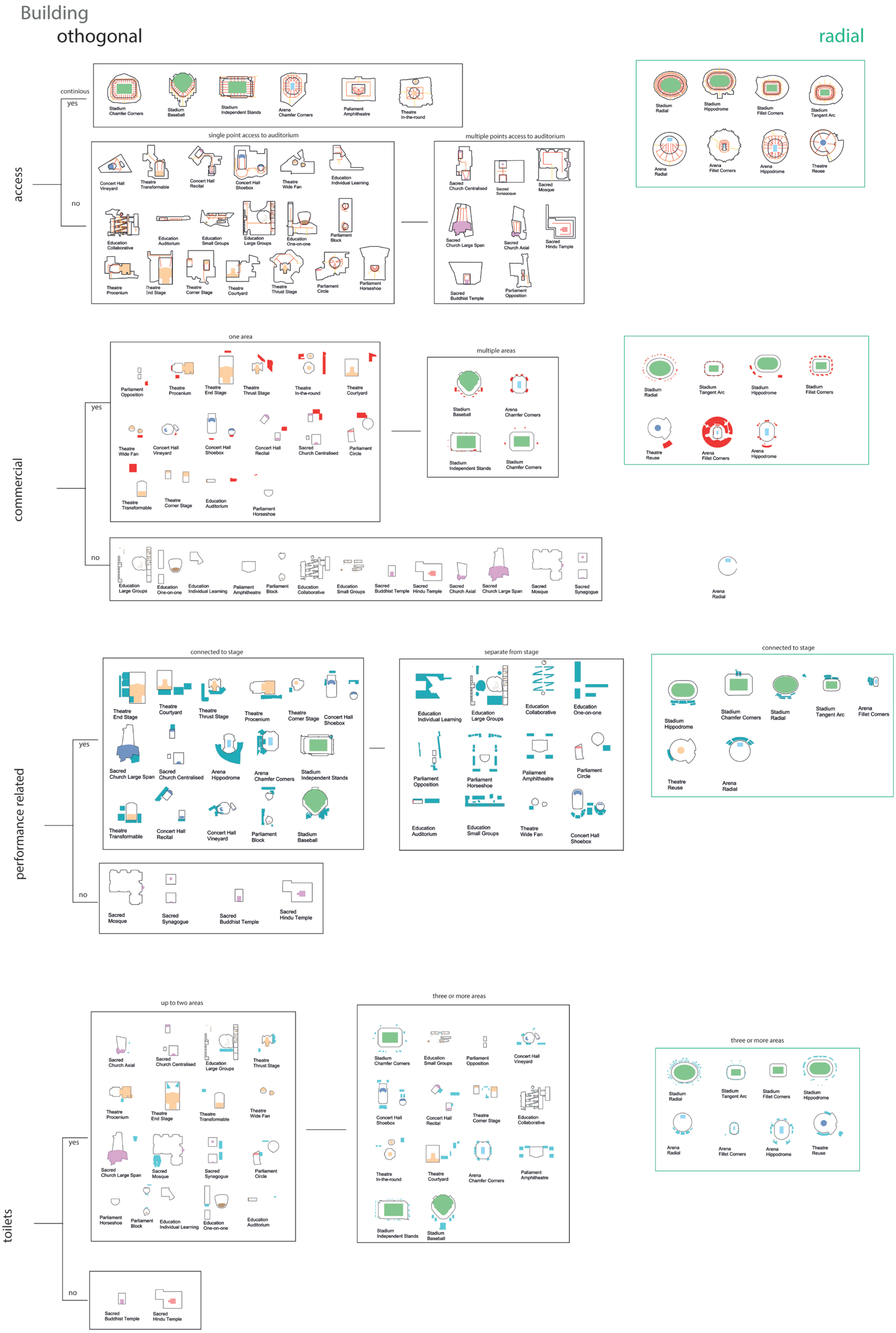





*Figure 2.64. Decision-making tree based on building properties (high resolution image)*

## 2.8 Design driver trees

The construction of the decision-making trees enables the creation of evolutionary hierarchy trees which map out all the genres of Places for Assembly and Recreation and stadiums through quantifiable properties and design drivers. This process is one of the pivotal steps that need to be taken to overcome the problem of bringing stadiums to 3D form from the available 2D information and the subsequent analysis across the case studies. Without this step it would have been impossible to measure distances and areas: hence it would not have been possible to make the step towards analysis and optimisation. With this step completed, however, the research succeeded in reaching the level at which analytical categories in the fields of layout, circulation, and morphology/ sightlines can be defined. These categories had previously been discussed by earlier researchers (Department for Culture, Media and Sport, 2018; John et al., 2013, 1981; Leacroft and Leacroft, 1984; Nixdorf, 2008; Wimmer and Martovitskaya, 2016) but had not been brought together into a single set of comparable hierarchy trees.

The hierarchy trees summarise the findings from the machine learning analysis and the decision hierarchy trees: they capture the structural and architectural properties of the buildings and present the different subtypes that emerge from this classification. They are also based on the presence of functional elements such as concourses, sanitary and commercial facilities, structural elements such as sections of the building envelope, basement, or moving elements, and the properties of the seating bowl. Each branch of these trees defines a specific public assembly building type and each horizontal line defines a variation category.

Following the analysis of the results from the morphological classification and the identification the regularities and patterns, the process moves towards mapping the typological characteristics. Each of the hierarchy trees is developed using dominant typological characteristics identified earlier. The trees are divided into two major sections – centralised plan and diffusing plan. They then map the design drivers for each scale of the building and categorise each case study based on its relation to the rest of the typologies.

### 2.8.1 Design driver tree properties

The specific circulation (spectators, staff, players) is indicated on each relevant level. The plans capture the basic design relationship between the stage, the auditorium, and the building footprint where the functional spaces at building scale are organised into three types: an inner ring which does not require daylight, a concourse (circulation), and an outer ring which borders the building envelope. Circulation is superimposed on the functional arrangement and cuts through these spaces. The sections present the basic design of the buildings, but if there are multiple floors or multiple tiers in the auditorium only two are shown. There is an indicator on the top left of each plan showing whether the space can be located above ground (L+), at ground level (L0) and/or below ground (L-).

### 2.8.2 Structural design driver tree properties

Another challenge for the research was the integration of structure into the design driver trees. The task is best approached from an engineering perspective – the building is split into its major sections – roof, stands, stage, basement, vertical elements, slabs, envelope, podium. The two main trees are similar – radial and orthogonal, followed by a division between purpose-built and refurbished. All the structural grids fall into the 6m – 10m group and most of the cases are multistorey with the exception of some of the sacred building typologies. Each of the building elements is then analysed by its main design feature, if present (an oculus in the case of a roof or a permeable envelope in the case of a stadium concourse, for example), structural system type and material.

### 2.8.3 3D Tree Diagram

The combined structural and organisational hierarchy tree summarises the relationships established in the previous phases and sets the foundation for the development of the parametric relationships that later inform the algorithmic modelling. As with the previous steps, the tree is divided into two main sections - assembly/centralised and dispersal/even distribution. The names of the two branches are based on space division theory from Henri Lefebvre's 1974 essay 'Social Space', in his book The production of space (2011). The design drivers are based on the previous steps and overall research analytical categories but differ in terms of their specific areas of analysis. The reason for this is the increased focus on the features that define the stadium category more clearly, such as organisational patterns and morphologies of the various building elements. The classification is further reinforced by the introduction of a full set of basic functions and more detailed descriptions of structural elements.

| Table 2.8. Revised analytical categories following numerical analysis | | |
|---|---|---|
| **Analytical category** | **Decision-making trees** | **Hierarchy trees** |
| Circulation | Access | |
| | Continuity | Circulation continuity |
| Layout | Stage materiality | Stage material |
| | Stage mechanics | Stage mechanics |
| | Stage multifunctionality | Stage multifunctionality |
| | Services and utilities | Services |
| | Commercial spaces | Commercial |
| | Performance related spaces | Backstage |
| | | Other performance support areas |
| | Non-performance related spaces | Hospitality |
| | | Media |
| | | WC |
| | | Basement |
| | | Podium |
| | Concourse - relationship with other functions | Concourse |
| | Auditorium acoustics | Acoustics |
| | Auditorium airflow | Air flow |
| | Parking and service areas | Parking |
| Sightlines | Auditorium seating continuity | |
| | | Structural organisation |
| | | Building organisation |
| | | Plan morphology |
| | Seat spacing | |
| | Auditorium slope | Auditorium slope |
| | | Viewing angles |
| | Auditorium lighting | Lighting |
| | | Auditorium moving elements |
| | | Auditorium material |
| | Stage area | |
| | Structural grid type | Structure type |
| | | Vertical support |
| | | Grid size |
| | | Space dividers |
| | | Slabs |
| | | Envelope |
| | Multiple auditoria | |
| | Part-to-whole stage to building | Stage/auditorium/ building relationship |
| | Roof | Oculus |
| | | Roof type |
| | | Roof material |
| | | Height |
| | Stage circulation | |
| | Stage alternative uses | |
| Building data | Auditorium capacity | |

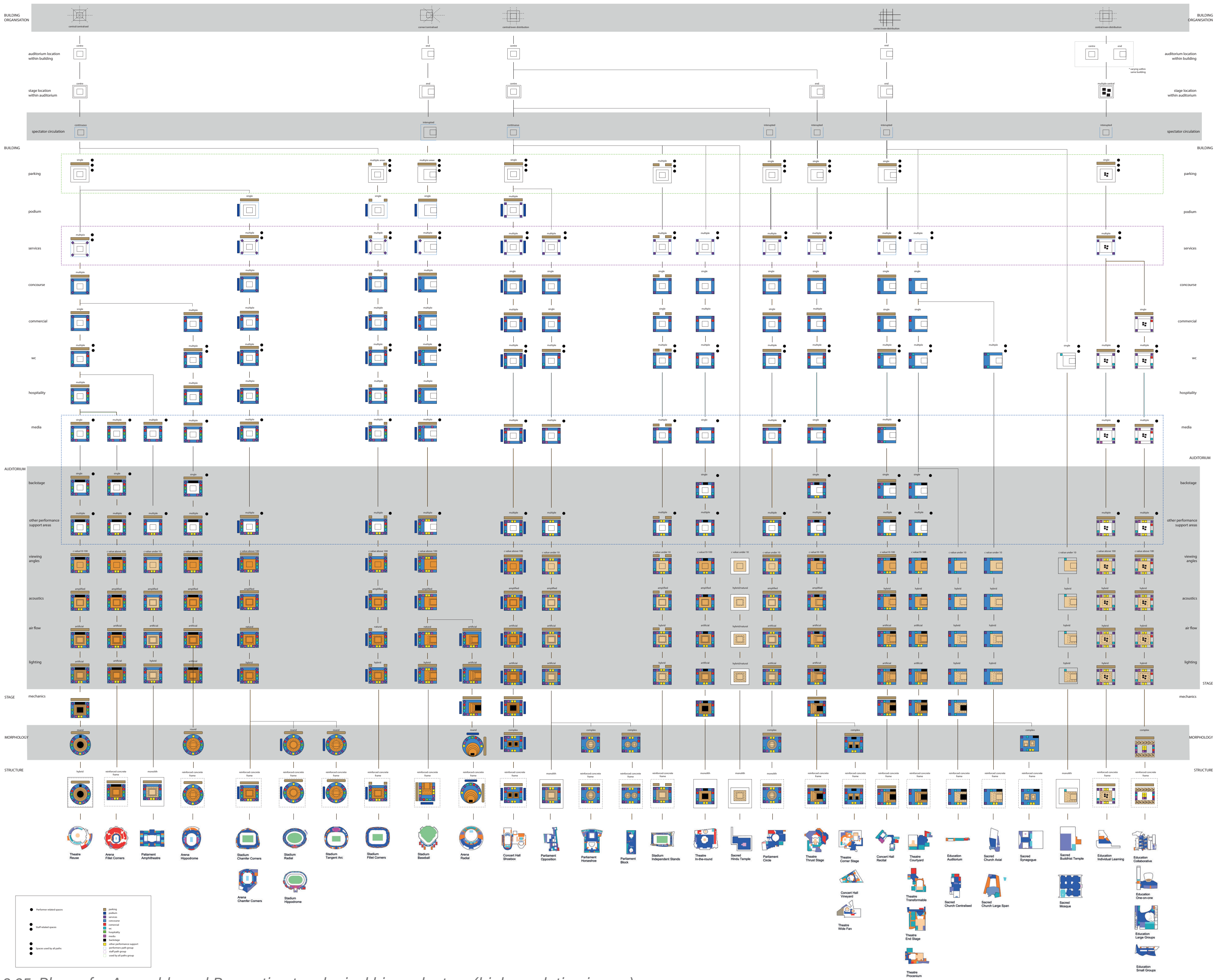


Figure 2.65. Places for Assembly and Recreation typological hierarchy tree (high resolution image)

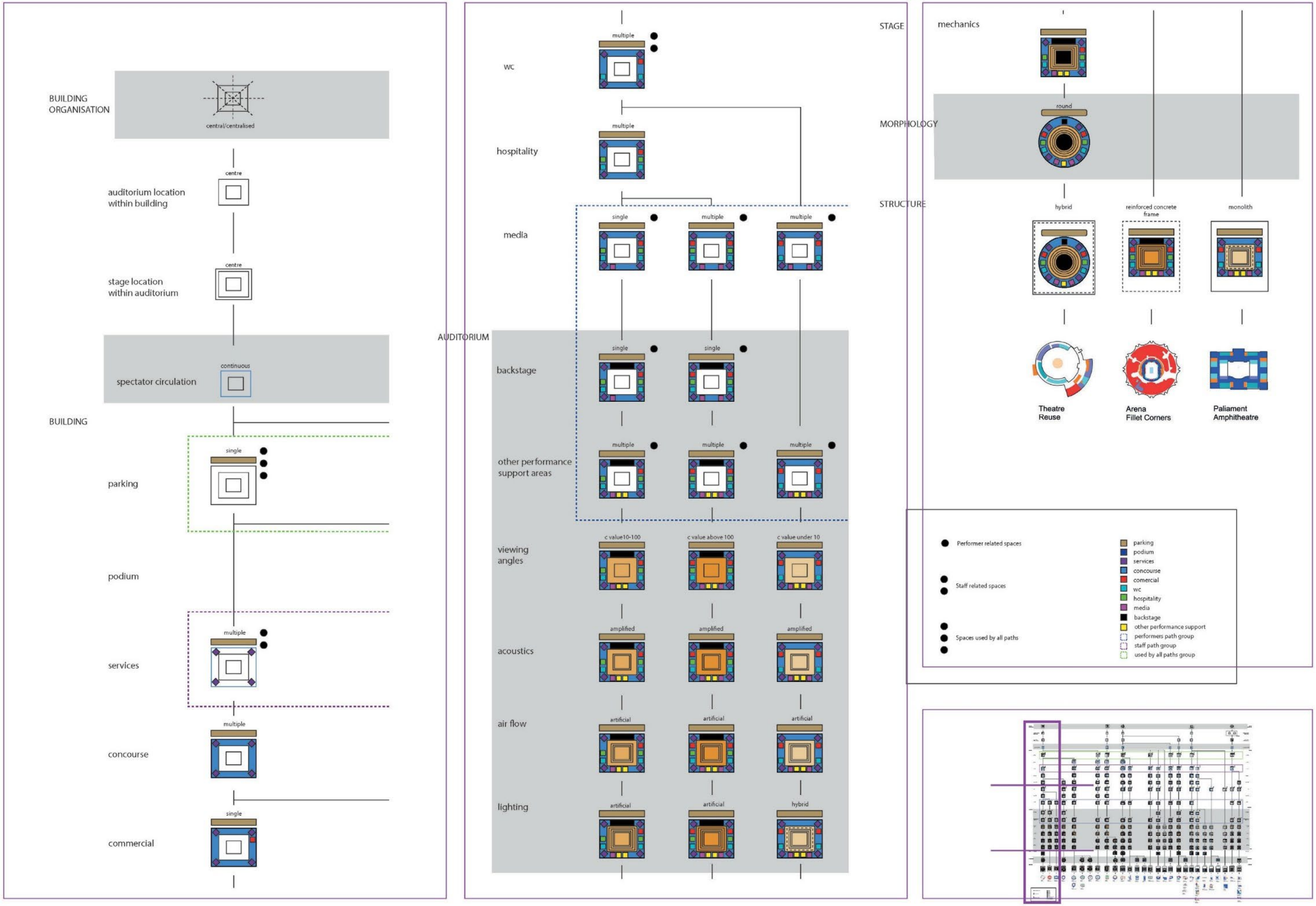



*Figure 2.66. Places for Assembly and Recreation typological hierarchy tree design drivers*

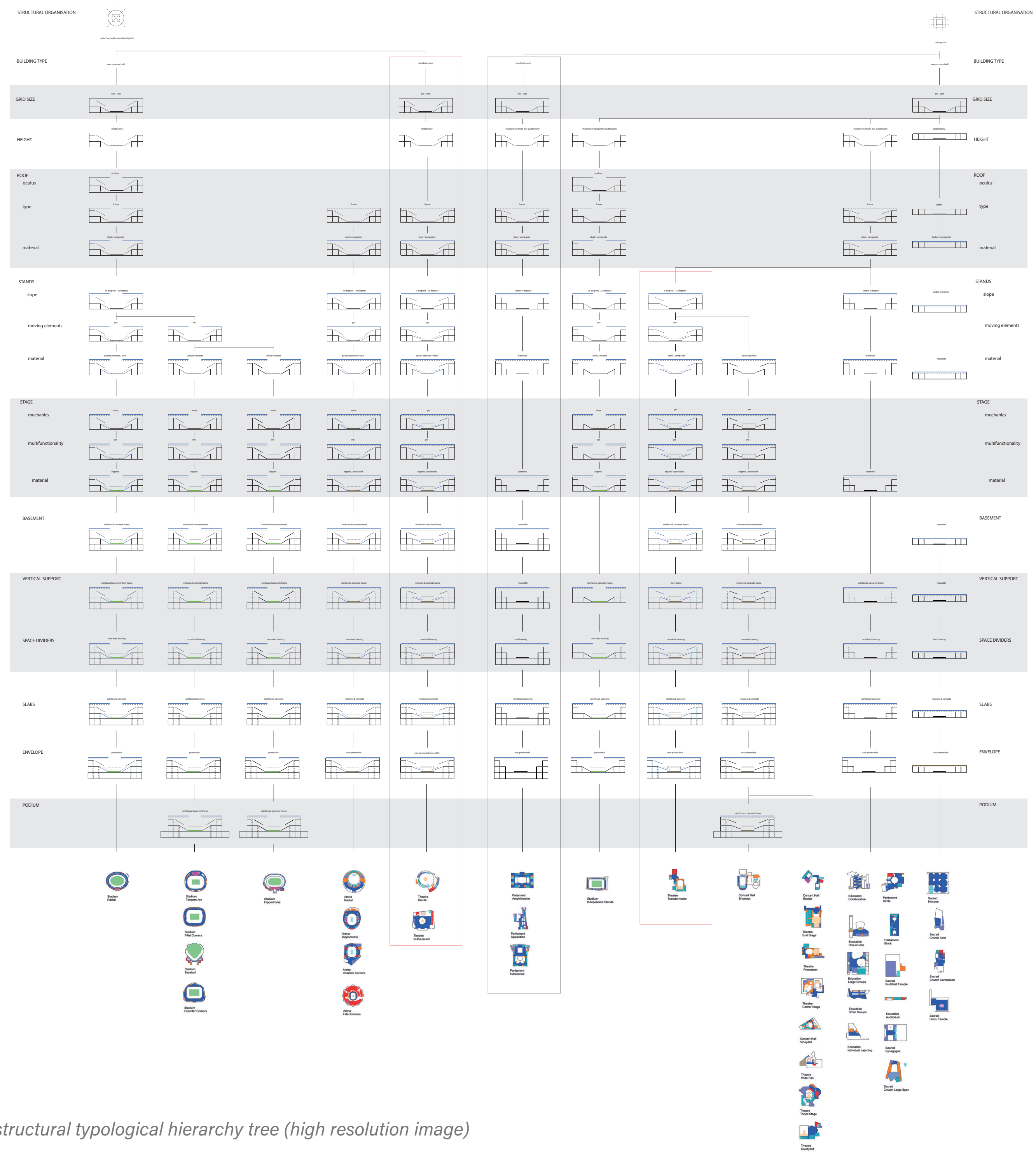


Figure 2.67. Stadium types structural typological hierarchy tree (high resolution image)

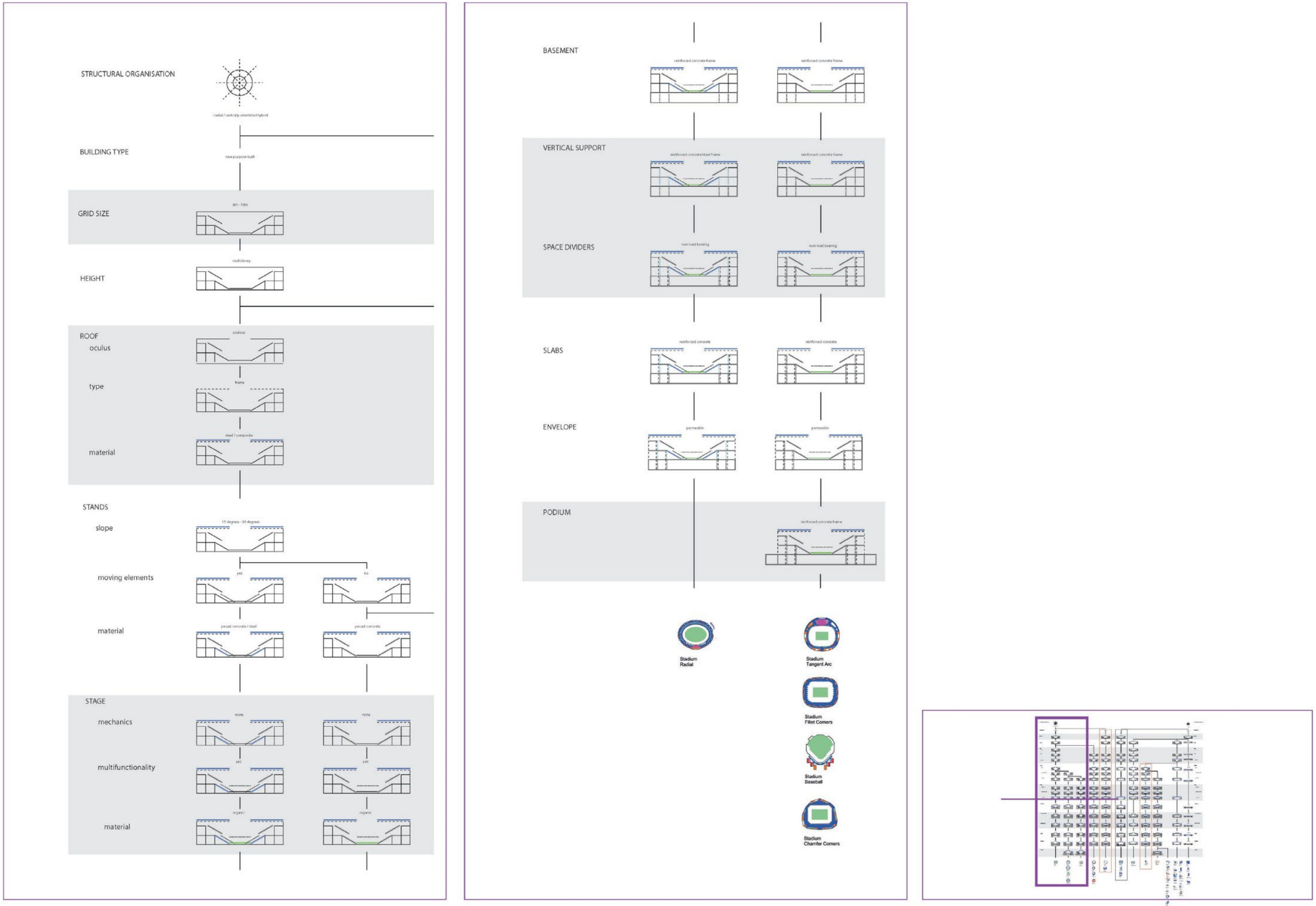



*Figure 2.68. Stadium types structural typological hierarchy tree design drivers*

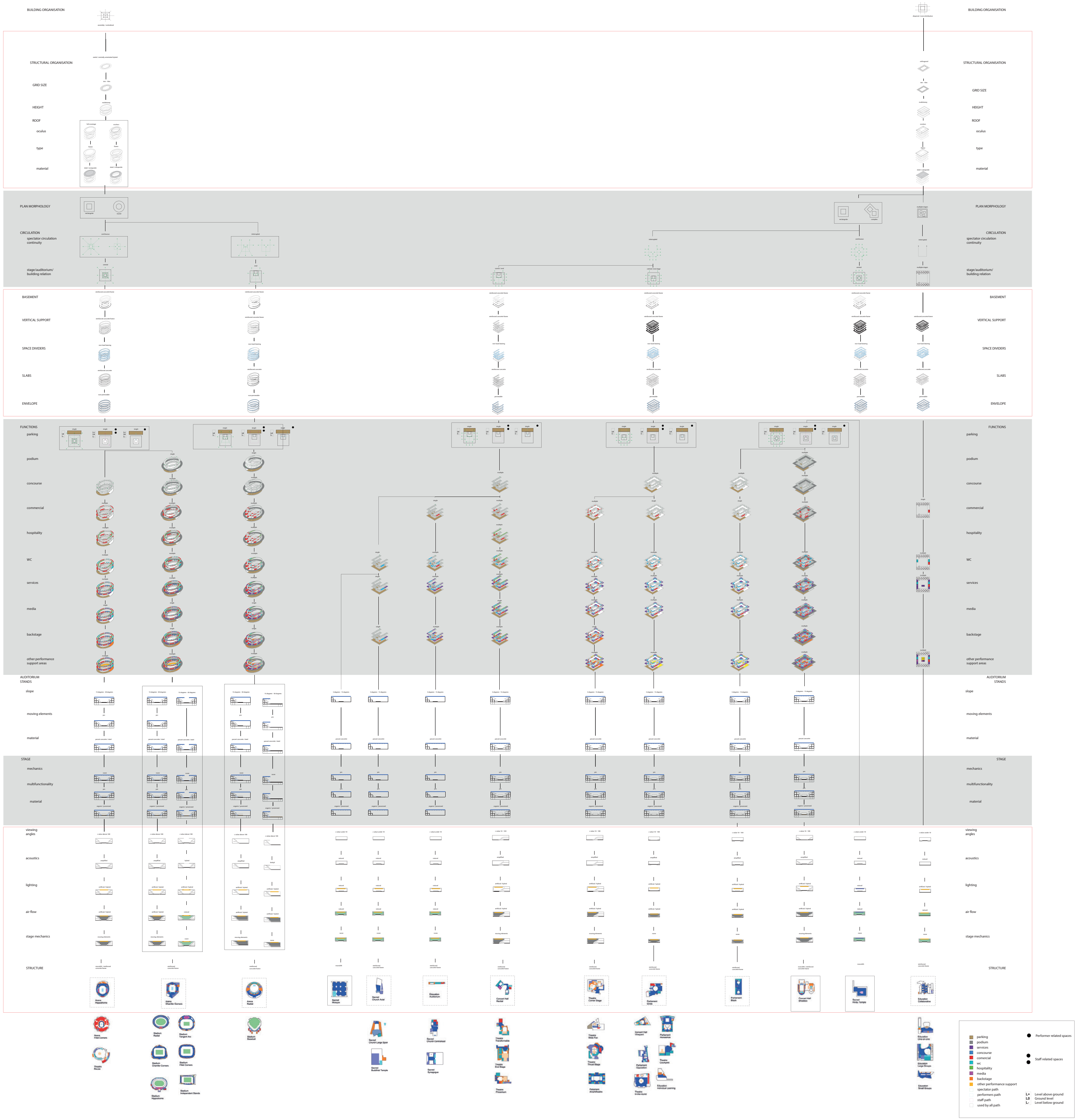




*Figure 2.69. Stadium types architectural and structural typological hierarchy tree (high resolution image)*

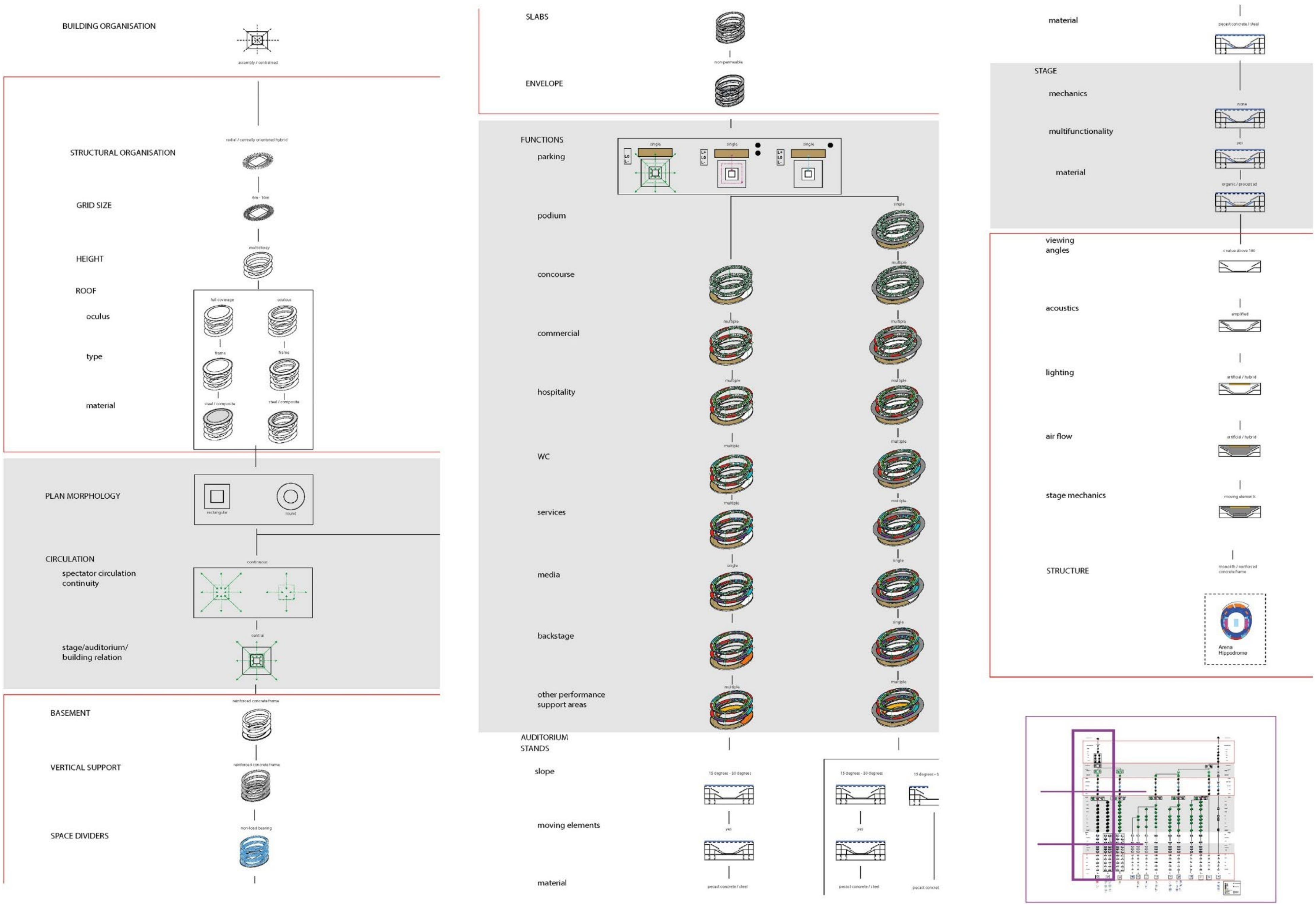



Figure 2.70. Stadium types architectural and structural typological hierarchy tree design drivers

## 2.9 Construction of parametric relationships

The second phase of the research involved the transformation of typological analysis into the construction of an algorithmic model. This approach is utilised so that the research can establish parametric relationships between the design drivers that define stadium design performance in terms of sightlines, layout, and circulation. This approach allows further multidimensional and multi-scale digital representation that covers not only the overall building morphology but also layout and experiential features. The establishment of parametric relationships between design features also allows the use of machine learning to be expanded beyond 2D architectural and structural analysis towards 3D systems. Building on the functional, historic, organisational, legal, experiential, circulation-related, infrastructural, and economic data from the typological studies, parametric representation is used to bring this data into a holistic model. The data is structured as numerical inputs for the related design drivers in the parametric system and allows for a substantial number of previously unattainable analytical dimensions. The multi-dimensional parametric model is consequently used to generate a second dataset that carries all the relevant performance information dimensions.

In terms of performance analysis, the analytical dimensions of the parametric model are grouped into the categories of circulation, structure, envelope, seating bowl, technical, and programme data. By parametrising the stadium genre, the research fully utilises the closed system aspect of the morphological typology and creates an analytical representation that can easily be understood by both machines and humans. The benefits for both academia and practice are found in the level of detail, the ease of interpretation and the use of data that is relevant not only to designers but also to construction professionals and stadium operators. The development of the parametric and machine learning models benefits researchers in other typologies in the areas of public assembly, infrastructure, hospitality, healthcare, and any other building types by creating a framework and set of workflows that can be adapted to other design-specific tasks.

# Chapter 3 Parameters: Stadium Design Criteria

Modularity and adaptability are two of the primary design drivers of stadiums. Along with the safe provision of a high quality viewing experience, the construction of viewing platforms with repeated sections and the ability of the building to adapt to different uses are two of the basic design challenges that architects and builders from antiquity until today have had to face (Kierkuc-Bielinski et al., 2012).

As stadium design evolved throughout history, its complexity increased, as did the understanding of modularity and the different spectator experiences that can be accommodated in stadiums. Due to the intrinsic principle of centralised organisation in this type of building, repetition plays important roles at varying scales – from the basic building block through a repeated structural element along the outer edge of the playing field, to whole sections of the stadium, such as the grandstand and the roof, to masterplanning solutions like separate stadiums for different sports built with the same engineering solution.

The primary reason for this repetitive and modular approach is rooted in the economics of construction and structural stability – repeated elements are easier to manufacture in large quantities, and when assembled together form a stable topology. Adaptability, on the other hand, is a far more complex problem that is yet to find a solution that can work across multiple functions. The typological studies presented in Chapter 02 highlight the importance of morphology and functionality for the final design – different events require different stages, but sightline quality depends on the distance and angle from a fixed seat to a fixed playing field, while at the same time different events attract different groups of spectators who have different requirements in terms of access to and the provision of facilities.

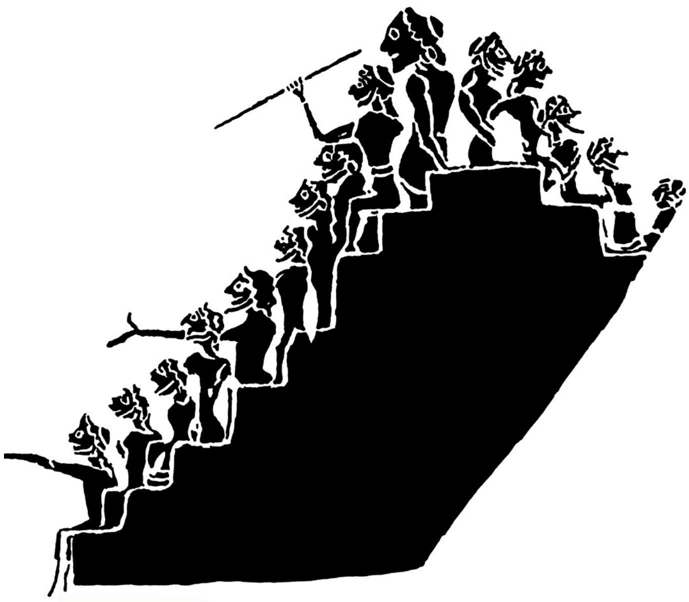


*Figure 3.1. Vase painting by Sophilus c. 580 BC (Leacroft and Leacroft, 1984)*

## 3.1 Evolution of modularity in stadium design

As history has taught us, bringing large groups of people together in a stadium creates risks which are not present at a comparable scale in any other building typology. The process that started more than 2,700 years ago not only demonstrates the technological, engineering, and architectural accomplishments of the period but also gives us a clear image of how society has functioned and perceived itself at any given time.

### 3.1.1 Greek theatres and stadiums

The earliest architectural text on the specific topic of public assembly buildings is Vitruvius' Ten Books on Architecture: the earliest manuscript that exists today originated in ninth-century Germany (Wight, 2021). Vitruvius (1914; 1513; 1511) focuses on theatres and traces the radial organisation and morphological origin of the stadium to the way sound travels in space and the ability of the spectators to hear the speaker on stage. In other words, the Greek theatre was designed as a structure to facilitate the communication of information to the largest number of people in the vicinity of the performer. Continuing from the concept described by Sheard (2005), the primary driver for the morphological changes in the stadium in later years was the changing information presented on stage – first it was a vocal performance, then a visual performance, then the audio-visual information accompanying an athletic competition; in later antiquity, the amphitheatre was required to transfer the audio-visual information produced from gladiatorial combats to the spectators.

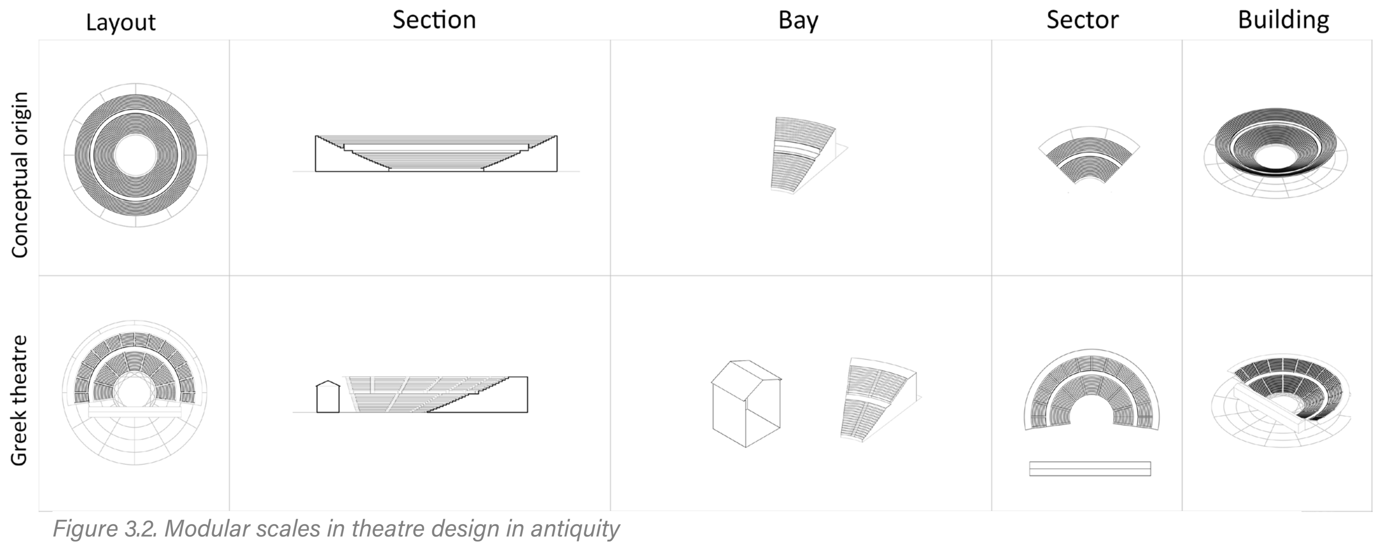



*Figure 3.2. Modular scales in theatre design in antiquity*

Following the construction techniques developed over millennia in Egypt, the ancient Greeks faced two primary challenges in terms of modular construction and prefabrication – the production of the basic building block and the resolution of the overall geometrical solution of the design of an assembly building. The construction technology of the period was not advanced enough to allow the stand to be separated from the ground, which resulted in two scales at the end of each spectrum of design. The primary task was to develop a geometrical solution that enabled the repeated units to be produced off site, and assembled in their final configuration. The aim was to quarry stone slabs of the same size and shape, which were then brought to the site and reconfigured if needed.

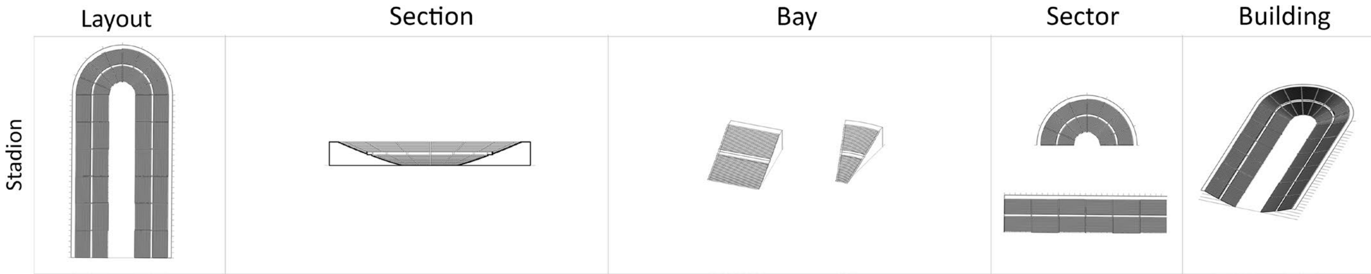



*Figure 3.3. Modular scales of ancient Greek stadion*

The geometrical solution to this was the pure radial grid of the theatre and the hybrid radial and orthogonal sections of the *stadion*. The aim was to produce only two types of slabs that could be used for the safe and robust construction of terraces. In terms of adaptability the ancient Greeks were the first society to face the challenge of accommodating different programmes in the same public space. The theatre could accommodate only artistic performances and close contact sports, while all the athletic events had to take place at a different venue. In a society created and dominated by the spectacle of public assembly, this meant that two separate designs had to be developed to serve the same function. The implications of this split went beyond the field of architecture, as the rituals of art and sport became separate entities manifested in separate locations in different buildings. What is more, the spectators also came from different social groups – the theatre was open to the whole *polis*, while the spectacle of the Olympic event was limited to men and married women (John and Parker, 2020). At a masterplanning scale it also affected the presence of temples of different deities in the vicinity of the public assembly building.

In terms of layout, the focus was on the separation of the audience according to their social class, and there were no permanent sanitary or commercial facilities. The Greeks, however, established the basic system of horizontal and vertical auditorium circulation that is still used today, with the introduction of gangways and super risers. The horizontal aisles were known as *δῐάζωμᾰ* [*diazoma*], and were in continuous use, as events lasted throughout the day.

### 3.1.2 Roman theatres, amphitheatres, and hippodromes

The Romans dramatically improved the Greeks' modular approach to their model of centrally organised public assembly buildings. The Romans' contribution to stadium design was unprecedented in four major areas. They developed construction technology and materials that permitted them to create foundations, columns, and slabs that could support a varying live load, a feat which allowed them to safely separate the stand from the ground, which in turn opened the space under the stands for circulation and programme, and they developed retractable roofs on a scale that is impressive even by twenty-first-century standards. The invention of the concrete, mass-produced bricks, and the arch allowed them to conceptualise the stadium at the same scales of geometry and basic building blocks as the Greeks, but also on the scale of structural topologies. Within the domain of masonry or stone structures, modularity is primarily a structural design property. The Colosseum, like other similar oval amphitheatres of the period, utilised elongated radial grids based on a system of arches (Hudson, 2008) for its structural and architectural organisation. Each section between the radians formed a separate module, which followed the same structural principles as the rest of the building. In this way it was possible to construct the whole edifice with a working knowledge of only the principles of a single bay section.

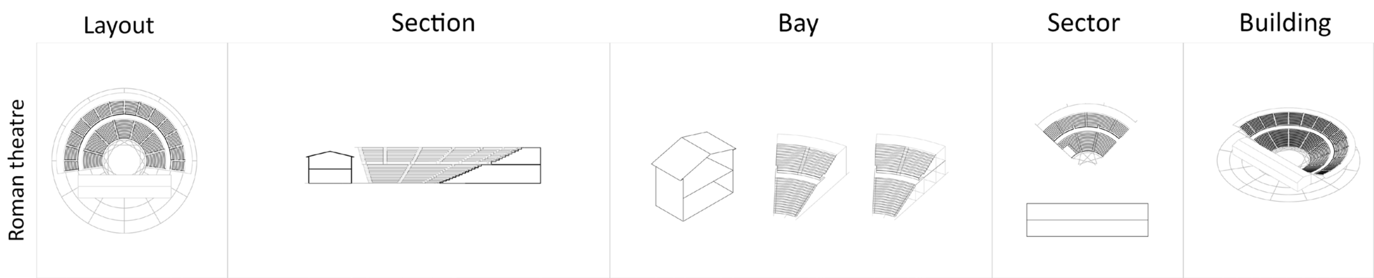



*Figure 3.4. Modular scales of Roman theatre*

The Colosseum is an important case, because it demonstrates also a modular construction principle on a larger scale, with its four sides built by separate contractors (Kierkuc-Bielinski et al., 2012). The modular approach to the structure brought other benefits, such as better control over the internal circulation and spectator segregation, the introduction of a basement, the introduction of a flooding system for naval events, and the organisation of temporary commercial stands on the street circumnavigating the amphitheatre. Another important addition to the development of stadium design was the introduction of drinking fountains and toilets within the facility, a feat of engineering that took more than 1600 years to replicate in the modern age.

At the outset, permanence was not one of the early Roman builders' initial primary goals. Unlike the Greeks' buildings, the Romans' structures for public entertainment were originally temporary and made of timber (Yegül and Favro, 2019). This approach enabled the independent construction of such facilities and their brief incorporation into the urban fabric. The removal of the need for a fixed form and structural topologies also allowed builders to design stand-alone

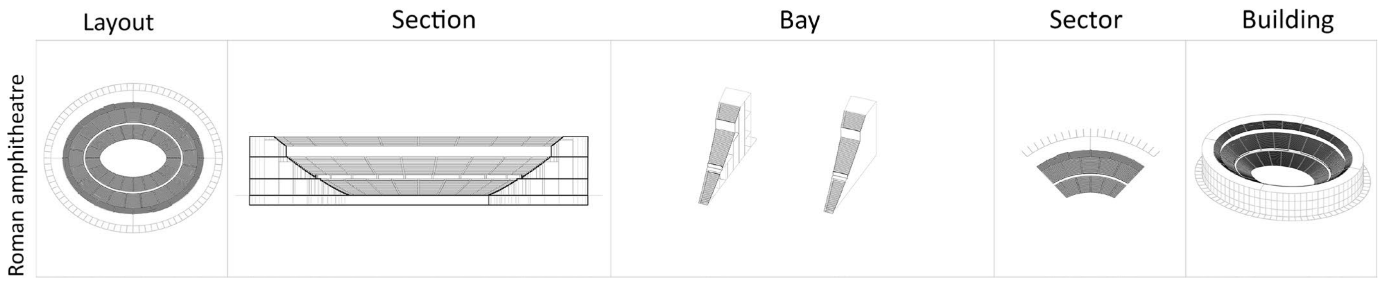



*Figure 3.5. Modular scales of Roman amphitheatre*

structures. In later years, Roman urban planning elevated the importance of amphitheatres and hippodromes: they made them a central feature of the ceremonial and cultural manifestation of the enclosure of all the towns that could afford them, by positioning the two buildings at the ends of the East-West main road (Welch, 2009). The ideas developed in the early modular constructions became the blueprint for the permanent theatres, amphitheatres, and hippodromes in this evolutionary phase of the type. Once their designs became permanent, the only issue that the Romans could not fully master was the adaptation of the building for different performances. They attempted to create a variety of staged entertainment by changing the materiality of the stage from sand to water and by experimenting with the overall morphology of the building. Examples of the geometric transformation of the building types based on modular design can be found in the combination of the Greek *stadion* and amphitheatre in Aphrodisias in Turkey and in the Roman theatre and amphitheatre in Paris, France.

In the fourth century, with the beginning of the Christian period, the popularity of mass entertainment decreased dramatically, and most spectacles were progressively outlawed in the late Roman empire. All such practices in a permanent purpose-built facility were abandoned with the fall of the Byzantine empire in the fifteenth century.

The Roman amphitheatres and hippodromes, however, remained long after anyone could remember their original purpose. Later societies did not demolish them but tried to adapt them to their own needs. The most common adaptation for these centrally organised structures was to use them as fortifications in the numerous armed conflicts that took place in Europe from the fifth century onwards. In the next stage of this process the city tried to inscribe itself within them by allowing people to construct houses and churches within the confines of the amphitheatre. For example, the Colosseum was planned to be redeveloped as a shrine to Christian martyrs with the construction of a church on the arena. The amphitheatre in Arles became a separate neighbourhood for more than a thousand years until it was identified as a cultural treasure in the eighteenth century and restored to its former state. Another important example is the amphitheatre in Siena, where the stands were adapted for housing – and still function as homes today – while the arena itself became a public square.


*Figure 3.6. Arles Amphitheatre (Guibert, 1686)*

### 3.1.3 Medieval period

Religion changed European, Middle Eastern, and North African societies profoundly. Nevertheless, people found reasons to come together beyond communal worship, and the facilities for such events had to be developed somehow. As a result, the permanent construction of amphitheatres and hippodromes was abandoned completely, and temporary assembly buildings became the norm. Chariot racing was abandoned in 1200 AD, but sports did not disappear. Instead, they were transformed into another military-inspired activity, jousting, from 1066 AD onwards. The design of the list (or list field, the jousting arena) was based on the same organisational principles as its precursors, with a stage and seating area orientated towards the spectacle. In terms of construction, however, the design was revised completely. The new material of choice was timber, and seating was provided only for people from the highest social classes. There are several extant manuscripts from this period that investigate the design of these structures. Usually, the field of play was fenced off by a repeated modular timber frame and the standing area was enclosed by another fence. The dignitaries and ladies of the court sat in dedicated pavilions, which were also based on modular designs.

The use of timber and the limited foundations of these structures means that there are no traces of them today, but they nevertheless expand our understanding of adaptability. Their ease of construction allowed them to be adapted according to the number of contestants and the size of the list. It also allowed for varying spectator capacity and the physical separation of social classes. However, there are no surviving records of the quality of sightlines or the provision of services or commercial facilities.

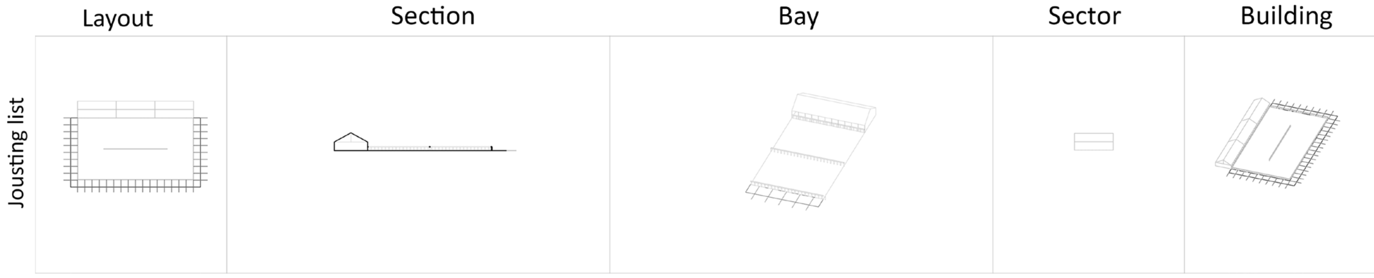



*Figure 3.7. Modular scales of jousting list*

### 3.1.4 The Industrial Revolution and return of permanent construction

Jousting had declined in popularity among the nobility by the seventeenth century, and a new interest in competitive sporting events that were similar to the ancient Olympic games started to emerge in England. The first record of such an event, the Cotswold Games, dates back to 1612 (Kähler et al., 2012). This event was something between a country show and a sports event. Like the early Greek Olympics, it was held in an open field, with a few tents providing food and drink. In the 1860s, the French aristocrat Baron Pierre de Coubertin visited one of these events, the Wenlock Olympian Games, which inspired him to establish the modern Olympic Games internationally (John and Parker, 2020).

Stadium design only returned to the architectural discourse with the advent of the Industrial Revolution. French architects were the first to re-examine stadium typology and propose new designs based on concepts developed more than 1,500 years earlier. The work of Étienne-Louis Boullée and Armand-Guy Kersaint during this period offered speculative designs based on the design principles of the Roman amphitheatre. Boullée's designs utilised geometric design principles from ancient Roman architecture: but, unlike Kersaint, he proposed an entirely monolithic construction. His designs were focused on the performer-spectator relationship and did not provide additional facilities for the spectators. Boullée's main contribution was to return the construction of permanent venues to public discourse.

Working at the watershed between artisan and machine production, Boullé's and Kersaint's designs present ideas from both fields. After the French Revolution, society in France was being reinvented, and social change needed to be manifested to the masses. To facilitate this process, Kersaint designed a *stadion*-shaped temporary timber stadium for 500,000 spectators for the July 14th celebration on the Champ de Mars (Leith, 1987). This construction was based on the same modular scale as Roman stadium designs, and its success served as a catalyst for a new wave of stadium designs. However, like its medieval precursors, Kersaint's design provided no sanitary or food and beverage facilities.

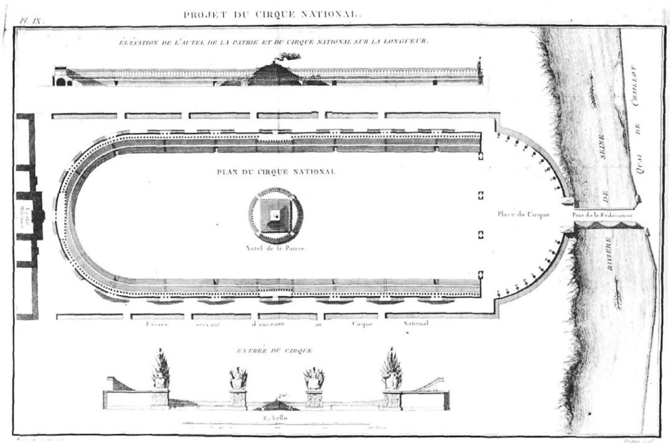


*Figure 3.8. Plan of temporary national amphitheatre for 500,000 spectators, Kersaint (1790)*

### 3.1.5 Spanish bullrings and cricket grounds

The re-emergence of the stadium as a permanent element within the urban fabric started in late eighteenth-century Spain with the construction of the Plaza de Toros de Ronda, a bullring in Ronda, Andalucía. Stylistically, its design combines a Roman amphitheatre and southern Spanish architecture. In its modular approach it adopts ideas from antiquity: the building is organised as a series of repeated modules around a central space. This radial approach allows the integration of columns on the inner side of the stand, which support a second tier.  The seating is entirely covered by a roof. The void under the grandstands offers space for facilities such as toilets, commercial spaces, and a chapel.

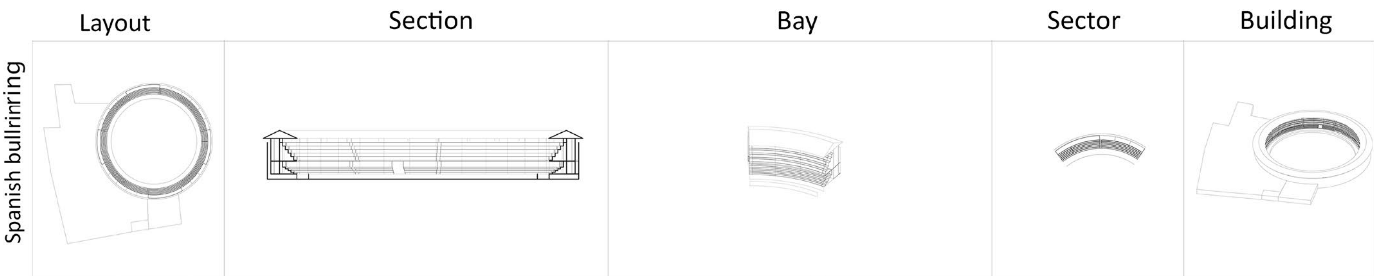


*Figure 3.9. Modular scales of Spanish bullring*

The rules of cricket were codified in the mid-eighteenth century, and by the mid-nineteenth century it became the first truly international sport since jousting. The infrastructure for professional cricket followed soon after this: a Code of Laws for the game was established by Marylebone Cricket Club, based at the first cricket ground, Lord's, that was opened by the entrepreneur Thomas Lord in 1787. There are a number of morphological similarities between the cricket ground and the bullring: both are based on a centrally organised spatial arrangement. However, the British designers' approach contrasted strongly with their Spanish counterparts' aim of a uniform construction. Most cricket grounds are today still conceptualised as a series of pavilions and stands organised around the playing area, and the design of each of these separate facilities rarely relates to the rest of the architectural composition. The structures have separate circulation systems for different types of spectators and provide facilities for their specific target groups. In terms of modularity, these venues are also based on repeated elements within the unit, and in many cases the designers intentionally create different organisational structures for them, so their design differs from the rest of the building.

After 1863, when the codification of the rules of football and rugby was established, cricket grounds became an unlikely place for the clash between classical and medieval design. Cricket had always been played on a circular or elliptical playing field, while the two new sports required a rectangular pitch. Cricket was well established and popular among the upper classes in Victorian

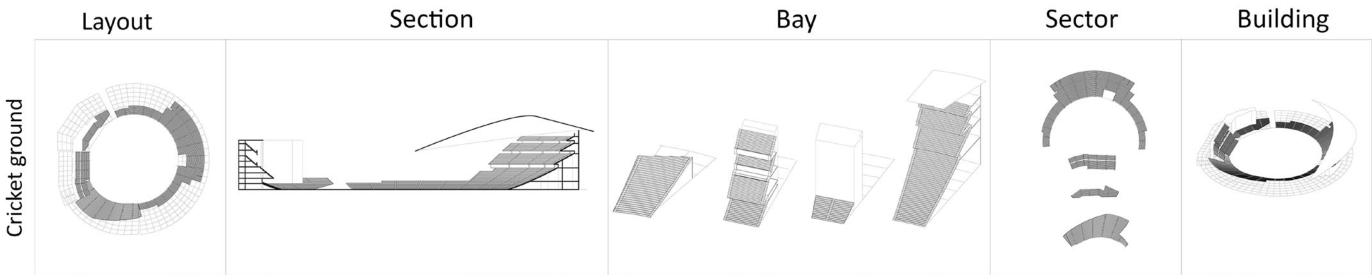



*Figure 3.10. Modular scales of British cricket ground based on Kia Oval by HOK*

society, but at in the early days of football and rugby clubs had to rent their grounds. With the emancipation of the working classes, however, the two new sports became increasingly popular, and designers began to think about how to adapt the cricket grandstands for a rectangular playing field. As with the previous design attempts at multifunctionality, this was deemed to be unachievable, and the modern football stadium emerged from the impossibility of adapting the cricket ground to these new requirements. A different phenomenon can be observed in Australia, where the rules of rugby were changed so that it could be played on an elliptical field – thus establishing Australian rules football.

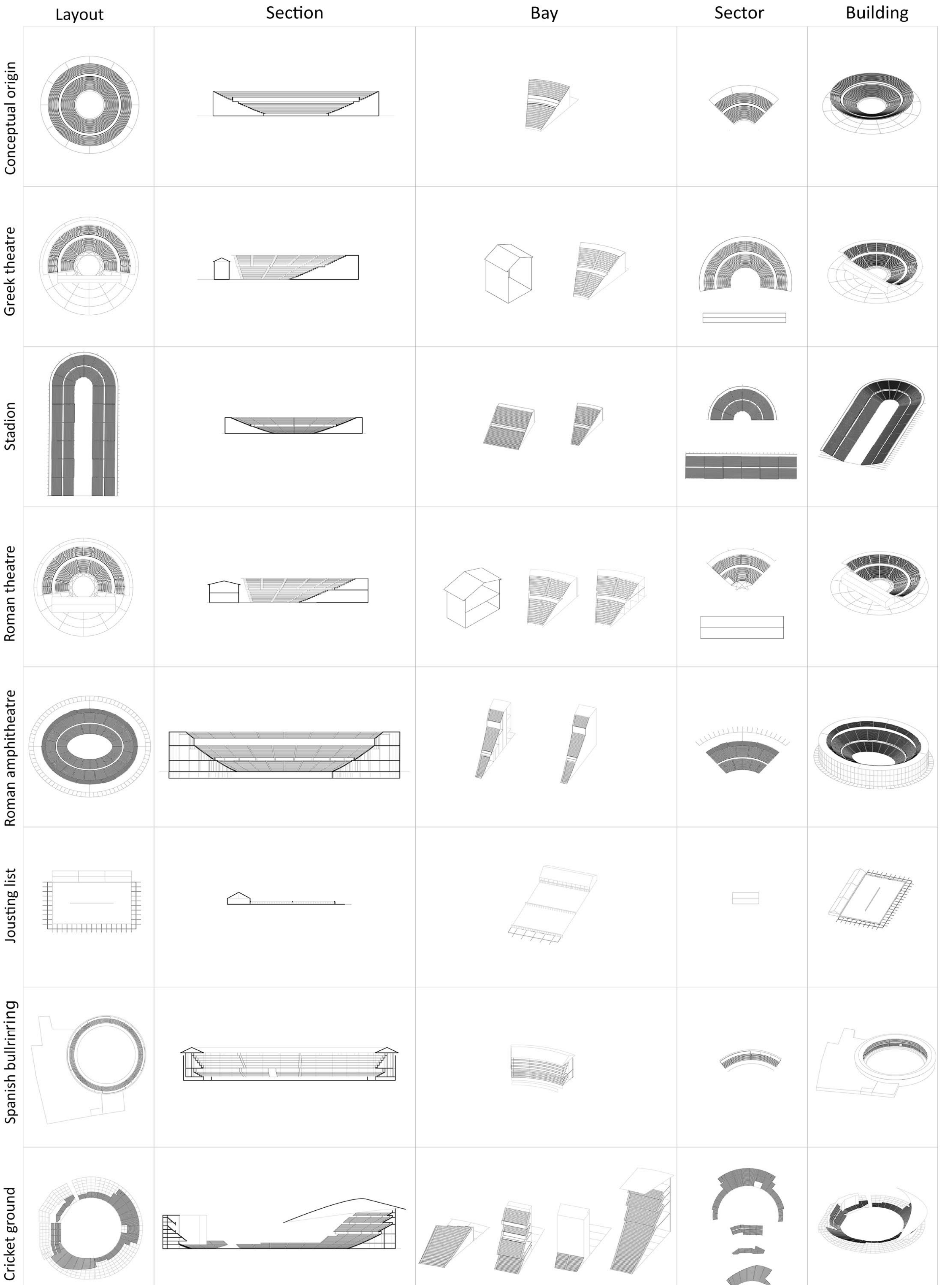



*Figure 3.12. Scales of modularity in the historical development of stadiums, and places for performances and public assembly*

### 3.1.6 The football ground

At the date when the trajectories of cricket and football ground design diverged, architectural design was not regulated. Originally there were two structural solutions of choice, temporary timber frames and earth banks. Developers started using timber as it provided the flexibility and ease of assembly needed for the modular design adapted from medieval precedents. Unfortunately, timber did not perform well structurally at the scale required and it had to be abandoned. In comparison, earth banks were simple to produce and became popular all over the world. If additional facilities were required, cast iron or steel-framed grandstands were constructed. Chelsea Football Club's Stamford Bridge stadium is one of the best examples of the development of this type of thinking in England, as the facility has remained in the same place for more than 150 years. Originally it was an athletics field with a pavilion, constructed with reference to cricket ground design. When the football club took over and the popularity of the team grew, terraces were constructed in order to maximise the space of the plot. In later years, additional pavilions were erected as stand-alone features. In the 1960s a comprehensive new scheme was proposed that worked across all scales of modularity. From this scheme, only one of the stands was actually constructed with in-situ concrete instead of precast slabs. The reasons for the partial completion were the incorrect calculation of the slope of the stands, which made them too steep, and the economic changes of the 1970s. This development brought one of the most popular football clubs in England to bankruptcy (Benson, 1987). The earth terraces remained until the 1990s, when a new scheme was constructed that was volumetrically different from the remaining 1960s stand. The latest unrealised scheme, developed by Herzog & de Meuron in 2015, was based on a modular approach that scaled each segment in order to maximise the capacity.

The story of Stamford Bridge not only reflects the development of structural and architectural thinking in England: it also represents the entanglement between the requirements of the urban context and the venue. As it took considerably longer to rebuild the grandstands, the provision of auxiliary functions that linked the venue with the area surrounding it also took years to complete. The breakthrough in this part of design of the building came in the 1990s when an office building, a hotel, and a nightclub were designed as part of the current final redevelopment of the ground.

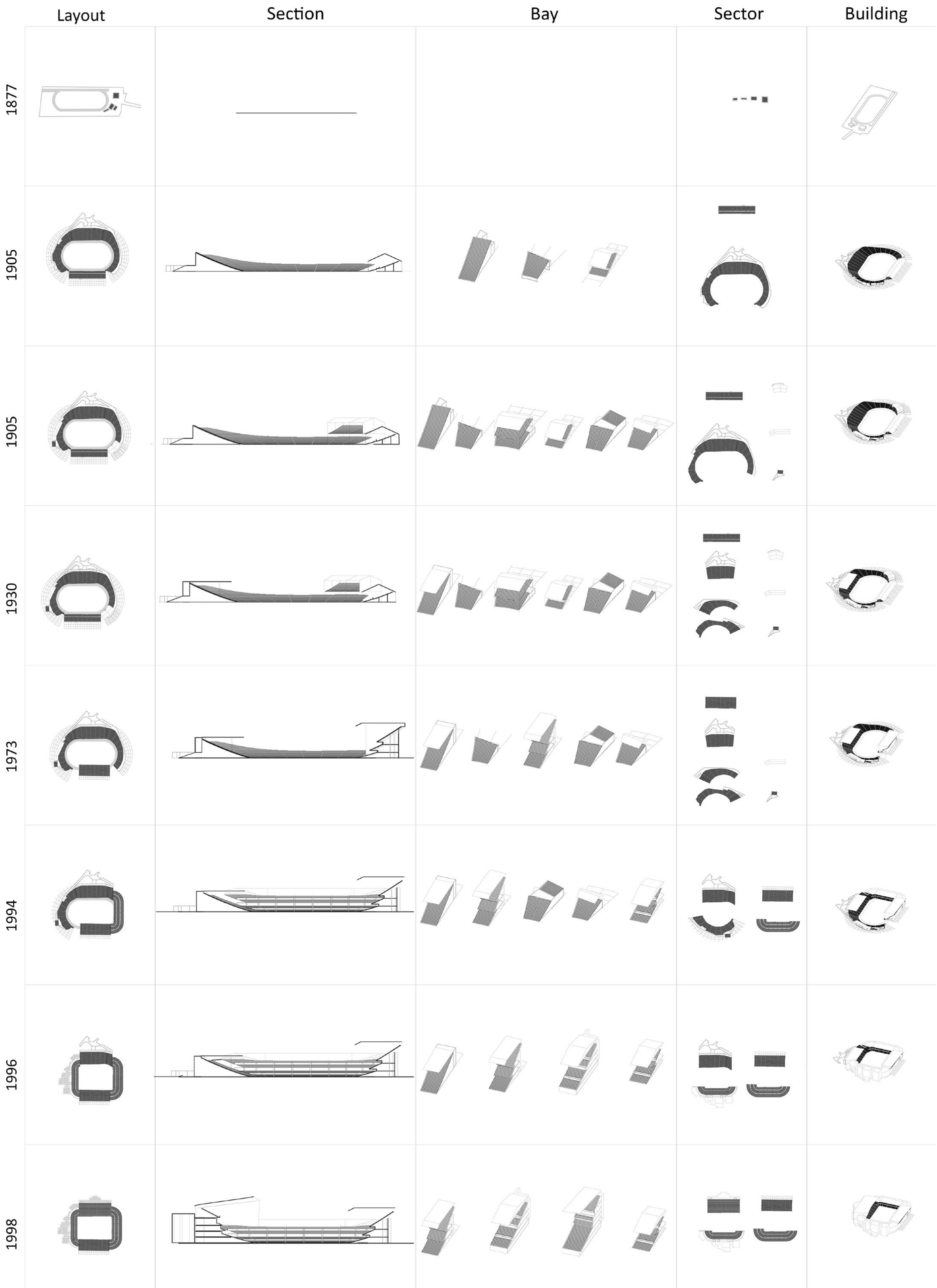



*Figure 3.14. Scales of modularity in the development of Stamford Bridge stadium, UK*

## 3.2 The effect of stadium legislation and design standards on morphology and layout

In terms of the literature on stadium typology, the primary sources are legislative documents and design manuals such as the *Guide for Safety at Sports Grounds* (2018) edited by Simon Inglis and issued by the UK Government's Department for Digital, Culture, Media & Sport. Similar manuals are published by international sports federations, and guides such as *Stadia: The Populous Design and Development Guide* (2013) by John et al. are compiled by practising architects.

*Στάδιον* [*stadion*] in Greek meant a space roughly 600 feet or 180m – the length of the track used for ancient Olympian running competitions (John and Parker, 2020). With this numerical definition and the secondary meaning of a place where people gather to observe an event, it was possible for the ancient builders to build a structure with the same basic parameters in different places with no other guiding information but the word itself. Sport and society have both developed significantly since ancient times, along with the dimensional requirements for both the sporting event and spectator accommodation. Nevertheless, in terms of legislation and standards, stadium design surprisingly advanced very little in the more than two and a half thousand years since the original dimensional requirement inscription established the etymological basis for the typology.

### *Public Health Acts Amendment Act 1890*

*37 Safety of platforms, &c. erected or used on public occasions*

*(1) Whenever large numbers of persons are likely to assemble on the occasion of any show, entertainment, public procession, open-air meeting, or other like occasion, every roof of a building, and every platform, balcony, or other structure or part thereof let or used or intended to be let or used for the purpose of affording sitting or standing accommodation for a number of persons, shall be safely constructed or secured to the satisfaction of the surveyor of the urban authority.*

*(2) Any person who uses or allows to b e used in contravention of this section, any roof of a building, platform, balcony, or structure not so safely constructed or secured, or who neglects to comply with the provisions of this section in respect thereof, shall be liable to a penalty not exceeding fifty pounds.*

(HM Government, 1890)

In 1890 the Public Health Acts Amendment Act attempted to address a series of incidents involving spectators at sports grounds by setting a fine for organisers of public gatherings who did not provide safely constructed or secure sitting or standing accommodation whenever a large number of people were likely to assemble. Unfortunately, this early legislation provided no specific safety design requirements, putting the onus of the decision on the urban authority's surveyor, and crowd management in the same legal category as sanitation.

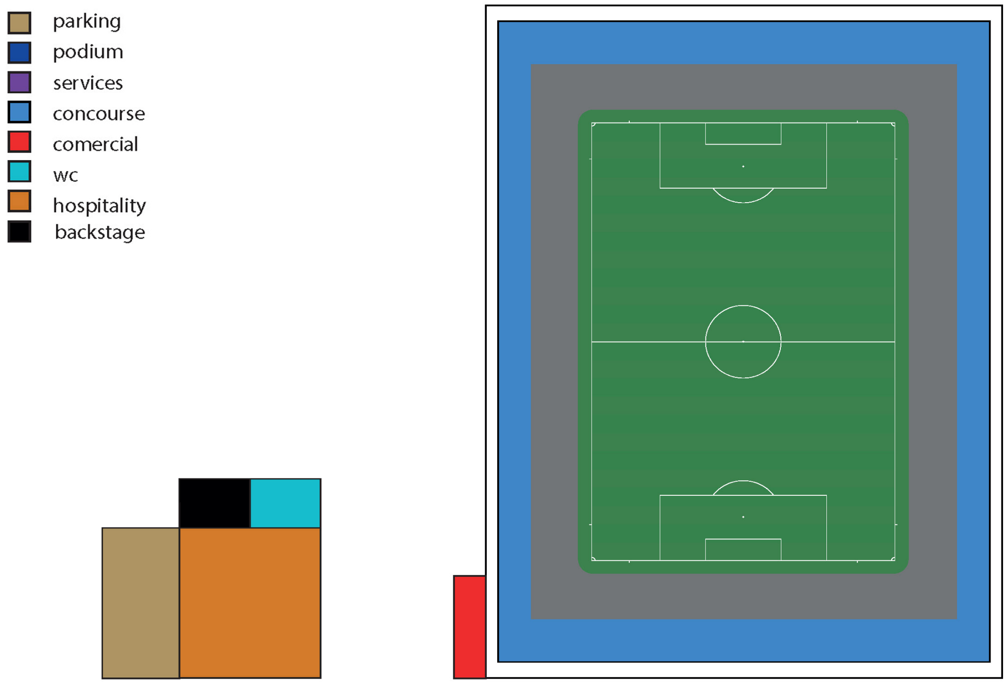



*Figure 3.15. Schematic representation of football stadium layout in the late nineteenth century, based on Inglis (1987)*

As a result, early football stadium design in the UK evolved almost naturally from the conditions of the Victorian towns and the design of cricket grounds, as described earlier in this chapter. Inglis (1988) summarises the genesis of the modern stadium type through the interaction of two of the existing urban elements at the times - first there was a public house with a field next to it, then the field was transformed into a pitch and the crowds would start gathering around it. The pub served as a pavilion which provided the services required by sportsmen and spectators – food and beverages, changing rooms, toilets and accommodation for horses were separate and associated with the public house. Inglis (1988) further identifies the turning point between physical exercise in social settings and organised sport, when the football club started fencing off the playing field and charging gate.

When football started gaining momentum as an activity, crowd numbers exploded. Matches with more than 20,000 spectators were common from the end of the First World War, but the legislation did not change. Due to the lack of regulation, dangerous incidents were accepted as part of the experience. Stadium design was part of the loose normative framework of rudimentary building regulations and was primarily the result of economic pressure. Development was based entirely on the whim of the clubs.

*Figure 3.17. March 5th, 1921: Cardiff City v Chelsea (A.R.Coaster, 1921)*

***Safety of Sports Grounds Act 1975***

*Safety certificates for large sports stadia*

*(1) The Secretary of State may by order designate as a stadium requiring a certificate under this Act (in this Act referred to as a " safety certificate ") any sports stadium which in his opinion has accommodation for more than 10,000 spectators.*

*(2) The Secretary of State—*

*(a) may estimate, by any means which he considers appropriate, for how many spectators a sports stadium has accommodation; and*

*(b) may require any person concerned with the organisation or management of a sports stadium to furnish him within such reasonable time as he may specify with such information as he considers necessary for the purpose of making such an estimate.*

(HM Government, 1975)

*Figure 3.19. April 15th, 1989, Hillsborough Stadium, police officers carry an advertisement board to be used as a stretcher for injured spectator (Inews.co.uk, 2016)*

In 1975 the government decided to exercise some form of targeted control for the operation of sports stadiums through the creation of a licensing system for stadiums that could accommodate more than 10,000 spectators. However, this document provided few specific guidelines on the design of these venues. The Secretary of State was allowed to estimate capacity based on whim, and the law required neither a relevant background or the appropriate skills for the task from the holder of this office. In practice, what this Act did was to further separate stadium construction and design from that of other buildings in the legal category of Places for Assembly and Recreation, and only a handful of architecture offices chose to specialise in this field.

It took another 15 years and hundreds more incidents for the public to force the government to act. The Hillsborough disaster served as a catalyst for change. After this catastrophic event the Thatcher government commissioned a report on the reasons why it had occurred; this document became what is known as the *Taylor Report* (Taylor, 1990). This extensive review is one of the most influential texts in the history of stadium design. Through a rigorous and systematic analysis of every aspect of the event – legislation, infrastructure, venue operation – the report highlighted all the failures of the system and proposed potential solutions in both the short and the long term. The best known proposals were that venues should be fully seated and that the sale of alcohol should be banned during events, but the report also covered the design reasons for stadium disasters, including faults in the legal system that governs these events, the way these designs are interpreted throughout the world, the financial aspect of the game, accessibility, medical facilities, crowd control and policing, overall masterplanning, and provisions for future legislation (Taylor, 1990). The *Taylor Report* (1990) shifted the responsibility for governing the design of sports grounds to the Department for Culture, Media, and Sport, who still publish the set of licensing design recommendations that emerged from the report, in the *Guide to Safety at Sports Grounds* [Green Guide] (2008, 2018). This stadium design guidance is accepted as standard throughout the world and covers the entire lifecycle of stadium development and operation, focusing on the calculation of venue capacity, its management, circulation, safety fixtures, spectator accommodation, fire safety, communication, electrical and mechanical systems, medical facilities and media spaces. These categories create the basic generators of the form and internal organisation of sports venues and are continuously updated to reflect social and technological developments. The focus of the guide is the safe operation of the stadium, and its latest version quantifies a large number of design aspects related to circulation, sightlines, and functions (Department for Culture, Media and Sport, 2018). When analysed holistically, these recommendations form the basis of the design of every stadium in the UK, and are similar to those used globally, based on international sports organisations' facility guidance manuals. This set of regulations is essential for this research, as itis based on the dimensions of the human body and each design feature is strictly defined through its size and relative position, which can be easily translated into a parametric and machine learning-based model. The regulations are important for an understanding of the overall design process, because the actual design input of the

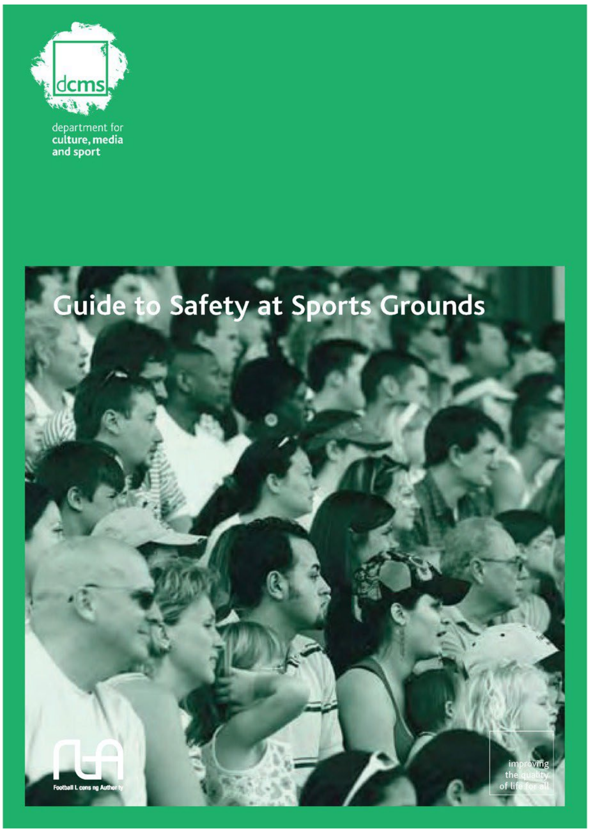


*Figure 3.21. Guide for Safety at Sports Grounds (Department for Culture, Media and Sport, 2008)*

architect and other related disciplines has to satisfy these requirements while at the same time delivering a unique and iconic architectural design (Sheard, 1996). Other organisations with a personal stake in this legislative document include several government departments, international sports federations, local councils and committees, entertainment and sports organisations, fan organisations, the construction industry, and professionals related to public performance events.

The most important difference between the post-Hillsborough legislative basis and the diagram of the nineteenth-century proto-stadium is the establishment of five concentric zones of

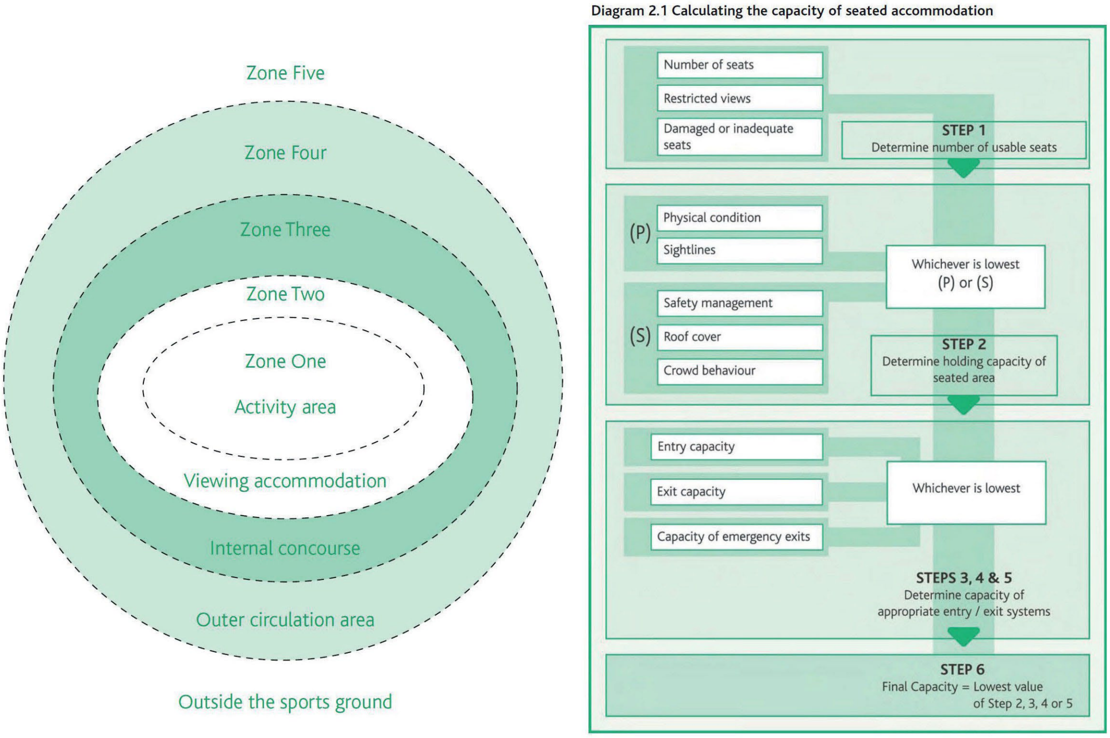



*Figure 3.22. Stadium zones from the 2008 edition of the Green Guide and method for estimating capacity. The 2018 edition of the Guide introduces a sixth unmanaged zone around Zone 5 (Department for Culture, Media and Sport, 2008)*

access: the stage and auditorium are the first two, the internal concourse is zone three, and a controlled external ring and the stadium vicinity are zones four and five. Based on the *Taylor Report*'s recommendations, a clear methodology for estimating the capacity of the venues was established, which considers the current state of a venue rather than its statutory capacity.

The other major improvement was the introduction of seated-only venues for league football. Apart from safety, this change created the conditions for a fully parametrised design of the entire venue – the stage defined the sightlines, which in turn defined the height and depth of the rows.

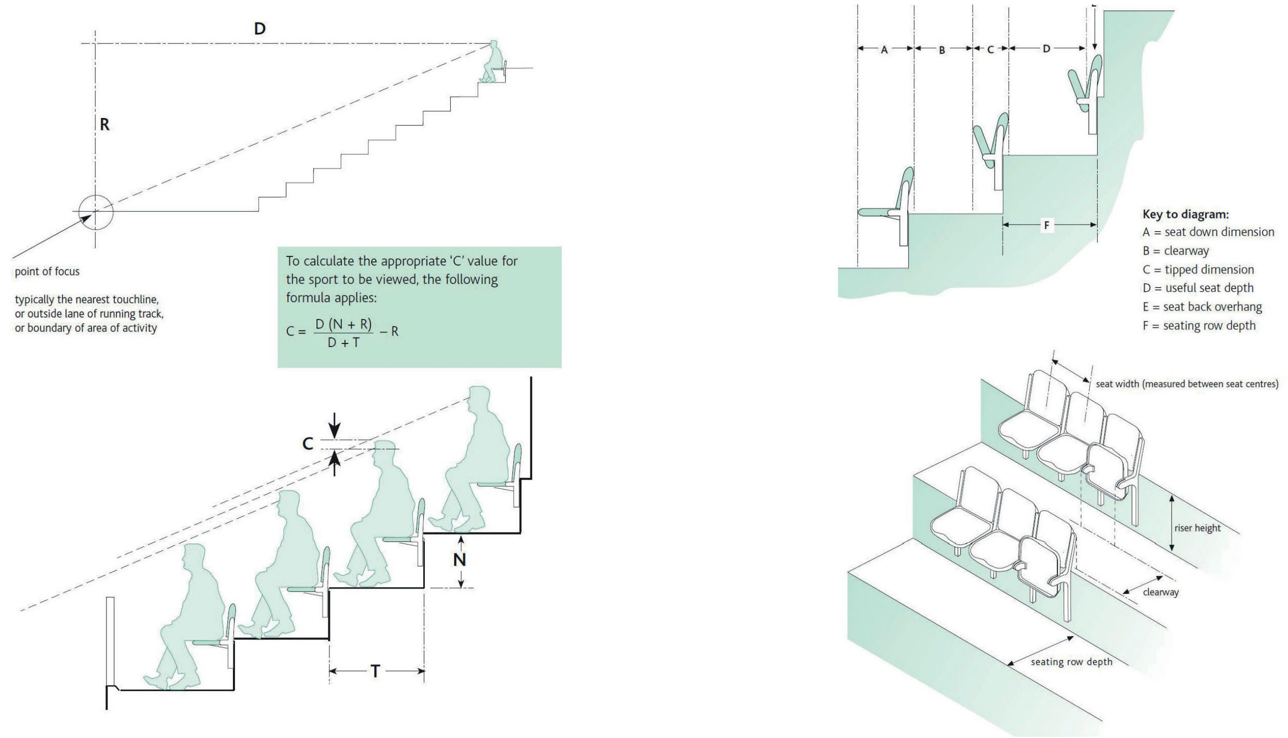



*Figure 3.23. Guide for Safety at Sports Grounds 5th edition: seating characteristics (Department for Culture, Media and Sport, 2008)*

The seats are organised in blocks and the circulation is through radial and lateral gangways, based on the stadium capacity, and all the functional areas outside the pitch are also proportionally related to the number of spectators.

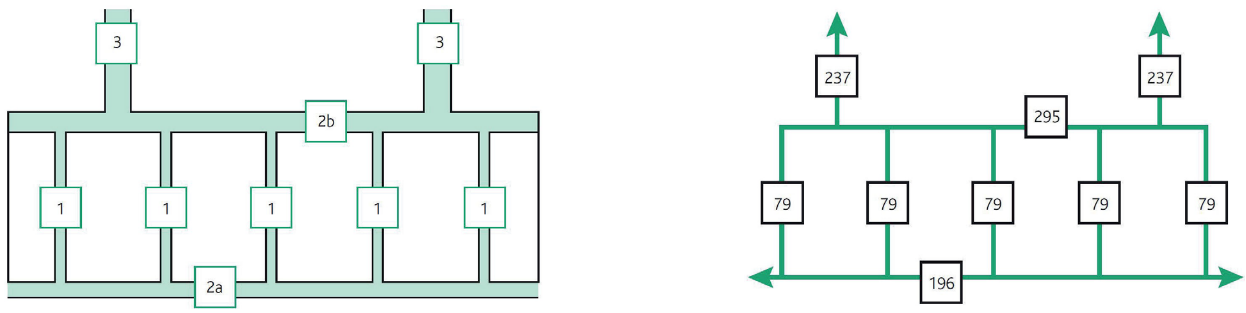



*Figure 3.24. Guide for Safety at Sports Grounds 5th edition: seating block arrangement (Department for Culture, Media and Sport, 2008)*

These ideas were quickly adopted by the international sports organisations: this is evident from the excerpt above from the *Technical Manual of the International Olympic Committee* (International Olympic Committee, 2005); each operation was very strictly defined and these requirements needed to be met for venue to gain an international certificate. FIFA (Fédération Internationale de Football Association, 2011a) went even further and specified a detailed programme for the venues hosting its events, based on the different participant streams.

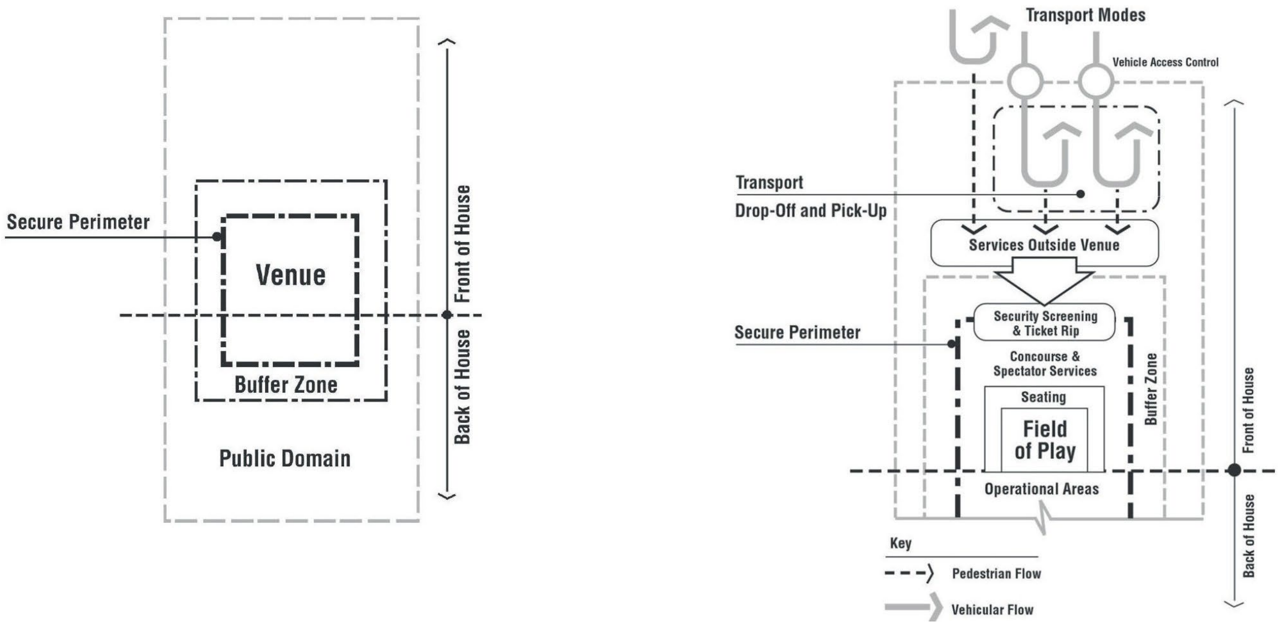



*Figure 3.26. Stadium zones and access International Olympic Committee (2005)*

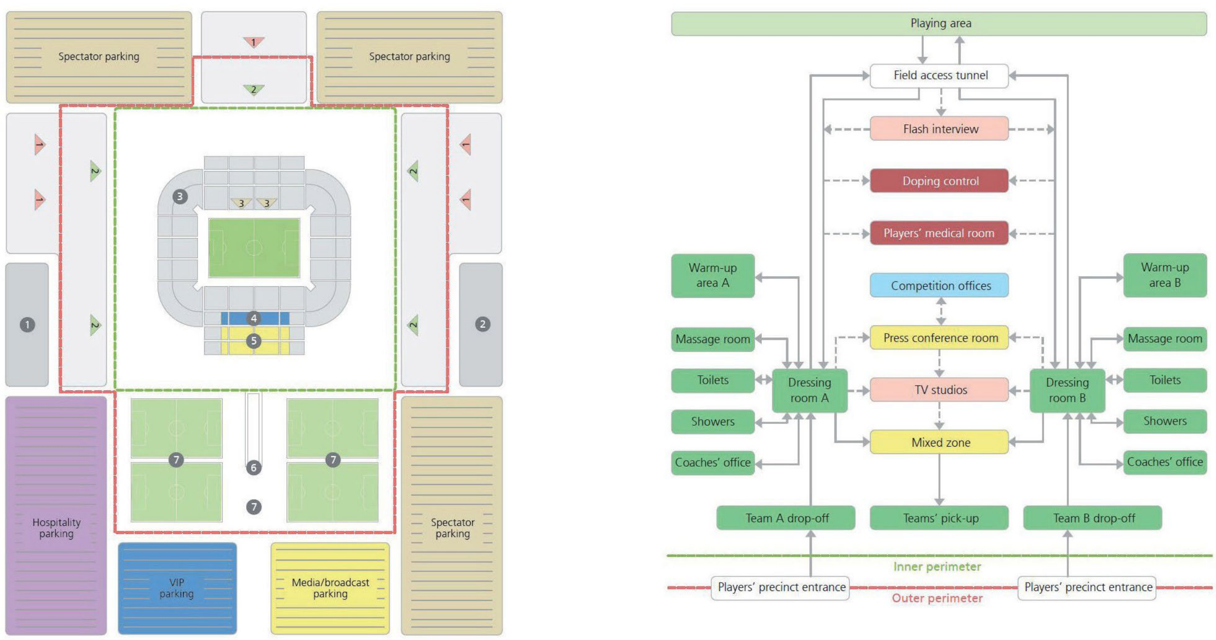



*Figure 3.25. Stadium area layout and player flow diagram (Fédération Internationale de Football Association, 2011b)*

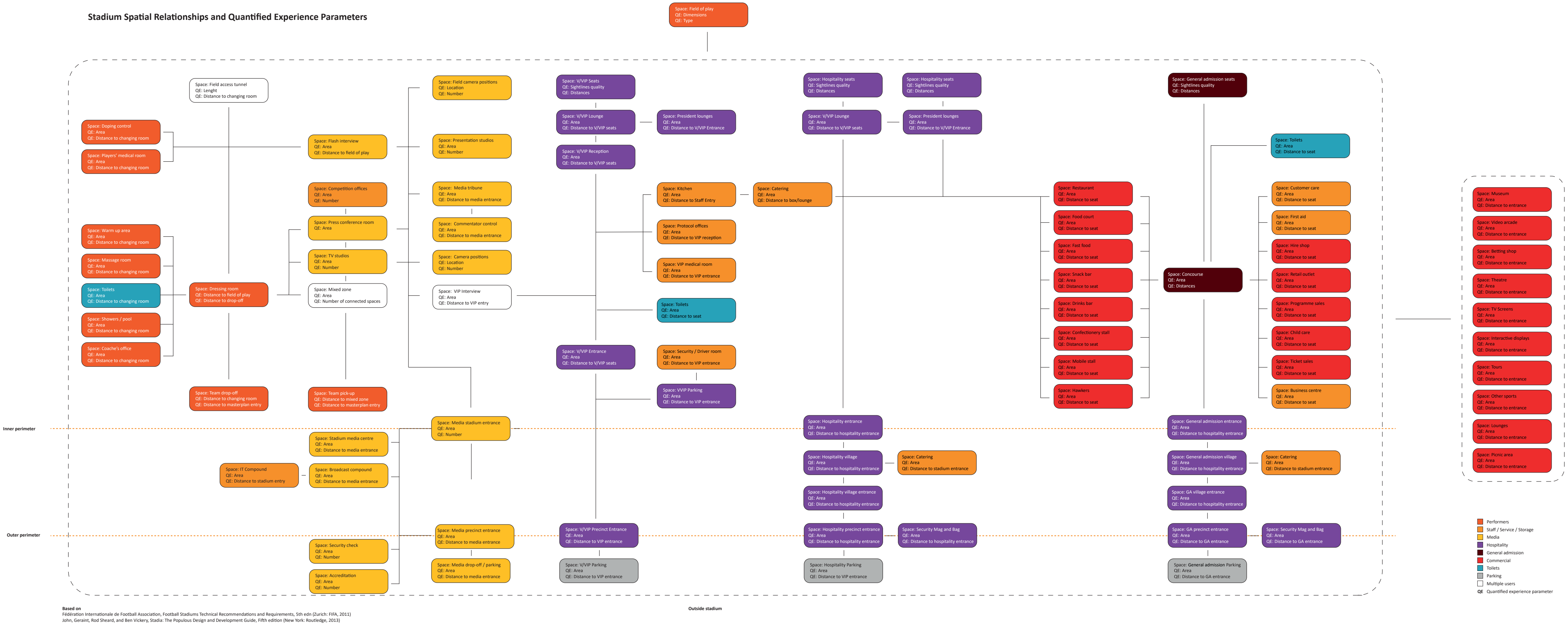



*Figure 3.27. Combined spatial relationships within stadium functions based on Fédération Internationale de Football Association (2011b) and John et al (2013) (high resolution image)*

The standard that guides the design and management of sports facilities in the EU and the UK is (BS) EN 13200-1:2019 (European Standards, 2019). This document is a simplified version of the *Green Guide* and covers the same areas of interest in terms of the design drivers of stadium morphology. The primary differences in the UK recommendations are the variations from the building regulations of the EU countries regarding seat spacing and row depth. This document focuses on the structure and materials for the facilities, different types of seating provision, accessibility and crowd flow, sightlines and viewing distances, and a general classification of facilities based on their capacity. This standard highlights the most important design drivers for stadiums and presents an overview of how different European countries adapt their regulations to satisfy or bypass these recommendations.

The most important international design manuals that refer to the *Green Guide* are the IOC *Technical Manual on Venues* (International Olympic Committee, 2005), FIFA's *Stadium Guide* (Fédération Internationale de Football Association, 2011b) , FIFA *Stadium Safety and Security Regulations* (Fédération Internationale de Football Association, 2011a), and the UEFA *Guide to Quality Stadiums* (Union of European Football Associations, 2014). Each international sports federation also publishes specific manuals for the design of venues that host events under their patronage. These documents focus on the facilitation of the safe and positive delivery of international events and detail the practical operation of the venue. They contain very specific guidance on the design of the surrounding area, the venue itself, the spectators, players, stewards, catering, security, and maintenance and media facilities. These design drivers are presented as quantified matrices that are used to evaluate and manage the risks for each event.

In addition, the Building Regulations in the UK are the statutory instrument that guides stadium morphology and design beyond the specific recommendations found in the *Green Guide*. These are based on the Building Act 1984 (HM Government, 1984) and are applicable only to England and Wales. Stadiums are mentioned specifically in these regulations and are classified as part of the category of Places for Assembly and Recreation. The areas relevant to stadiums that are regulated by these norms are structural stability, fire safety, construction materials, workmanship, site preparations, moisture exclusion, inclusive design, sound, daylight, ventilation, and vertical movement (Culley and Pascoe, 2009). Structural stability, the prevention of collapse, and health and safety issues are paramount in the aims of the Building Regulations, and the requirements for these are different in different areas of the country, as the environmental pressures and risks can vary. For example, in the north of the UK there is a much higher risk in terms of snow load than there is in the south, and the form and structure of the buildings have to reflect these specific conditions. The situation with wind loads is similar: buildings in an open area are allowed to be nearly five metres taller in the south than those in the north (Culley and Pascoe, 2009).

The circulation in a stadium or arena, as with any other building, is almost entirely defined by fire regulations. Each spectator must be able to escape to a point of safety within eight minutes, and the number of required escape routes is directly linked to the capacity of the venue. Other factors that influence the stadium's morphology are the compartmentalisation and fire resistance of the structure. In terms of materials and workmanship there are British Standards and international standards such as ISO, EEC, and ASTM (Culley et al., 2015). These standards are important, as they define the span, thickness, and materiality of the building structure and its internal finishes. These features can be easily included in a parametric design model, thus facilitating a comprehensive machine learning-based analysis and optimisation model. In addition, this kind of design approach can produce feedback to institutional bodies, as parametrising legal requirements can inform a more efficient production of new standards and regulations.

There are several manuals and guides published by architectural practices that focus on stadiums. The architecture office that dominates the current market, Populous (Building Design + Construction, 2019), publishes its own guide to stadium design: this was developed by John and Sheard (John et al., 2013). Already in its fifth edition, this manual serves as the basic reference point for everything related to stadium design. The building design scales described in this guide start from the stadium masterplan, then covering the immediate vicinity of the venue, the stadium's form and structure, circulation and security, additional activities, and its adaptability for multipurpose use.

This resource is essential for this research as it covers all the major themes of the study and connects them, based on the vast experience of Populous's practice. It also structures the stages of the design process in an optimal way in order to deliver a successful outcome. Sheard (1996; 2005) also produced two earlier publications that cover his professional understanding of the field and acted as a precursor to the work by Populous. The ideas and dimensions described in this guide were later included in the *Metric Handbook* (Buxton, 2018) in the chapter on sports facilities by Philip Johnson and Tom Jones, two of the senior architects in Populous. The design drivers investigated thematically by Wimmer (1976; 2016) include location strategy, building footprint, spectator accessibility, grandstand morphology, safety provisions, hospitality, structure, field, and lighting. By taking this perspective, Wimmer offers a more comprehensive overview of the field and uses concrete examples to identify the basic structural and formal stadium types.

As a structural engineer, Culley focuses on the technical delivery of the design and the detailed resolution of each project. In *Stadium and Arena Design* (2015), edited by Culley, the authors present essays on the parameters and constraints that each of the design disciplines involved must adhere to. An overview such as this enriches the understanding of how the built form is affected not only by its architectural qualities but also from the perspective of engineering. In this book, Culley presents the evolution of stadium engineering design from its origins as a landscape feature to the modern steel frame vertical support and seating bowl made from precast concrete, but also other important issues like safety, wayfinding, crowd control, and acoustics. In the second part of the collection, Culley focuses on aspects of parametric design, structural material properties and use, and morphology from a structural perspective. In his other major work, *Sports Facilities and Technologies*, Culley's (2009) approach is much closer to Sheard and Wimmer's, but he focuses his research on the whole spectrum of facilities for sport, their legislative constraints and technical requirements.

Nixdorf (2008) attempts to find a balance between Sheard's work and Culley's, and in his technical manual he contrasts the stadiums designed for the FIFA World Cup in Germany. The features highlighted by Nixdorf include seating capacity, viewing distance and angle, structure type and circulation, and individual tier dimensions and distances from the pitch. Each of the chapters is supported by a highly detailed case study and the plans, sections, and detailed drawings included are much closer to the construction drawings used on site than the more schematic stadium conceptualisations used by other authors. However, all the authors concur with the view that prefabrication, modularity, and standardisation play a major role in stadium design, and that a successful design should work across all design and operational scales.

| *Table 3.1. List of primary legislative and reference documents related to stadium design* | | |
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| **Doc** | **Main themes** | **Rules and Quantifications** |
| *Guide to Safety at Sports Grounds* | **Focus:** spectator safety<br>**Type:** license<br>**Themes:** Crowd management<br>Emergency evacuation<br>Seating arrangements<br>Sightlines<br>Circulation spaces | **Sightlines**: ensure unobstructed views, maintain minimum viewing distances, and avoid dangerous protrusions<br>**Circulation:** provide sufficient width and capacity for entrances, exits, and vomitories; define crowd flow and avoid congestion<br>• Radial gangways: min exit 280 mm<br>• Radial gangways: max riser 190mm<br>• Radial gangways: min width 1200 (1100mm existing)<br>• Stairways: min width: 1200mm Maximum width: 1800mm (existing 1100mm – 1800mm)<br>• Stair treads: Min depth: 280mm Preferred depth: 305mm<br>• Stair risers: Min height: 150mm (preferred) Max height: 170mm, or 180mm where the stairway is a secondary stairway for escape only (existing (150mm – 190mm)<br>• Stair landing: The exits of each landing, at the head and foot of stairways, and between flights, should be not less than the width of the channel of the flight.<br>• Number of stair risers: individual flights should consist of<br>• no more than 12 risers. However, where the stairway is a secondary stairway for escape only this may be increased to 16 risers. If there are more than 36 risers in consecutive flights, the path of the stairway should change the direction of travel by at least 30 degrees.<br>• Minimum width of aisles, corridors, and staircases 1200 mm (1100mm)<br>• Minimum headroom – 2300mm horizontal, 2000mm vertical circulation<br>• Entry capacity - max 660 persons per entry point per hour<br>• Vomitory width - number of spectators / emergency egress time in minutes *66 (min 1200mm, time - 150sec to 4800sec)<br>• Base crowd flow calculation rates: on a stepped surface, 66 persons per metre width per minute; on a level surface, 82 persons per metre width per minute<br>• Exit distance seat – vomitory – 8 minutes<br>**Programme/Layout:** design layout to optimise safety and comfort for spectators, taking into consideration capacity and contingency plans. Focuses on safety-related spaces, including entrances, exits, vomitories, and concourses.<br>Addresses spectator facilities, such as seating areas and standing areas<br>• Min seat spacing – seated: 500mm (460mm existing)<br>• Seat height – min 400mm<br>• Seat depth – min 350mm |

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| *Guide to Safety at Sports Grounds (continued)* | | • Max seats per row – 28 for 2 gangway exits, 14 for single gangway<br>• Tier max steepness – seated: 35o<br>• Tier max steepness – standing: 25o<br>• Crush barriers: min. 1100mm height (min height 800mm for front row seat)<br>**Safety and Barriers**<br>• Maximum capacity based on the number of spectators and the available space: 1 spectator per 0.45 sq m<br>• Minimum number and location of exits, gates, and emergency exits (e.g., 1 exit for every 500 spectators)<br>• Type and quality of materials used in construction<br>• Installation and maintenance of safety equipment.<br>• Concourse amenities - should be distributed evenly throughout the concourse and wherever possible they should not be positioned immediately next to turnstiles or entry points, or next to the foot of vomitories or stairways leading from viewing accommodation.<br>• Concourse area – 0.5m2 per spectator |
| *British Standards BS (EN) 13200-1:1200* | **Focus:** spectator facilities<br>**Type:** legislative<br>**Themes:**<br>Accommodation (seating, standing)<br>Sightlines<br>Comfort and well-being<br>Access and egress Safety and security | **Sightlines:** maintain minimum viewing distances and angles, ensure unobstructed views<br>**Circulation:** provide accessible routes and sufficient width for entrances, exits, and vomitories<br>• Radial gangways: min exit 250 mm<br>• Radial gangways: max riser 200mm<br>**Programme/Layout:** balance spectator facilities, services, and access routes to optimize comfort, well-being, and safety<br>Addresses seating areas, circulation spaces (entrances, exits, vomitories), and spectator facilities<br>Includes spaces for disabled spectators<br>• Min seat spacing –seated: 450mm<br>• Min row depth –seated: 700mm<br>• Min row depth –standing: 350mm<br>• Min sightline: 90mm<br>• Max seats per row: 40<br>**Safety and barriers**<br>• Max steepness –seated: 35°<br>• Max steepness -standing: N/A<br>• Exit distance seat – vomitory – 8 minutes |
| *British Standards BS (EN) 6465:2009* | **Focus:** sanitary facilities provision<br>**Type:** legislative | **Sightlines:** N/A<br>**Circulation:** N/A<br>**Programme/Layout:**<br>• Urinals – min 2 per 50 spectators plus 1 for every other 50 males or part thereof<br>• WCs – min 2 per 250 spectators plus 1 for every other 250 males or part thereof<br>• WCs – min 2 per 20 spectators plus 1 for every other 20 females up to 500, then 1 per 25 or part thereof |

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| *Building Act 1984* | **Focus:** Building Regulations (UK)<br>**Type:** legislative<br>**Themes:**<br>Structural safety<br>Fire safety<br>Ventilation<br>Drainage<br>Access and egress | **Sightlines:** not explicitly addressed<br>**Circulation:** ensure safe and efficient access and egress, including emergency evacuation routes<br>**Programme/Layout:** follow UK building regulations for structural safety, fire safety, ventilation, drainage, and access<br>Does not provide a specific list of programmatic spaces for stadium design<br>Addresses general building regulations related to safety, fire safety, ventilation, drainage, and access<br>• Structural safety and stability.<br>• Fire safety (e.g., minimum distance between seats and emergency exits, fire-resistant materials).<br>• Ventilation and air quality.<br>• Accessibility for people with disabilities (e.g., minimum number of accessible seats, ramp slope and width)<br>• Energy efficiency. |
| *Equality Act 2010* | **Focus:** building regulations (UK)<br>**Type:** legislative<br>**Themes:**<br>Access | **Sightlines:** not explicitly addressed but ensure accessibility for disabled users<br>**Circulation:** provide accessible routes and facilities for disabled users, make reasonable adjustments<br>**Programme/Layout:** design layout to eliminate discrimination, ensure accessible facilities, services, and information<br>• Provision of accessible facilities and services for people with disabilities (e.g., minimum number of accessible toilets, wheelchair spaces). |
| *UEFA Guide to Quality Stadiums* | **Focus:** UEFA competition requirements<br>**Type:** licence<br>**Themes**:<br>Stadium categories<br>Seating capacity<br>Spectator facilities Media facilities<br>Infrastructure requirements | **Sightlines:** follow UEFA guidelines for minimum viewing distances and angles, ensure unobstructed views<br>• ‘C’ value min 60<br>• ‘C’ value recommended min 90<br>• ‘C’ value 120 optimal<br>• Max 190m distance from ball<br>**Circulation:** provide accessible routes, sufficient width for entrances, exits, and vomitories<br>**Programme/Layout:** Follows UEFA competition requirements for stadium categories, seating capacity, and spectator facilities.<br>Considers spaces for players, officials, spectators, media, and event operations<br>Addresses changing rooms, media facilities, VIP areas, and stadium operation spaces<br>**Accommodation:**<br>• Urinals – min 2 per 50 spectators plus 1 for every other 50 males or part thereof<br>• WCs –min 2 per 250 spectators plus 1 for every other 250 males or part thereof<br>• WCs – min 2 per 20 spectators plus 1 for every other 20 females up to 500, then 1 per 25 or part thereof |

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| *UEFA Guide to Quality Stadiums* | | • Minimum capacity and dimensions<br>  o Category 1: 1,500 spectators minimum<br>  o Category 2: 5,000 spectators minimum<br>  o Category 3: 10,000 spectators minimum<br>  o Category 4: 30,000 spectators minimum<br>• Minimum seat width – 500mm<br>• Pitch dimensions and quality: 100m -105m x 65m – 68m |
| *FIFA' s Stadium Guide* | **Focus:** FIFA competition requirements<br>**Type:** license<br>**Themes:**<br>Stadium structure Field dimensions Spectator facilities Media facilities Lighting and sound | **Sightlines:** adhere to FIFA guidelines for minimum viewing distances and angles, ensure unobstructed views<br>• 'C' value min 60<br>• 'C' value recommended min 90<br>• 'C' value 120 optimal<br>• Max 190m distance from ball<br>**Circulation:** ensure accessible routes, sufficient width for entrances, exits, and vomitories<br>• Riser min. 0.3m<br>• Tread min. 0.8m<br>**Programme/Layout:** follow FIFA competition requirements for stadium structure, field dimensions, and spectator facilities<br>Addresses spaces for players, officials, spectators, media, and event operations<br>Includes changing rooms, media facilities, VIP areas, and stadium operation spaces<br>• 28 WCs for every 1,000 women<br>• 3 toilets, 15 urinals for every 1,000 men<br>**Safety and Barriers**<br>• Rake angle (d) = max. 34°<br>• Emergency exits and evacuation plans<br>• Security measures, including CCTV and access control<br>• Safety equipment, including fire alarms and first aid stations<br>Fan behaviour and crowd management. |
| *IOC Technical Manual on Venues* | **Focus:** Olympic venues<br>**Type:** license<br>**Themes:**<br>Competition and non-competition venues<br>Sustainability and legacy<br>Venue overlay<br>Accessibility<br>Technology integration | **Sightlines:** follow sport-specific requirements and maintain unobstructed views<br>**Circulation:** provide accessible routes, plan for efficient crowd flow, and avoid congestion<br>**Programme/Layout:** separate competition and non-competition areas; consider sustainability, legacy, and accessibility<br>Considers spaces for athletes, spectators, media personnel, and event operations<br>Includes competition and non-competition areas, such as warm-up areas, changing rooms, and medical facilities |

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| *Metric Handbook* | **Focus:** Spatial parameters<br>**Type:** reference<br>**Themes:** Sports facilities | **Sightlines**: Emphasises the importance of clear and unobstructed views for spectators; provides information on 'C' value calculations for various sports to ensure appropriate sightlines.<br>• 'C' value min 60<br>• 'C' value recommended min 90<br>• 'C' value 120 optimal<br>**Circulation:** Highlights the need for efficient crowd flow, adequate width for entrances and exits, sufficient access points, and accessible routes.<br>• Gangway – 1.2m min<br>**Programme/Layout:** Covers a range of programmatic spaces, including seating areas, players' facilities, media facilities, and support spaces; provides design guidance on seating layout, pitch dimensions, and other aspects of stadium design.<br>• Various field dimensions<br>• Seat spacing – min 500mm<br>• Max number of seats in row – 28<br>**Safety and barriers**<br>• Max tier angle 34°<br>• Exit distance seat – vomitory – 30m |
| *Stadia: The Populous Design and Development Guide* - 5th Edition | **Focus:** design and development<br>**Type:** reference<br>**Themes:**<br>Stadium typologies<br>Sustainability<br>Seating bowl design<br>Spectator facilities<br>Ancillary facilities | **Sightlines:** consider spectator comfort and unobstructed views, optimize seating bowl design<br>• 'C' value recommended min 90<br>• 'C' value 120 optimal<br>• Max 190m distance from ball<br>**Circulation:** plan for efficient crowd flow, provide accessible routes, and sufficient width for entrances, exits, and vomitories<br>**Programme/Layout:** balance stadium typologies, sustainability, seating bowl design, spectator facilities, and ancillary facilities Covers spaces for players, officials, spectators, media, and event operations<br>Considers seating bowl design, roof structures, and ancillary facilities<br>• Urinals – min 1 per 70 spectators plus 1 for every other 50 males or part thereof<br>• WCs min – min 1 per 600 male spectators<br>• WCs min – min 1 per 35 spectators |
| *Stadium Buildings: Construction and Design* | **Focus:** construction and design<br>**Type:** reference<br>**Themes:** Design<br>Structure<br>Material selection<br>Building envelope<br>Site-specific factors | **Sightlines:** maintain unobstructed views, consider architectural and structural considerations<br>**Circulation:** ensure accessible routes, avoid congestion, and provide efficient access and egress<br>**Programme/Layout:** optimise layout for architectural considerations, structural systems, material selection, and site-specific factors<br>Addresses architectural considerations, structural systems, and material selection for stadium design |

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| *Stadium Atlas* | **Focus:** stadium development<br>**Type:** reference<br>**Themes:**<br>Planning and design<br>Construction techniques<br>Stadium financing<br>Sustainability<br>Case studies | **Sightlines:** Considers spectator comfort and unobstructed views<br>**Circulation:** Ensures efficient crowd flow, provide accessible routes and sufficient width for entrances, exits, and vomitories<br>**Programme/Layout:** Balances planning, design, construction techniques, stadium financing, and sustainability<br>Provides case studies and examples of stadium design, focusing on planning, design, construction techniques, financing, and sustainability |
| *Stadium and Arena Design* | **Focus:** design, architecture, and engineering<br>**Type:** reference<br>**Themes:**<br>Stadium typologies<br>Seating bowl design<br>Roof structures<br>Sustainability<br>Technology integration | **Sightlines:** optimise seating bowl design, maintain unobstructed views<br>**Circulation**: provide accessible routes, plan for efficient crowd flow, and avoid congestion<br>**Programme/Layout:** consider stadium typologies, roof structures, sustainable design, and technology integration<br>Covers spaces for players, officials, spectators, media, and event operations<br>Considers stadium typologies, roof structures, sustainable design, and technology integration |

## 3.3 Multi-use stadium definition

'Multi-use' is defined by this research as a set of varying functions that fit within the structural framework. The typological study in Chapter 02 identified the rectangular playing field as predominant shape, so the focus of this research is the accommodation of alternative performances within the football and athletics fields. Multi-use further implies the use of the building for events such as football, cricket, rugby, concert, athletics and non-match day events, that have different spatial requirements.

The gap in knowledge identified by the research is that there are no previous studies that utilise computational technology to analyse stadium design drivers and designs for varying functions. In addition, there is no major study of the relationship between the architectural and structural design of stadia for varying functions utilising architectural methodologies – this includes typological analysis and structural engineering, such as parametric design and the analysis of design space with machine learning.

## 3.4 Performance-based stadium design

The concept of performance-based stadium design originates in the task of designing a venue that allows large groups of people to see an event together. This creates design problems specific to each sport, and it defines the primary quantifiable characteristics of a stadium. (Department for Culture, Media and Sport, 2008; John et al., 2013; Nixdorf, 2008).

*Figure 3.28. Original 1967 proposal for the Truman Sports Complex for a multifunction arena that was rejected due to performance issues. (Kansas City Public Library, 2019)*

Early examples can be found in the United States, built in the 1960s and 1970s when architects and industry professionals first saw the stadium as a system of quantifiable relationships (Newcomb, 2018). The Truman Sports Complex in Kansas City, designed by Kivett & Myers, is an example of successful stadium analysis and design in terms of the scale of the building and its relationship to the surrounding area. In the 1960s, the norm in the United States was the construction of circular multi-purpose arenas, which, however, performed below expectations. Sources differ in whether they credit Charles Deaton (Kansas City Public Library, 2019) or Ron Labinski (Newcomb, 2018) with highlighting the obvious: the spectator experience was unsatisfactory because each type of sport has specific spatial requirements. These can be quantified and resources can be shared by more than one venue, but the construction of the circular morphology that was dominant in this period hindered the performance of

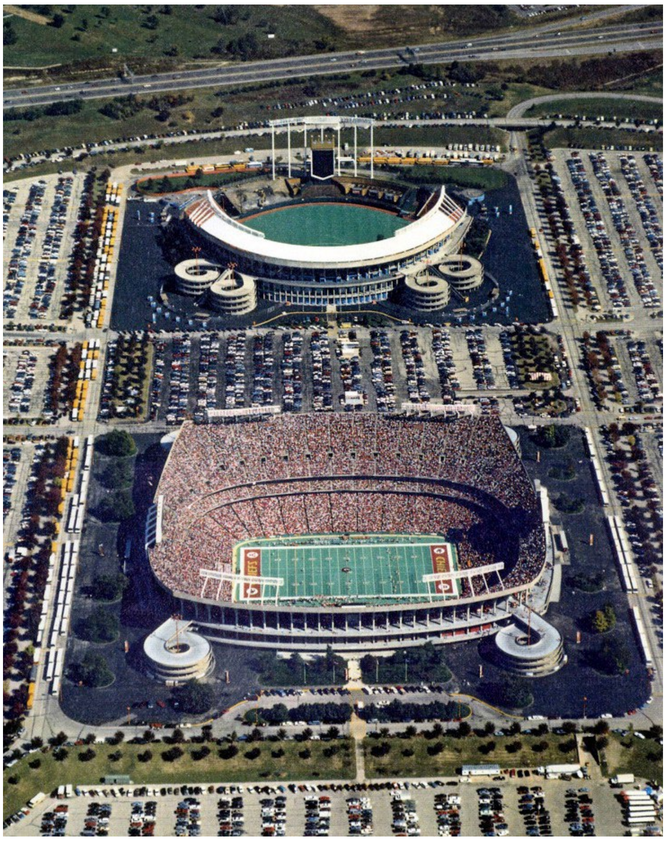


*Figure 3.29. Truman Sports Complex Kansas City, two buildings performing optimally while sharing resources. (Kansas City Public Library, 2019)*

the stadium across all purposes, meaning that the stadium could not host multiple uses successfully (Kansas City Public Library, 2019). In the late 1960s, Kivett & Myers' proposal for two separate stadiums adjacent to each other that share resources and facilities was ground-breaking at the time and led generations of architects after this project to pursue the investigation of this type of design performance optimisation through the quantification of elements of the hosted spectator experience. Following the success of this project, Labinski worked for several different companies, joining HOK in 1983, and within two decades this new partnership, Populous, became one of the most prominent sports architecture practices in the world.

## 3.5 Quantification of stadium design features

The idea that it was possible to quantify the performance of the stadium became popular in Europe in the 1980s through the work of John and Sheard (John et al., 2013, 1981; John and Parker, 2020; John and Sheard, 1994; Sheard, 1996; Sheard and Bingham-Hall, 2005). Two major events accelerated the development of stadium design, the Hillsborough disaster (Taylor, 1990) and the introduction of computer-generated geometry in architectural design (Sheard, 1996; Sheard and Bingham-Hall, 2005). The Taylor Report (1990) concluded that stadiums in the UK were out of date and dangerous and needed to be replaced by better designed venues. Computer-Aided Design [CAD] provided the design environment that enabled the use of simulation and visualisation to inform the entire design process .

*Figure 3.30. Early stadium CAD model by LOBB Architects (John and Sheard, 1994)*

These two conditions created an environment in which new stadiums became a priority, and John and Sheard had access to the technology to radically redefine their typology by quantitatively evaluating their performance in reference to the requirements of different users (Thompson et al., 1998). For the first time in history, it was possible to design a stadium with all the legal and functional constraints embedded within a comprehensive digital design model that could be analysed and improved. John and Sheard were also active in the development of legal technical requirements and specifications (Football Stadia Advisory Design Council, 1992). Their work became the theoretical and practical basis for the division of design into different disciplines, the segmentation of the design team, the formation of the legal requirements for stadiums, and the structure of all the stadium design guides. John and Sheard's work informed the *Green Guide* (Department for Culture, Media and Sport, 2008) and the EU (BS) standards for spectator facilities.

This research evaluates their work and proposes a departure from the description of typology based on themes or design disciplines, suggesting a move towards a definition based on the quantification of design performance within the modular scales in which stadiums are designed – 2D section, bay, stand, and stadium. The rationale for this approach is the integration of the practice aspect of the research with professional practice and the research objective to automate sections of the design process through the creation of a design analysis, optimisation, and the generation of a machine learning pipeline. This will assist designers, clients, regulatory bodies, and stadium operators to analyse and optimise stadium designs and their performance. The new approach enables a better integration of the entire design team based on the use of repeated design elements with the specific scale.

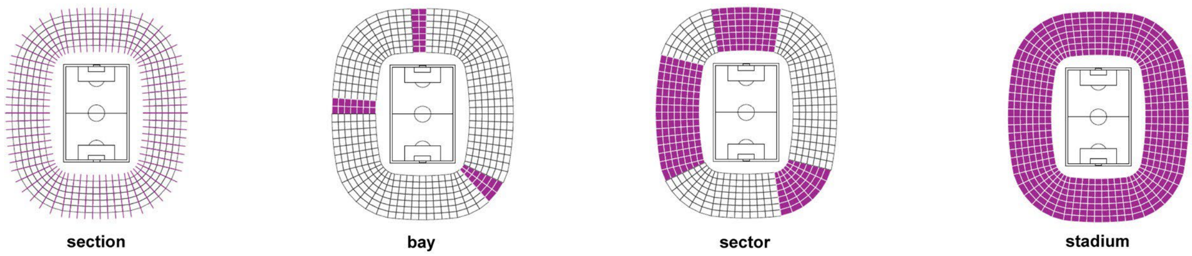



*Figure 3.31. Stadium modular scales defined by this research*

### 3.5.1 Sightline analysis

The ability of the spectator to see an event from their seat in the stadium bowl is the primary generative force in the overall morphology of the stadium. Identified first in the modern period by Russell (1938) in the context of theatre design, sightlines are a quantitative means of controlling the viewing performance and experience. The evolution of computational technology dramatically affected both architecture as a whole (Schumacher, 2016, 2008) and stadium design in particular (Hudson, 2010). In terms of the primary function of the building – watching an event – this development meant that the designer had an unprecedented ability to virtualise and simulate the spectator experience through its quantified properties (Hudson and Westlake, 2015). It was only after the early 1990s that the quality of view from each seat could be fully quantified in terms of the area a spectator can see above the head of the spectator in front (Hudson, 2008; Shepherd and Hudson, 2007). This new approach to understanding the stadium has led to a new generation of design and construction approaches since the mid-1990s (Sheard, 1996).

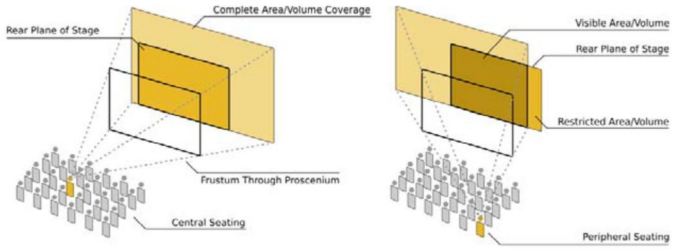



*Figure 3.32. Spectator visual fields based on seat location (Rafailaki and Dritsas, 2007)*

Nevertheless, it was only in the late 2000s that sightline analysis was developed fully – by Hudson, who rediscovered the theory that had been developed in theatre design (Russell, 1938) and the relationship between visual experience, perception, and the morphology of the auditorium (Hudson and Westlake, 2015). Hudson's primary reference is the work of Dritsas and Rafailaki (2007), who identify many other quantifiable properties of the visual experience in an auditorium, such as the angle towards the stage, distance from the stage, and the height of the seat in relation to the stage (Appleton, 2008; Bearsdslee and Wertheimer, 1958; Carlson, 1989; Gibson, 1979, 1950; Goodale and Milner, 2004; Haber, 1968; Schechner, 1988; Siegel and White, 1975). Translating visual cognition theories into a parametric model creates a new tool for assessing sightline quality – the A-value – which takes not only the visual space in front of the spectator into account but also their angle and

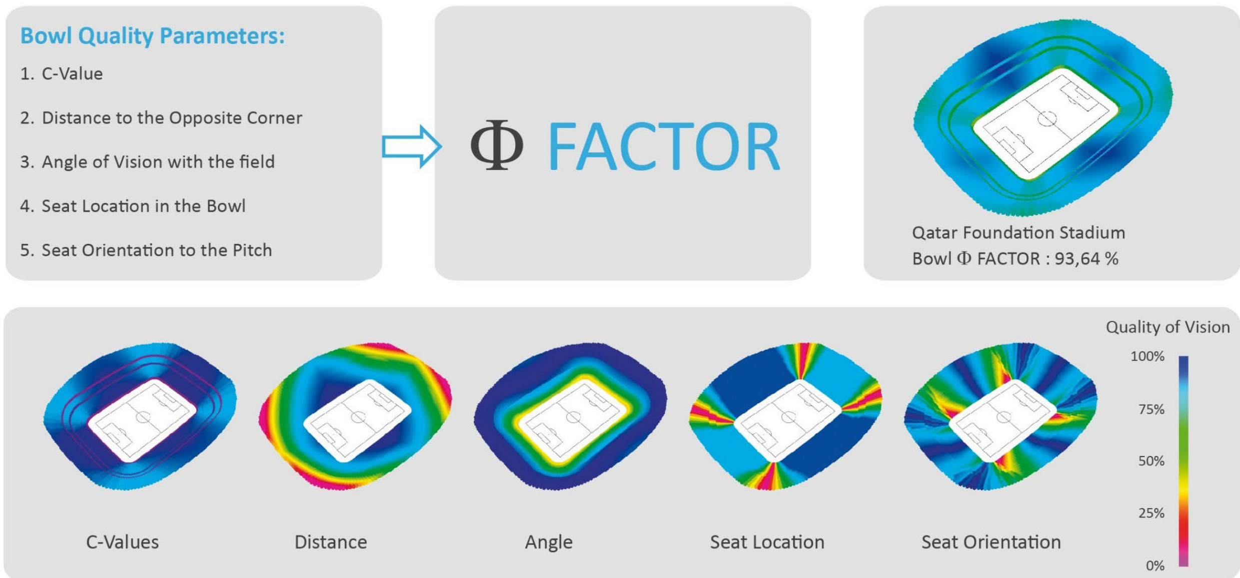



*Figure 3.33. Fi-Factor (Fenwick Iribarren Architects, 2018)*

distance from the playing field (Hudson and Westlake, 2015). Hudson's work was advanced further by Fenwick Iribarren Architects and their 'Fi-Factor', which takes 'C' value, distance, angle, orientation, and location to present a more complex estimation of the sightline performance of the stadium bowl (Fenwick Iribarren Architects, 2018). This type of analysis was used in the design for the FIFA World Cup stadiums in Qatar (Morales and Sykes, 2019) and by Herzog & de Meuron for their Stamford Bridge stadium project (Castro, 2020).

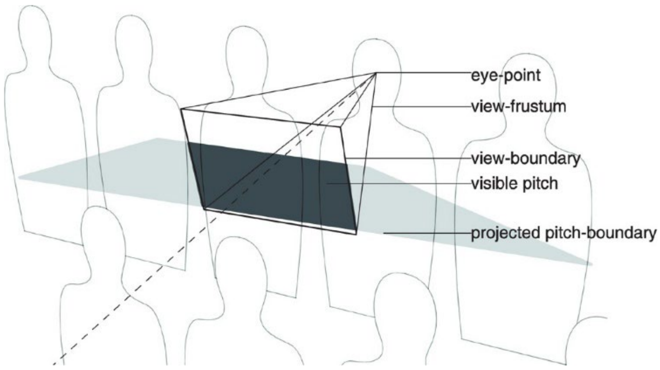


*Figure 3.34. Hudson A-value (Hudson and Westlake, 2015)*

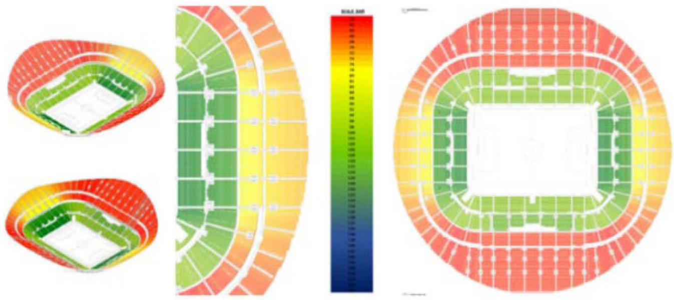


*Figure 3.35. Luseil Stadium Qatar 'C' value analysis Polulous/AFL (Morales and Sykes, 2019)*

Currently there are two software products which enable the parametric generation and sightline analysis of stadiums, BowlBuilder (Marschall, 2018) and Torro (Hudson, 2021), but these are technical investigative tools that work only within the Rhino/Grasshopper environment and are limited in terms of the information they can analyse. Both tools generate the stadium grid and the seating bowl, and work with pre-established morphologies. One of the outputs of the PhD overcomes those limitations, by fully rewriting the analysis modules and expanding the scope of assessment.

Building on existing approaches to the quantification of sightlines, this PhD develops a set of datasets which are analysed with machine learning. In this way the quantifiable sightline quality becomes the first major section of the parametric model output for the machine learning model. Previously Joseph and Kim (2015) attempt to bring Hudson's parametric approach to design (2010; 2011; 2008; 2015; 2007) to optimisation. Joseph and Kim (2015) simulated the spectator's view in reference to the micro scale of each individual seat and the obstructions to the view caused by circulation elements such as handrails and balustrades. This research was deemed to be unsuccessful due to

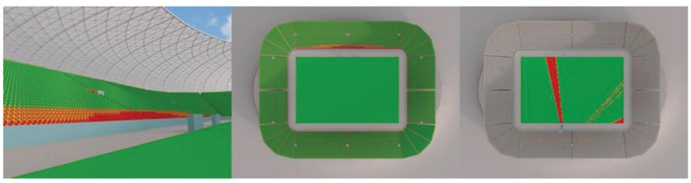


*Figure 3.36. Sightline optimisation based on distance to playing field (Joseph and Kim, 2015)*

the complexity of the script and the computational resources required for analysis of the obstructions (Joseph and Kim, 2015).

This PhD aims to produce new knowledge about sightlines through a new method of analysis with machine leaning based on point cloud analysis of the distribution of seat sightline quality. The evaluation of existing case studies and design space is based on quantified performance parameters encompassing  all the means of sightline quantifications addressed in the literature and professional practice. In contrast to the Fi Factor study, stadiums are not ordered in this PhD by a specific value, but the datasets area is analysed based on patterns found within the point cloud distribution of values of each individual seat and additional spatial, circulation and structural data. Later, the research relates the sightline quality to the internal layout and the structure of the buildings.

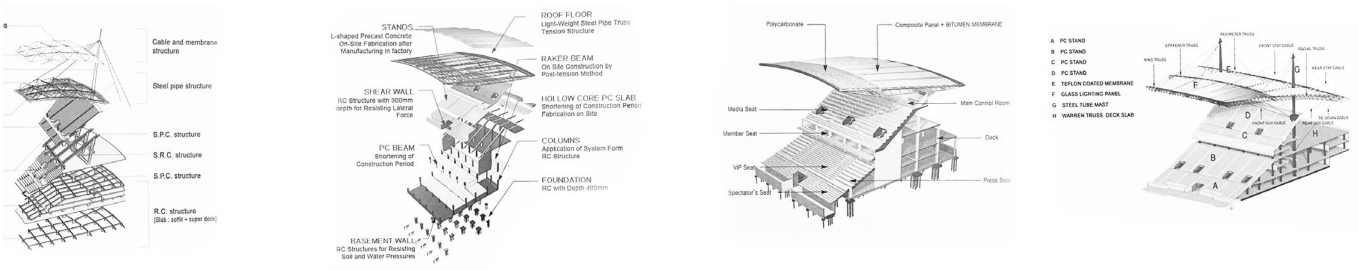



*Figure 3.37. Stadium modular units for the venues for the 2002 FIFA World Cup in Japan and South Korea (Shin et al., 2008)*

## 3.6 Parametric representation

The structure and the development of construction technology have been an inseparable part of the evolution of stadium design (Thompson et al., 1998). This PhD takes Kirsch's (2002) definition of structural topology as a network of load distribution elements and creates a parametric representation of those design drivers. In this way the type, number, amount, and volume of each structural member can be measured, added to the dataset and consequently analysed.

Based on the previously defined stadium modularity scales and the approach taken by the designers of the stadiums for the FIFA World Cup in Japan and South Korea (Shin et al., 2008), this PhD explores the properties of the stadium's structural bay in terms of modular repeatability.

As with the approach taken by Culley and Pascoe (2015; 2009), the elements that were evaluated are the primary structural elements – columns, beams, rakers, foundations, slabs – and the secondary ones – bowl rows, volumetric façade and roof, and moving elements. The standards for those elements can be found in the *Approved Document A: Structure* and *B Fire* from the UK's Building Regulations (2020). The primary source for structural design is the work by Culley and Pascoe (2015; 2009, 2005) who enumerate all the aspects of the structural design and performance of the stadium. This research also builds on the thesis by Bader (2008), who catalogues the structural elements of the stadium but also expands this further by establishing performance benchmarks across real life case studies through an analysis of the amount and number of types of elements used. In academia, from a structural topology perspective, the primary research directions are towards the optimisation of the envelope and the roof canopy, as seen in work by Ohlbrock (2016), and the optimisation of the use of stand material, in work by Altair (2021).

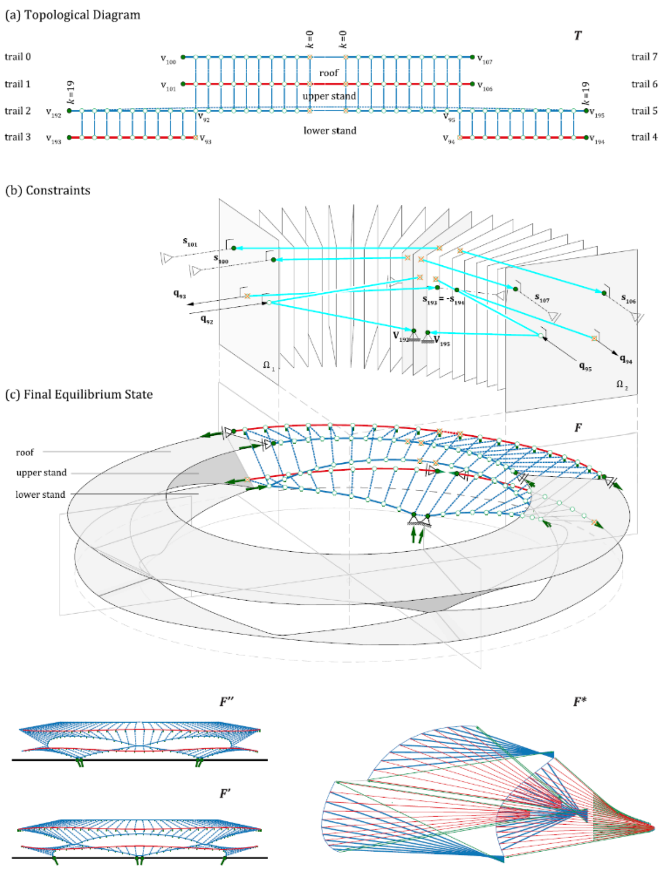


*Figure 3.38. Ohlbrock (2016) stadium canopy optimisation*

## 3.7 Circulation and layout analysis

This research instrumentalises Space Syntax methods for circulation and layout analysis. Space Syntax is a well-established methodology in the communication of the required spatial relationships in FIFA's (2011c) and IOC's (2005b) stadium design guides. Work by Hillier (2015; 1987; 2005) is relevant to this PhD, as it focuses on spatial and functional relationships, but it has not yet been investigated academically in terms of addressing stadiums from the perspective of multi-objective optimisation. The concept of Space Syntax is a spatial analysis strategy based on sequences of spaces, distances, angles between spaces, and visibility between spaces (Hillier, 2015). Hillier's work can usefully be applied to the functional planning and analysis of stadiums. Hillier's interest in urban systems and the relationships between their different functional parts can be translated into buildings of similar scale; they bring this type of architectural reading to a typology with a different historical development. In addition, Suziki (2018) has successfully utilised Space Syntax for the analysis of crowd movement with machine learning, an area of vital importance for the design and operation of stadiums from both a legal and economic perspective, due to the importance of circulation in stadium design (John and Sheard, 1994). Approaches from the Space Syntax methodology in terms of relationship between spaces, the sequence of spaces, and the distances between spaces are used for the analysis of the case studies, the production of layout variations through parametric variation and machine learning, and for the creation of a methodology for new designs. The output of the parametric model produces all three concepts of distance as defined by Hillier – topological, angular, and metric distances – but the research focuses only on metric distance as it is reflected in the legislative literature (Hillier et al., 1987; Space Syntax network, 2022). Further, as the machine learning analysis is reliant on numerical output, the parametric model does not output the chain graphs that are typical with the use of Space Syntax. Another limitation using Space Syntax is the representation of floor layouts – the functions in the stadium case study models are simplified to their basic usage – concourses, commercial, hospitality, players, etc. This representation is sufficient to measure the basic spatial relationships across case studies, but does not provide a higher level of detail – for example, there is no distinction between a shop, a restaurant, and a museum – they are all defined as commercial spaces. To balance this limitation, the research has developed an overall Space Syntax map based

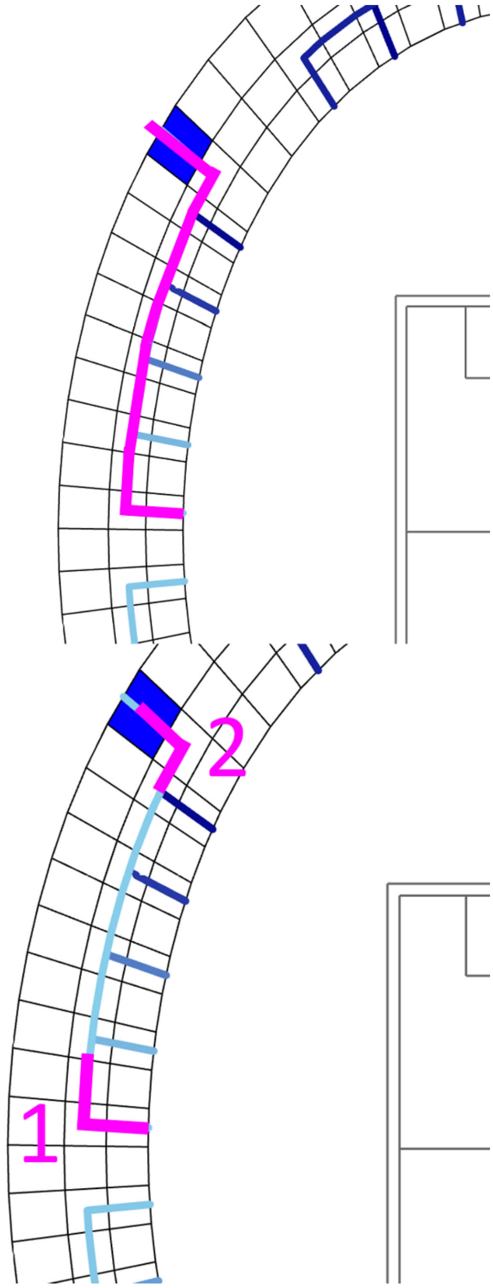



*Figure 3.39. Practice-side measurement of metric and topological distances between bowl exit and vertical circulation*

on the FIFA stadium guidance (Fédération Internationale de Football Association, 2011) which allows for the interpretation of different functional zones in terms of specific uses. The aim is to have a layer of additional information that can inform the functional composition or the larger areas – an approach similar to that of Chaillou (2020, 2019b), who takes the outlines of the buildings in a city plan and then populates them with the layouts. This detachment from the detailed plan produces simpler machine learning models while retaining the organisational data that relates to the rest of the research themes.

The research considered utilisation of Space Syntax Grasshopper plugins like Depthmap (Space Syntax Network, 2013) and Syntactic (Nourian, 2018). As mentioned in Chapter 01, the reason for not including those tools in the parametric model is the additional focus morphology and sightlines. Further on, those plugins are designed with specific focus on urban planning and internal layout and thus fall outside the scope of this research.

## 3.8 Multi-objective optimisation

Pan (2021) describes optimisation as a process of finding the optimal of several objects within a defined range, according to specific criteria. This selection is achieved through a feedback loop which informs the input values of the parametric model. Turrin (2014; 2012, 2011) identifies multi-objective optimisation as the process that supports trade-off decisions between multiple conflicting design objectives, with the aim of selecting the best-performing design option. Turrin (2012, 2011; 2014) also defines multi-discipline optimisation as one that relies on an interdisciplinary design methodology. The methodology of this PhD is closely linked to those three concepts and introduces the concept of multi-scale optimisation, or the selection of best-performing cases across modular scales. Working across scales, disciplines, and objectives creates a very large set of building design performance data that can only be analysed through computational means, and specifically machine learning.

Nguyen et al. (2014) defines the process by which parametric modelling and building performance simulations are combined as 'simulation-based optimisation'. Nguyen et al. (2014) further describes this process as a 'black box' method – in most cases there is no obvious relation between input and output, and thus specific search optimisation algorithms must be identified. Wortman and Nannicini (2016) present a comparison of three main types of black box optimisation algorithms – metaheuristics, model based optimisations, and direct search. Metaheuristics involves selecting a sample which serves as the basis for the following generation of solutions. This approach is applicable to any problem type, is easy to implement, and is perceived as especially suited to multi-objective optimisation (Wortmann and Nannicini, 2016). Direct search methods explore the design space based on deterministic strategy, while model-based optimisations take advantage of surrogate model strategy and use the properties of the surrogate model to inform the next generation of solutions. Nguyen et al. (2014) and Pan (2021) focus on metaheuristics while Wortmann and Nannicini (2016) reason that the other two methods perform better if there is a larger design space, with more than 10,000 solutions.

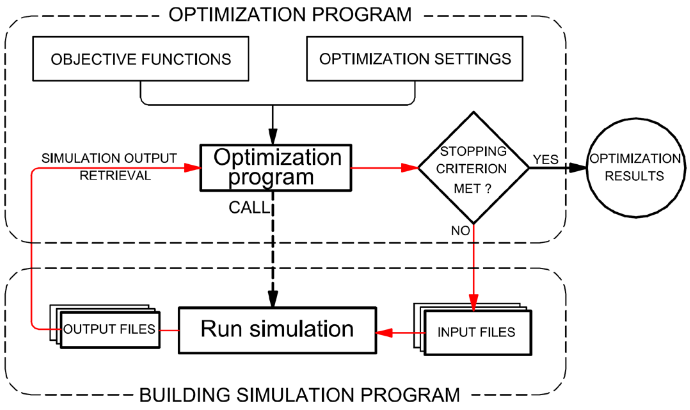



*Figure 3.40. Structure of performance based-building simulation optimisation algorithm Nguyen et al. (2014)*

The most widely used optimisation algorithm available for the scripting environment of the parametric model is Galapagos in Grasshopper which is a single objective evolutionary solver. This tool uses a compound fitness function to iteratively search for well-performing solutions and does not explore multi-objective optimisation through the exploration of Pareto fronts. There is another tool, Octopus, that is currently available for Grasshopper: it can process multi-objective optimisation, and uses SPEA-2 and HypE reduction algorithms. Both algorithms explore Pareto fronts, based on the Pareto rule stating that 80% of the results are caused by 20% of causes (Bader, 2011; Sheng et al., 2012). The reason for the selection of this tool is the integration with the parametric model, the control over the weights of each feature, and the control over the mutation rate of the optimiser genes.

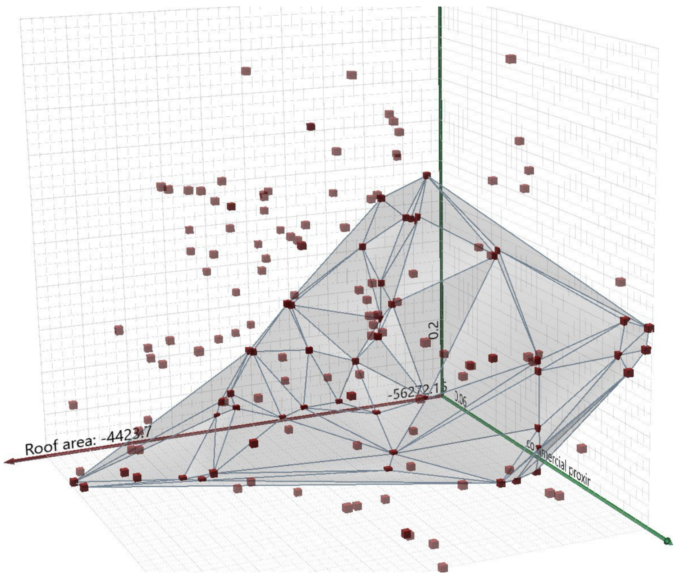



*Figure 3.41. Octopus multi-objective optimiser (practice side)*

## 3.9 Stadium design and performance optimisation

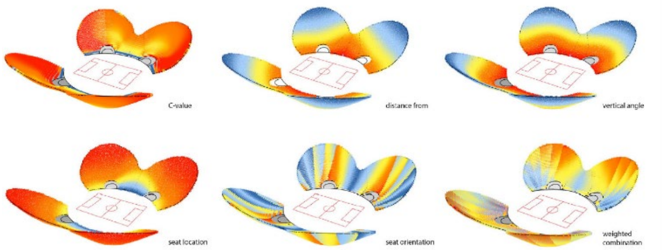



*Figure 3.42. Luigi Moretti stadium design analysis by Bianconi et al. (2019)*

There are a number of stadium performance optimisation studies that focus on bowl optimisation and sightlines, such as that by Joseph and Kim (2015), Bianconi (2019) – in terms of Moretti's designs – and circulation, such as that by Brocklehurst (2005), but to date no research has focused on the relationships between sightline quality, circulation, and layout through the prism of modularity. The primary reason for the segmentation of the existing research is the structure of the design team and the limits of computational technology for the virtualisation of case studies. This PhD attempts to overcomes these limitations through a revaluation of the entire structure of design drivers for the stadium type and the construction of a parametric model based on the analysis of primary design drivers that define their modular scales.

During the last ten years, there has been a significant amount of research produced by a group of academics at Delft University of Technology (TU Delft) on the analysis and optimisation of indoor arenas. This group's approach is aligned to the scope of this PhD in its exploration of the production of a parametric model, the evaluation of quantifiable design features, the development of design space, and the selection of best-performing cases.

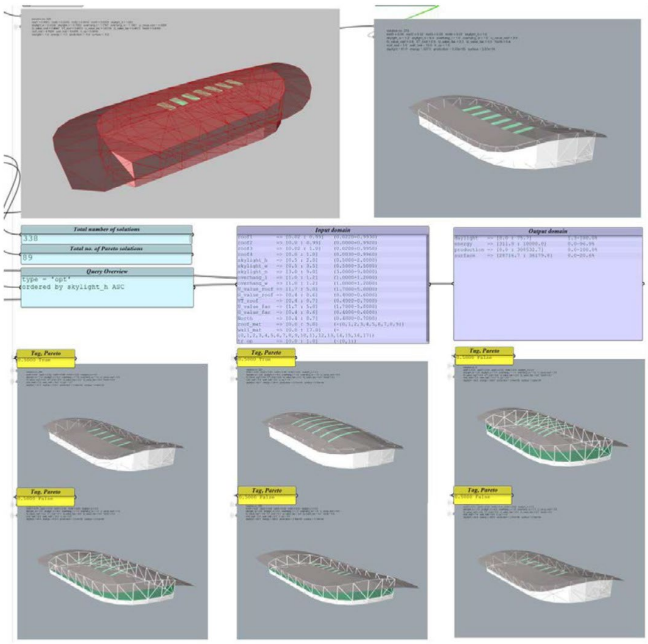


*Figure 3.43. Optimisation of swimming pool envelope design based on temperature and air flow (Turrin et al., 2016)*

The group's publications include the multi-objective multidisciplinary study by Turrin (2016) on the optimisation of swimming pool envelope design based on temperature and air flow, the sightline optimisation study by Joseph and Kim (2015), mentioned above, and Sun's (2013) methodology of grandstand analysis with shape grammars. All the researchers in this group focus on early concept design, and as a result their models are developed in a similar way to this PhD – primary elements of interest are identified and quantitively defined, while less important elements like façade structure or floor build-up are simplified.

Work by Pan (2021) explores the problem of how designers can be better supported in the concept design of indoor arenas and the integration of multifunctional spaces with long-span roof structures through computational means. Pan (2021; 2020) develops a practice framework that relates the design of the arena roof to the morphology of the auditorium and a basic estimate of acoustic and sightline performance. He develops a design space and proposes three workflows that utilise machine learning to select the best-performing case studies via multi-objective optimisation [MOO] and clustering algorithms. Pan's methodology (2020; 2021) is similar to the approach of this PhD, because it involves MOO in the context of the multi-disciplinary optimisation of a public assembly building.

Pan's (2021) first workflow focuses entirely on quantitative data analysis and defines a design space, then uses MOO in Matlab (MathWorks, 2023) to identify well-performing cases. His second pipeline is based on a visual interaction with the designer, who chooses a set of solutions from a narrowed-down design space based on self-organising map [SOM] clustering in order to then select a well-performing solution either manually or through MOO. In reference to this PhD, Pan (2021) uses

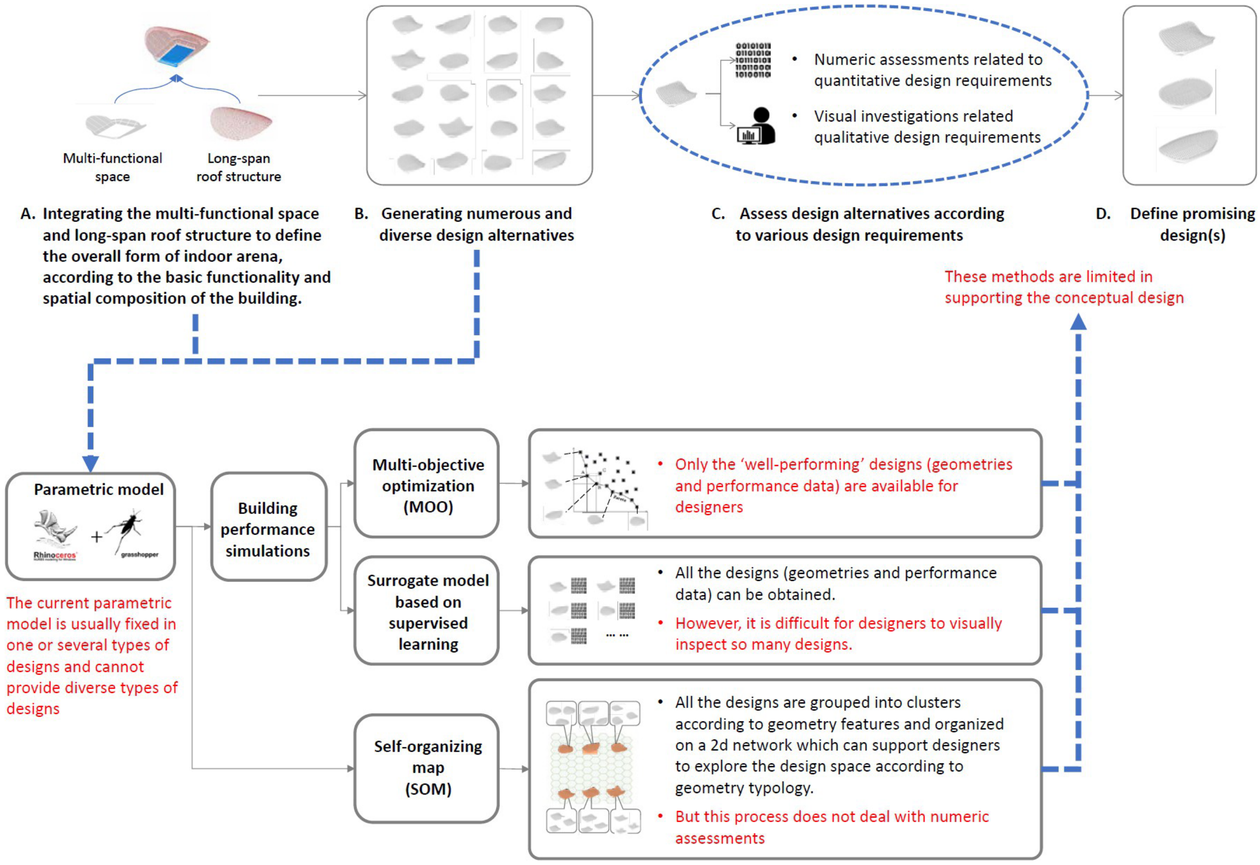



*Figure 3.44. Pan (2020) multi-objective optimisation workflows*

only SOM rather than other machine learning algorithms, because this type of clustering not only groups cases together but also groups related clusters together. Pan's (2021) third workflow is semi-supervised: labels are generated using SOM clustering on a sample from the design space and these are used to train a Multi-Layer Perceptron NN to classify the other members of the design space. Pan's (2020; 2021) methodology is similar to the approach of this PhD, especially in terms of developing a design space based on a parametric model, which is analysed with a set of measurements extracted from the parametrically generated design space. Pan's research objectives are aimed at the optimisation of the structural properties of the design, and do not focus on architectural aspects such as advanced morphologies, layout, or circulation.

## 3.10 Parametric design and variables in stadium design space definition

The development of a meaningful design space in this PhD also builds on work by Mueller and Brown (2019) and Turrin (2014; 2011; 2011b; 2016, 2012b; 2018). From an engineering perspective, variables are used to optimise structures, while in architecture variation is used for both qualitative and quantitative ends. The design space variables are extracted from the legal design requirements, guidance developed by international sports federations, practice-based research by leading architects in the field, and a typological study. Brown and Mueller (2019) propose a framework for a holistic approach to resolving design issues that brings together both engineering and architectural design through the creation of parametric models and the evaluation of the weight of the variables in these digital representations (Brown and Mueller, 2019b).

In terms of stadiums, digital design is already deeply embedded in professional practice (John et al., 2013), and the use of existing design parameters forms the basis of this PhD. Hudson (2008) describes parametric design methodology for stadium projects in several themes: knowledge used to solve design problems, analysis of existing projects and proposed design solutions, representation of design problems not as geometrical entities but as symbolic diagrams, and programmatic descriptions. In addition, Hudson (2007) describes a fully parametrically integrated design approach, used specifically for the façade of the Lansdowne Road stadium, where the architectural design, structural design and optimisation, and manufacturing and construction are presented as a continuous process, with different disciplines collaborating on the development of one digital model. This methodology is further expanded in the study of the design for the façade of the Aviva Stadium in Dublin (Hudson et al., 2011), where the main relationships between the design from different disciplines are retained, but the process is further elaborated with the use of parametric models for the detailed design of this section of the project.

*Table 3.2. Figure 03.41. Major phases of stadium design development in terms of sightlines, circulation, and layout/programme*

| **Type** | **Sightlines** | **Circulation** | **Layout and programme developments** |
|---|---|---|---|
| Preolympic | N/A | N/A | N/A |
| Ancient Greek Stadion | Earthen embankments | Clear separation of playing field/track and seating, introduction of diazoma (horizontal and vertical gangways)<br>Full-day event | Narrow compared to modern stadiums, στάδιον [stadion] was a U-shaped or rectangular topology with long straight sides and curved end<br>No sanitary provision Temporary commercial |
| Roman Amphitheatre | Tiered seating | Vomitoria for efficient entry/exit<br>Full-day event | Sanitary provision<br>Temporary commercial<br>Royal box, social class segregation |
| Hippodrome | Single tier | Wide entrances for spectators<br>Full-day event | |
| Jousting Lists | Temporary wooden stands | Unorganised Full-day event | No sanitary provision |
| Spanish Bull Ring | Tiered seating | Multiple entrances and exits<br>Limited-time event | Sanitary provision<br>Temporary commercial<br>Differentiation of viewing area by ticket price |
| Cricket Grounds | Multiple stands | Circulation paths around the field<br>Full-day event | Multiple bay module types |
| Early UK Stadiums | Rectangular stands | Limited organisation of circulation<br>Limited-time event | Rectangular playing field |
| First Olympic Stadiums | Tiered seating | Planned as public assembly buildings Limited-time event | |
| 1960s-70s | Tiered seating | First specific stadiums regulation<br>Limited-time event | Temporary and permanent commercial<br>Hospitality<br>Increased emphasis on multi-purpose facilities<br>Greater use of steel and concrete for construction<br>First laws about safety and capacity Improved amenities, |

| | | | |
|---|---|---|---|
| | | | such as sanitary provisions, concessions, and hospitality |
| 1980s | Tiered seating with enhanced sightlines | Improved spectator flow, but major incidents Limited-time event | First modern design manuals |
| 1990s | Computer models used to design seating based on sightlines | Beginning of regulation and quantification of stadiums specific design rules | Sport-specific stadiums with enhanced fan experience and revenue-generating amenities<br>Shift towards sport-specific stadiums<br>Taylor Report and emphasis on safety |
| 2000s | Tiered seating and push towards unobstructed views | Better access and egress | Sustainable designs with advanced technology<br>Integration of technology, such as video boards and Wi-Fi access |
| 2010s | Tiered seating and advanced sightline simulation and optimisation | Efficient and accessible transportation | Integration of advanced technology, such as high-definition video boards and mobile app integration<br>Enhanced fan amenities, such as premium seating options, diverse food and beverage options, and fan zones |

Since the origins of the stadium, it has evolved as a manifestation of the combined architectural and engineering development of the period. This has resulted in a predominant striving towards modularity and a perennial discourse on the adaptability of stadiums for hosting different types of events. The process of the quantification of stadium design drivers can also be traced to the origin of the type and follows closely the development of construction and computational technology. Recent developments in machine learning allow for a reconceptualization of the basic workflows in the design process aimed at evaluating and optimising the primary design objectives of stadiums.

However, data-driven processes have already transformed the way stadiums are designed, and this process can be taken further by a comprehensive parametric description of every existing and potential design that can help to compare existing designs and improve future construction. This research proposes the development of a dataset based on existing case studies and their parametric variations, which can serve as a reference for the performance testing of new designs.

# Chapter 4 Data: Algorithmic Modelling and Machine Learning Analysis

The core of the development of the datasets used in this research lies in the identification of the morphological and organisational type of the centrally organised public assembly building around a stage with a permanent or temporary roof opening above the stage. Based on the typological study presented in Chapter 02, the research identified that modular stadiums overlap

completely with the building type that describes their characteristics. This intersection enables the construction of a framework of shared design drivers that can be analysed and optimised through quantitative means. For this research project the typological framework served as the basis for the development of a parametric model that captures these shared characteristics, and its parameters represent the properties of stadiums design numerically. Taking the research a step further, the values of the parametric representation of the shared characteristics also form the basis for the creation of new datasets that were used for the training and optimisation of the machine learning models.

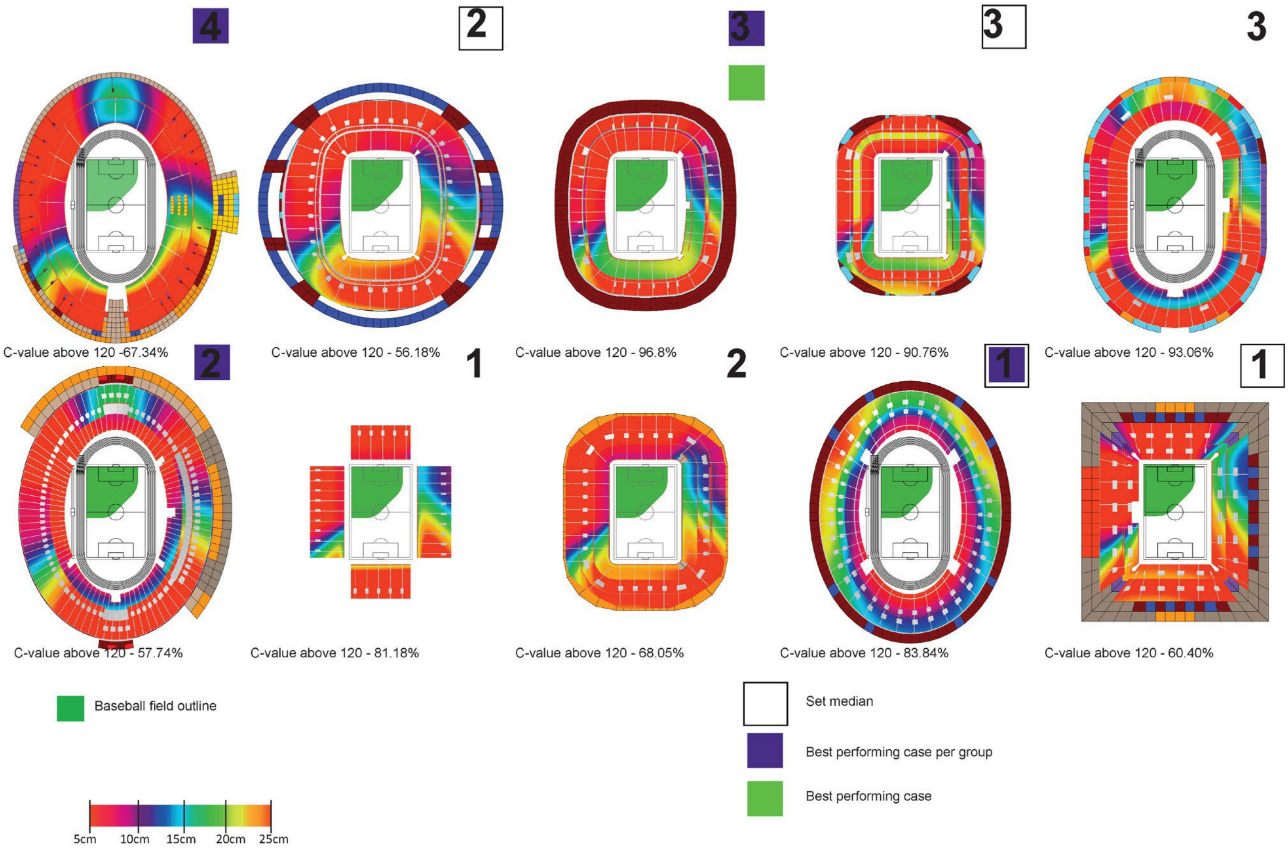



*Figure 4.1. Sample of performance benchmarking of existing case study dataset focusing on adaptation – quality of sightlines for baseball events at stadiums with rectangular or athletics playing fields*

## 4.1 Traditional approaches to stadium design analysis and optimisation

### 4.1.1 Modularity defining design focus and scale

Chapter 03 of this thesis explored the conceptual development of stadium design through the historical development of the morphological and organisational building type. The research identified modularity as one of the fundamental design drivers in the development of the type, an observation that is found in the work of scholars investigating the characteristics of assembly buildings, such as Leacroft and Leacroft (1984), Bader (2008), Welch (2009), Kierkuc-Bielinski (2012), and John and Parker (2020). Approaching the work of the previous researchers critically, the practice side of this thesis identified four primary modular scales, which define stadium design principles and create a parametric model which simulates the relationships between the elements of each scale. Each of the scales has separate numerical inputs and constitutes a separate semi-independent section of the parametric model. The output of the model is a comprehensive typological 3D stadium representation and a large set of additional analytical dimensions. The datasets are based on existing stadium case studies that have been analysed and recorded through the properties of the modular scales within the parametric model. As such, the parametric model is not only a generative tool, but also one that translates the properties of the design of the case studies for analysis with the machine leaning algorithms. The parametric input is also the first dataset to be structured for machine learning analysis. Later, the second part of the dataset is produced by the performance analysis, based on measurements within the parametric model.

### 4.1.2 Sightlines and the stadium section

The ability of the spectator to see an event from their seat in the stadium bowl is the primary generative force in the overall morphology of the stadium, and it defines the related performance space. The typological analysis at the beginning of the research project identified several additional characteristics that affect the viewing experience of the spectators – the number and location of tiers, the depth of landings and horizontal circulation, and the row depth. The properties of these characteristics are defined in the legislation related to stadiums and public assembly buildings and form an essential part of this modular scale in the parametric model. The section of each seating tier is generated independently, based on the 'C' value formula, and results in a parabolic curve (John et al., 2013). In terms of the dataset, the machine learning models are trained using the actual dimensions of the elements of the seating stand and the output is analysed comprehensively as a set of metrics reflecting the distribution of the performance values of each individual seat in the seating bowl. Depending on the morphology selected at the stadium scale the performance analysis is based on the number of seats, or the percentage of seats, that have a higher value than the 120 'C' that is recommended. (Department for Culture, Media and Sport, 2008; Nixdorf, 2008; John et al., 2013).

### 4.1.3 Internal layout organisation and the development of the bay, sector, and stadium scales

The black box nature of the optimisation problem in this research originates in the relationship between the different modular scales. Similar black box problems relating to parametric modelling have been described by Turrin et al. (2015), Nguyen et al. (2014), Brown and Mueller (2019a), and Pan et al. (2019). The multi-objective optimisation process requires the parametric definition of building elements that are interrelated, and changes in the input affect all elements of the model. The lack of linear relationships presupposes the utilisation of machine learning for the development and analysis of the design space. The parametric model allows the section to be generated independently, but the bay and stand sections are fully dependent on the overall morphology defined in the stadium scale. The stadium scale also defines the number of divisions and morphology of the structural bays – each basic outline has a specific effect on the form of the structural bays, and some shapes result in greater distortion in the corners as opposed to other, more consistent, forms like an ellipse or a circle. In terms of the process of training the machine learning models, this morphological design characteristic is represented through the overall area and number of elements in each bay. The dimensions of the modules are identified through the definition of the shape grammars used in the stadium scale and are not controlled through direct input in the parametric model.

The stand scale is simultaneously a result of the section and stadium scales. The type of modules selected is based on numerical input that identifies the specific type per individual grid cell. This selection results in a sequence of numbers that reflects the number of stadium bays and forms part of the dataset used for training the optimisation and generation algorithms. The internal organisation of the stadium functions is based on the allocation of specific functions per stadium grid cell per floor. This data is also input, numerically based, on the radial grid and results in consecutive rings of functional definitions. As it is a parametric input, the dataset for this section of the model is recorded as a sequence of lists, an independent Grasshopper data tree, and forms part of the training dataset. Due to the substantial number of possible functional allocations, the functions are simplified to the basic stadium requirements – commercial, sanitary, circulation, service, and hospitality spaces. This approach allows the supervised training of the NN machine learning model and a direct investigation of the relationships between the separate functions in the context of modular stadium design. The performance of the layout is later evaluated through the proximities of different functions, frontage to spectator areas, and area proportions.

### 4.1.4 Relationships between the bay module, sector, and overall stadium defining the internal circulation paths

Spectator circulation is one of the most commonly investigated elements of stadium design, due to its critical importance to the safety of the building. This research builds on the work of the previous researchers but also explores the relationships between layout organisation, morphology, and quality of sightlines. This approach, uniquely, uses the full extent of the capabilities of machine learning for finding previously unattainable patterns and relationships. The focus of the research is circulation, and it examines both horizontal and vertical movement. Later, the circulation is mapped from the entry of the stadium masterplan, the various safety zones, internal concourses, and bowl circulation to the individual seat per spectator. This process is based on the shortest path in

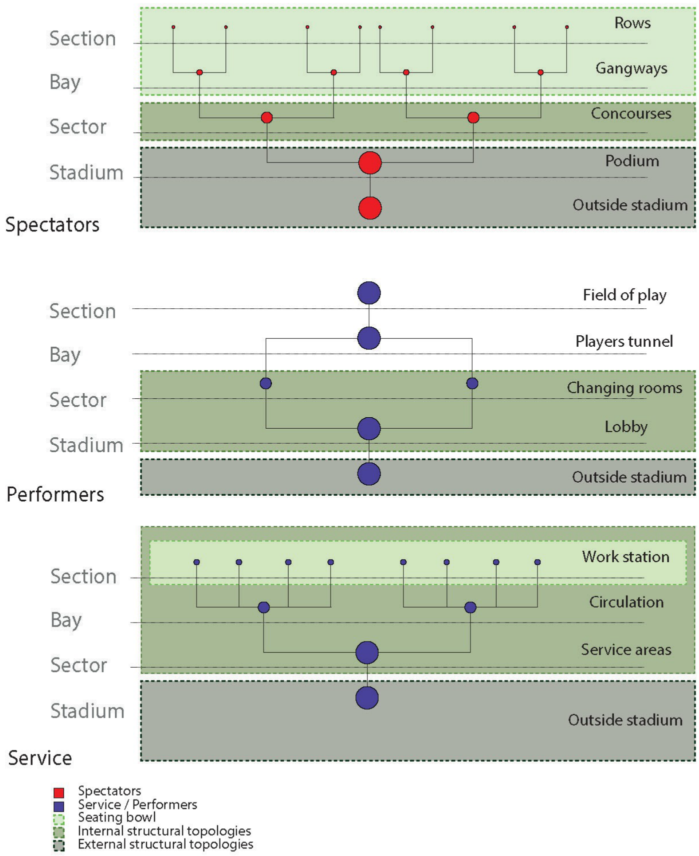



*Figure 4.2. Relationships between primary stadium circulation paths and modular scales*

terms of direct distance from the masterplan entry to the stadium building entry. The internal circulation is evaluated through the paths based on the internal stadium grid, the vertical circulation is based on the vertical distances between slabs, and the bowl circulation is based on the gangway length, added to the distance from the centre of the gangway to the centre of each individual set.

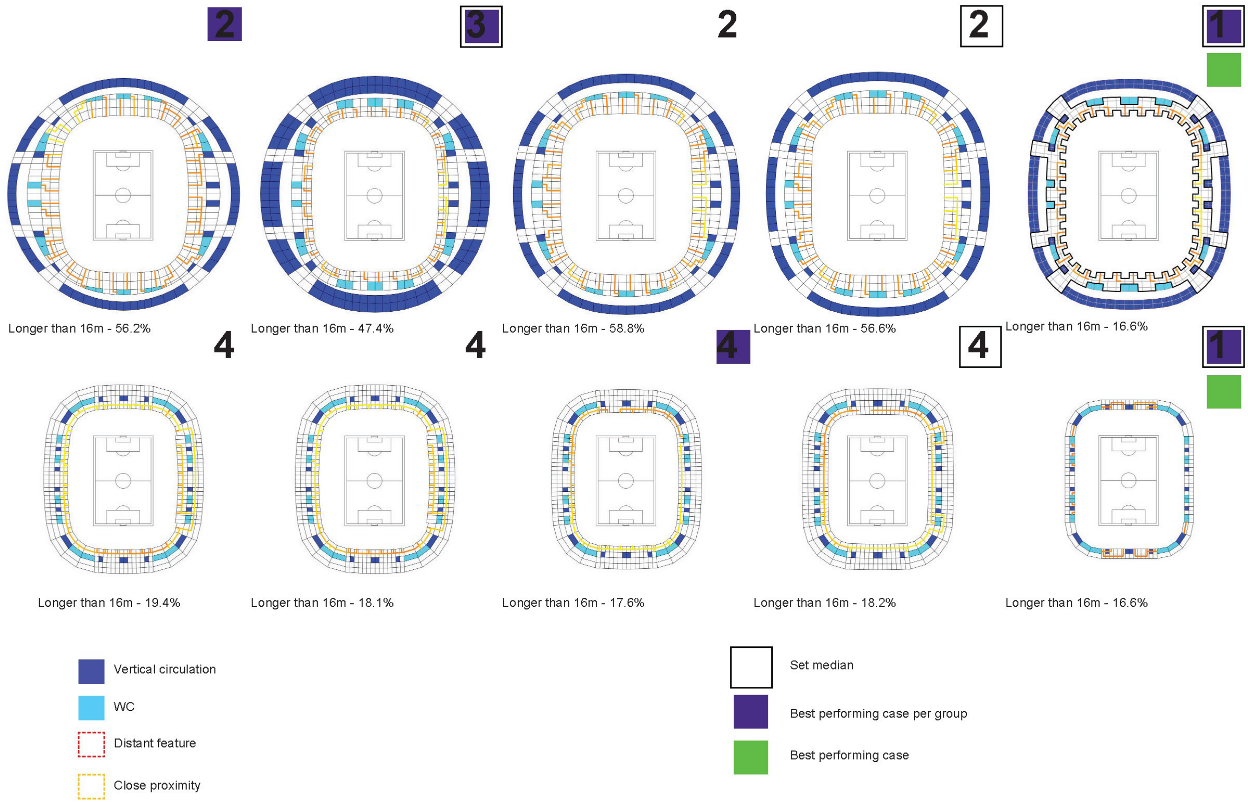



*Figure 4.3. Generation and analysis of internal circulation (bowl exit to WC) for parametric variations of case studies*

## 4.2 How parameters are coherently translated into a parametric model

### 4.2.1 Division of data sources

The sources for the spatial and structural information for the case studies are the freely available project descriptions on specialist architecture websites, magazines, books, and planning applications. In terms of the validity of the dataset, sourcing data from the public domain requires additional verification by manually cross-referencing different sources. The verification was completed through a visual inspection of the available plans and comparison with other available data such as photographs and virtual walkthroughs.

Another significant aspect of the process of parametrising the different case studies within the typological framework are the graphic standards for representation deployed by different designers. Through the process of gathering the plans and sections of the case studies, it was established that nearly all projects were drawn using a case study-specific graphic standard that differed not only in projects designed by different companies but also in projects designed by the same companies in different time periods (Ahmed et al., 2012; de las Heras et al., 2014; Marson and Musse, 2010; Nagy, 2017; Samet, 1994). At this point, the parametrisation became a vital tool, as it levelled all the information and allowed for a comparative study.

### 4.2.2 Parametrisation of case studies

As previously indicated, the closest methodology to this research is the work undertaken by Pan (2021; 2020) to optimise roof spans in indoor sports arenas. Pan (2021; 2020) takes a simplified approach to a holistic parametric model that works with the primary building elements such as the seating bowl and the roof, and does not take into account the modular systems deployed in the design of this type of public assembly building. This research takes a similar but significantly more detailed approach to the process of representing the case studies with the parametric model. All the features found in the typological framework are represented numerically. There are two types of

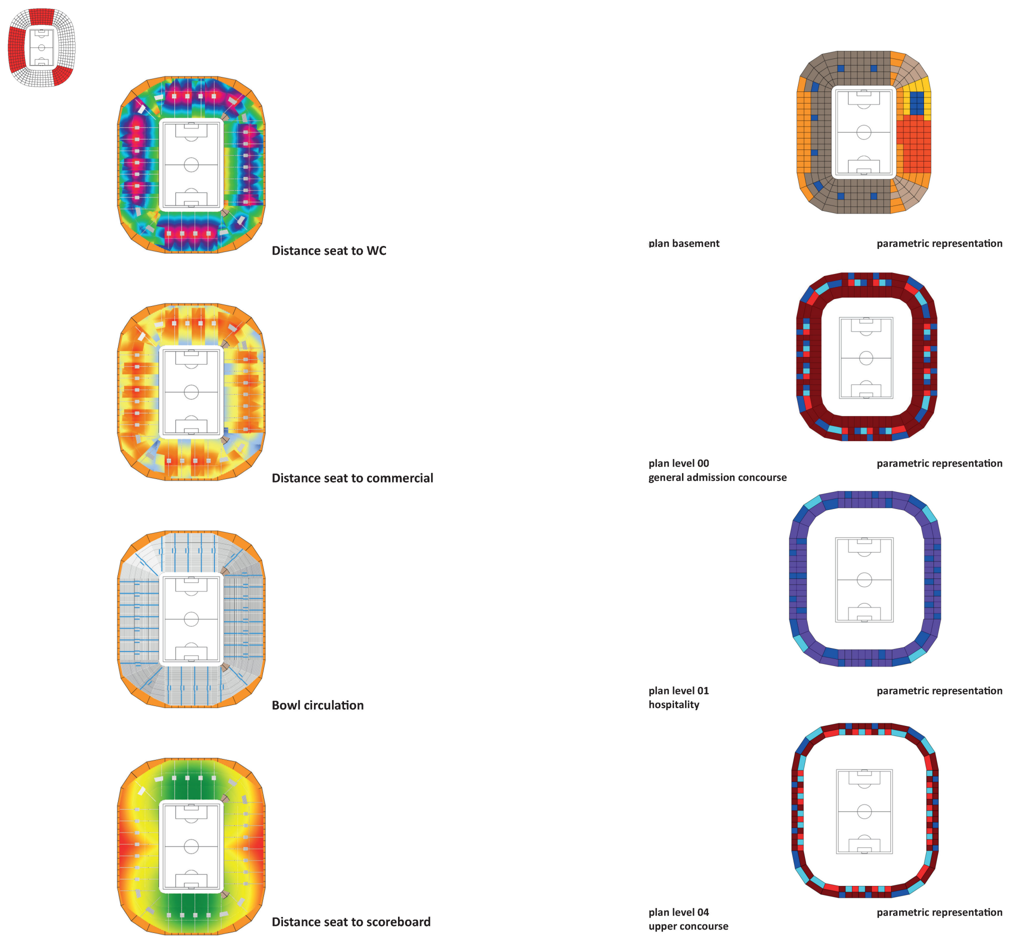



*Figure 4.4. Allianz Arena Munich, parametrisation of internal layout and quantification of various design features (Herzog & de Meuron, 2005)*

inputs – parametric values that indicate numbers and distances, and numerical values that represent geometric objects and distributions. The inputs that represent spatial values are input in metres at 1:1 scale. On the other hand, the objects and distributions select predetermined elements in the typological framework, such as building outlines and layout functional distributions. This novel approach allows for a detailed representation of a significant number of case studies.

### 4.2.3 Labelling data

The two major limitations in the machine learning analysis of the data produced are the performance evaluation and the legal constraints. Following the typological analysis, the performance targets were identified and recorded as optimisation targets within the machine learning model. There is a full set of benchmarks at the end of this chapter and each case study application has its own specific benchmark performance metrics that are indicated prior to the data analysis section. For the supervised workflows, the initial phase of the research focused on the manual labelling of the data, but once the model was advanced further, the labelling was done automatically within the parametric model. Once the dataset was large enough a supervised neural networks [NN] machine learning algorithm by the Accord Framework was trained to label. The legal constraints were identified from the literature review and consequently inscribed as limits within the parametric model, as described later in this chapter. Those constraints are fixed, and the designs can only either comply or fail, so there was no direct requirement to train an NN algorithm to perform additional labelling.

### 4.2.4 Implementation of a legal framework within the parametric model

The legal design requirements form a major part of the stadium design process and are fully reflected within the parametric case study generation and analysis. These are based on the legal framework existing in the UK and the EU, with the *Green Guide* (Department for Culture, Media and Sport, 2008) and the UK Building Regulations ('Building Regulations and Approved Documents index', 2022) being the primary references. All the morphology, circulation, and layout functional provision requirements are incorporated in the parametric model as input constraints. The only element that is omitted is the time limitations in terms of fire escape (Building regulations 2010. Approved document B, Volume 2, Approved document B, Volume 2, 2020), and these are analysed as travel distances, as described in the *Metric Handbook* (Buxton, 2018). Additional constraints in terms of functional layout and spatial provision are extracted from the stadium design guides of various international sports organisations.

### 4.2.5 Input parameters and variables

The hierarchy and grouping of the parameters are based on the way the parametric model is structured. The typological study in Chapter 02 identified a set of design drivers that are shared among centrally organised assembly buildings with an oculus. The typological study also identified a set of relationships among the design drivers. The critical perspective of modularity and the historic analysis of its evolution in stadium design enabled the design drivers to be grouped into four major scales of repetition in stadium design: 2D section, bay, sector, and stadium. This division of modular scales is the basis for the development of the parametric model.

The parametric model first generates the grandstand section in 2D for each bay type. Using the 2D section, the parametric model then generates the structural elements in bay scale. Then the parametric model arranges the bays into sectors and populates the programme for the internal layout. Then the sectors are assembled into a full stadium simulation model. Each scale is then analysed within its relevant analytical categories.

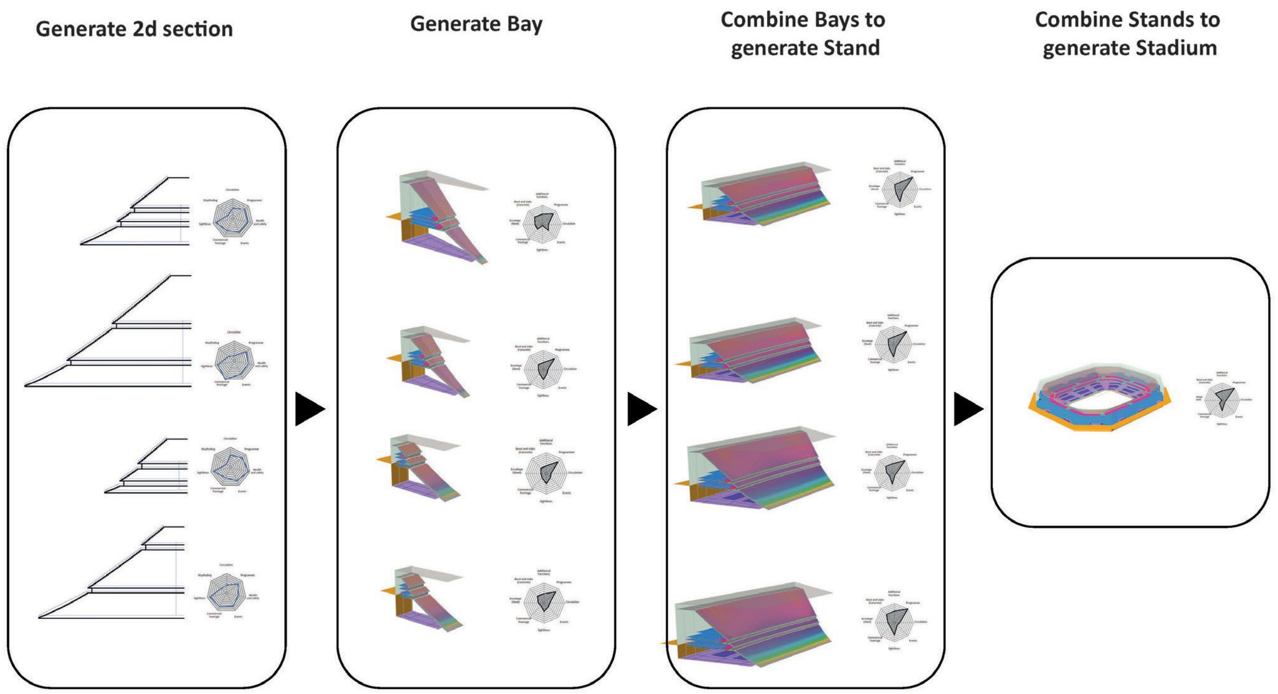



*Figure 4.5. Parametric model geometry generation pipeline based and modular scales and performance evaluation*

The parametric model input variables at each modular scale are grouped based on the stadium access zones defined by the *Green Guide* (Department for Culture, Media and Sport, 2018). The playing field and seating bowl form the innermost Zones 1 and 2, the internal concourses and rest of programmatic elements define Zone 3, the secured external Zone 4 control the spectator flow in the vicinity of the venue, while the unsecured Zone 5 allows the spectators to circumnavigate the whole masterplan. The latest edition of the guide adds another external zone, Ex, which defines the perimeter around the masterplan. The reason for this approach to grouping of the parameters is the functional relationship between those zones. They are designed to control spectator circulation and the features are interrelated. The input groups are made up of the specific elements that are included in the parametric model. The full set of input parameters and performance analytical categories metrics can be found at the end of this chapter. These elements were identified through a typology study, a historical study of the evolution of modularity in stadium design, and a literature review of existing legislation and design guides.

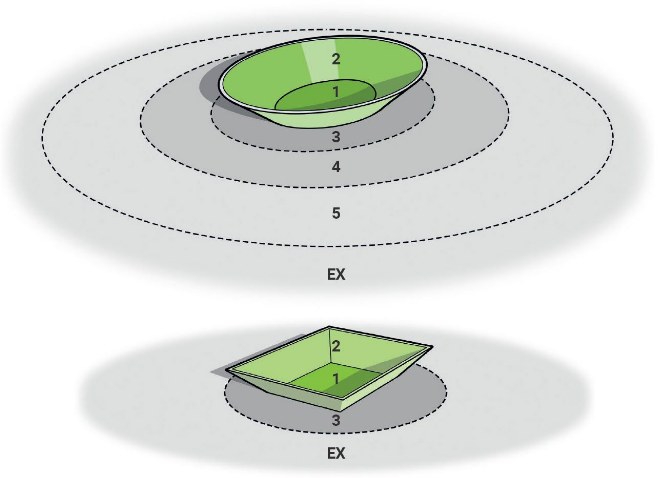



*Figure 4.6. Stadium access zones: Guide for Safety in Sports Grounds (Department for Cul-ture, Media and Sport, 2018)*

The specific parameters that control the generation of the design elements are defined in legislation in the form of building regulations, British and European standards, and specific sports federation requirements. The input numerical values are limited, with the ranges specified in BS standards and technical literature.

## 4.3 Measurements within the parametric model

### 4.3.1 Sightline quality

As described in the previous chapter, there are two primary ways of evaluating sightline quality in practice: through physical properties and through formulas based on physical properties (Hudson and Westlake, 2015). The basic quantifiable measurements are based on the theory developed by Rafailaki and Dritsas (2007). These are measured as straight line distances and angles between every seat and the closest point on the playing field from the relevant seat. The restricted views are identified based on field of view towards both ends of the closest edge of the playing field to the spectator. If a sightline is interrupted, the seat is classified as having a restricted view.

The research utilises 'C' value as primary evaluation tool. 'C' value calculation is based on the formula in the *Guide for Safety in Sports Grounds* (Department for Culture, Media and Sport, 2008). The calculations are per seat and produce full capacity point cloud simulations of the seating bowl. The performance evaluations are based on the number of seats. The calculations conducted for the main performances were identified through a typological analysis and consist of rectangular field sports, baseball, tennis, boxing, concerts, and athletics.

In terms of error margins, this study originates in a typological representation, and evaluates the shared properties between buildings. There is an inevitable loss of detail in the translation of the case studies, but the current model provides a robust system for the evaluation and optimisation of stadium designs that can inform and evaluate design choices throughout the entire design process prior to RIBA Stage 4 – Technical Design. This study focuses on the development of workflows: when taken in practice, the parametric model can be developed further to include all the specificities of a design project.

### 4.3.2 Circulation

All circulation is measured based on the stadium circulation paths and, in the case of the concourse, on the shortest path on a circulation grid using the Shortest Walk GH (Piacentino, G., 2010) component in Grasshopper. Agent-based crowd simulation was considered, but it is computationally prohibitive and could not be further tested. All distances from a seat are measured from the centre of the seat. Exterior distances are measured as straight lines. The results from the analysis are evaluated against relevant legal requirements and standards, design practice, and the performance criteria benchmarks derived from the case studies.

### 4.3.3 Layout

All areas are measured in square metres. The hierarchy is based on whether areas or views are analysed. The areas per seat analysis is based on the legal requirements for the provision of concourse area and WCs, and also extends to commercial offerings. The ratios of the space utilised by the contrasting functions are based on work by Herzog & de Meuron (Castro, 2020), as this design studio was the first to publish detailed data on specific projects.

Isovist in Grasshopper is utilised for the analysis of internal views. The analysis is based on analysing the 360-degree views from each structural grid cell in the concourse and informs the ability of the spectator to see destinations furthest away from their current position. Previously Standfest (2017) used this method of internal views analysis for residential designs.

## 4.4 Parametric model accuracy

A parametric model in this research is defined as a network of geometric and numeric relationships. The model is based on the modular approach to stadium design, whose historical development is described in detail in Chapter 03. The parametric model uses the approach of arranging bay modules around a central field of play. Using shape grammars, the parametric model generates a structural and organisational grid. This grid is the basis for the circulation and layout analysis. The rationale for this approach is the established design practice of using the structural grid as a reference for the development of internal floorplans. The functional allocation is also based on the structural grid, with each grid cell assigned a function based on the case study plan.

In the literature, two kinds of studies can be found that focus on stadium analysis through the use of case studies, such as Buro Happold's venue performance rating (Pottinger, 2021) and Fenwick Iribarren Architects' FI Factor (2018). Even though typologically different, Pan's (2020) study of indoor arenas also features case studies. Buro Happold's study (Pottinger, 2021) has seating bowl models that feature a modular approach, but the information presented is inconsistent, as some cases have bowl circulation and others do not. Fenwick Iribarren Architects' (2018) study features neither circulation nor modularity. Pan (2020) describes the different seating auditorium morphologies but does not include them in his actual simulation: he studies fixed bowl circulation, and his case studies only


*Figure 4.7. Buro Happold Venue Performance Rating (Pottinger, 2021) Note that only the two stadiums in Manchester have bowl circulation*

remotely refer to the actual designs. None of these studies refer to the internal or external circulation and layout of stadiums.

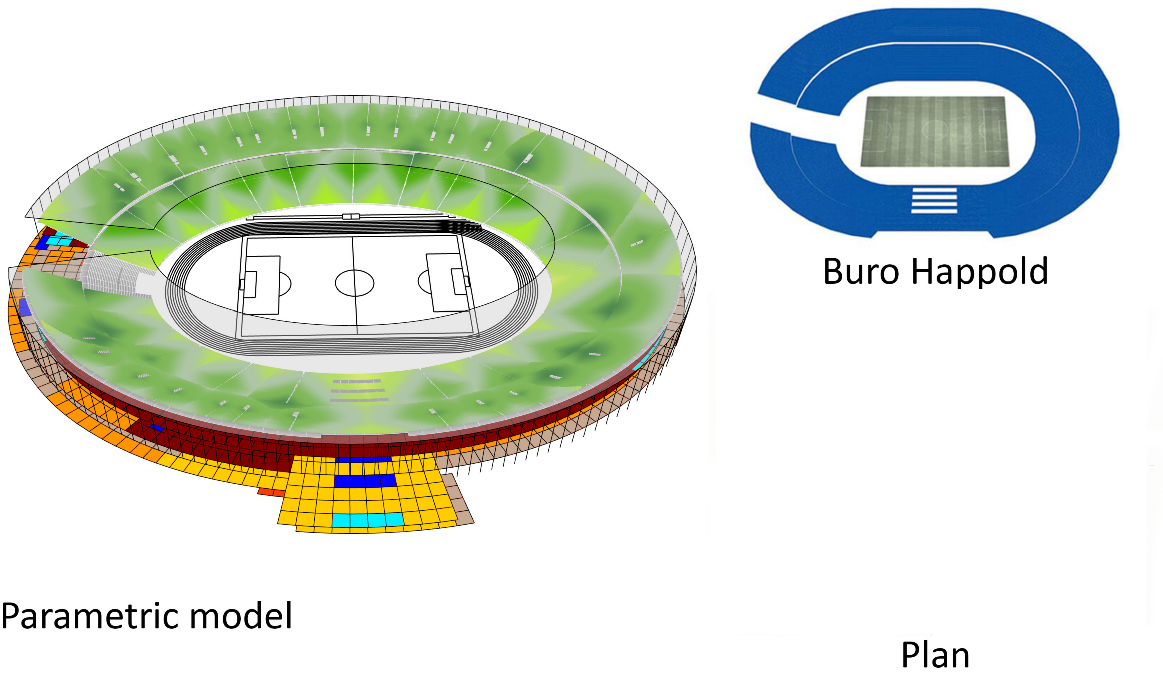



*Figure 4.8. Olympiastadion Berlin – simulation in parametric model, Buro Happold Venue Performance Rating (Pottinger, 2021), and original plan (gmp, 2000)*

In contrast to the existing studies, this research has significantly more detailed models that can benefit the design process until RIBA Stage 3 – Spatial Coordination. The modular approach enables the capturing of more detail than the other studies. The comparison across cases is also more accurate and rigorous, because all the data is structured and can be analysed in the same way.

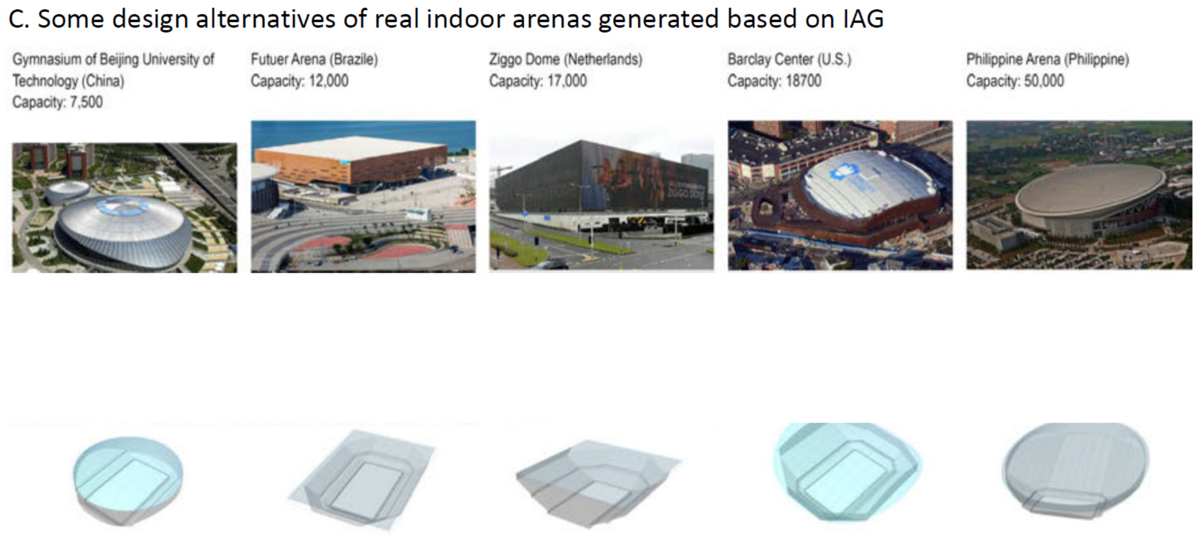



*Figure 4.9. Pan (2020) design alternatives based on case studies. Note that all of the cases have the same bowl morphology*

## 4.5 How this model works across different scales - modularity

### 4.5.1 2d Section scale

The 2D section scale defines the section of the seating stand, the number and location of tiers, the depth and height of the internal slabs, and the extent of enclosure through a roof and façade.

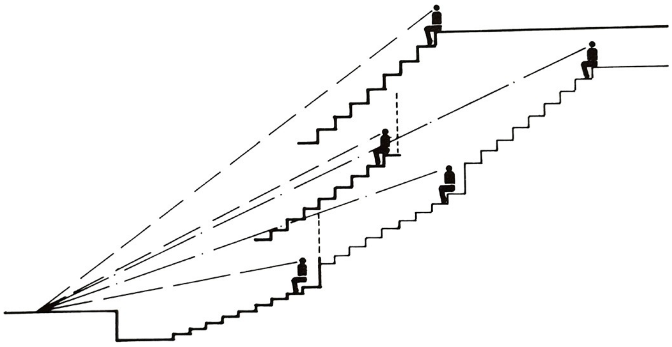


Figure 4.10. Stadium tier study by John (1981)

There is evidence of different approaches to the steepness of the tiers since antiquity and John (1981) has explored the economics of the implementation of different design solutions based on construction methodology throughout his published works. The primary objective is the provision of clear sightlines, with 'C' value calculations being the main approach to resolving these in literature and practice (Department for Culture, Media and Sport, 2018; Fédération Internationale de Football Association, 2011a; International Olympic Committee, 2005; John et al., 2013,1981; Union of European Football Associations, 2014). The rapid development of prefabrication techniques for precast concrete or hybrid steel elements (Culley and Pascoe, 2009) has brought advanced construction solutions that allow the implementation of customised designs based on computational analysis.

Figure 4.11. Lviv Arena, Ukraine by Albert Wimmer constructed with precast concrete elements (Consolis, 2010)

#### 4.5.1.1 Input parameters

The practice-led side of the research utilises the workflow described by John (2013b) based on the 'C' value formula to generate the stadium section via a custom Python script in Grasshopper, that was developed within this research. The script can be found in the annexe. The inputs are numerical values that define the location of the focal point and tier starting points, row depth, 'C' value, and number of rows per tier. The script works across multiple tier configurations with customisable inputs for every section. The output includes horizontal circulation such as landings and super risers and vertical sections for safety and access points. In terms of internal spaces, this scale defines the height and depth of the internal slabs and vertical access paths from the concourses to the stadium bowl. Further, this scale defines the roof coverage, as well as the amount of façade coverage.

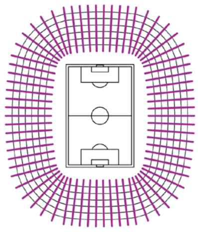
#### 4.5.1.2 Relationships and effect on modularity

The 2D section has been in continuous use as a representational and analytical tool for the design of public seating structures for centuries (Russell, 1938), because it captures information specific to the slope of the stand. This approach to representation has led to a standardisation of the elements represented in this scale: row beams, rakers, slabs, and envelope elements (Culley et al., 2015). The parametric model builds on this existing design practice and also enables the customisation of all the input parameters per seating tier. This is extremely important for stadiums, as a different ‘C’ value and row depth informs the types of seating zones it provides: general admission, hospitality, or VIP (Union of European Football Associations, 2014). The slope on the stand and the tier configuration also affects the usable space in the interior. The parametric model reflects this condition by excluding spaces that do not have sufficient head clearance.

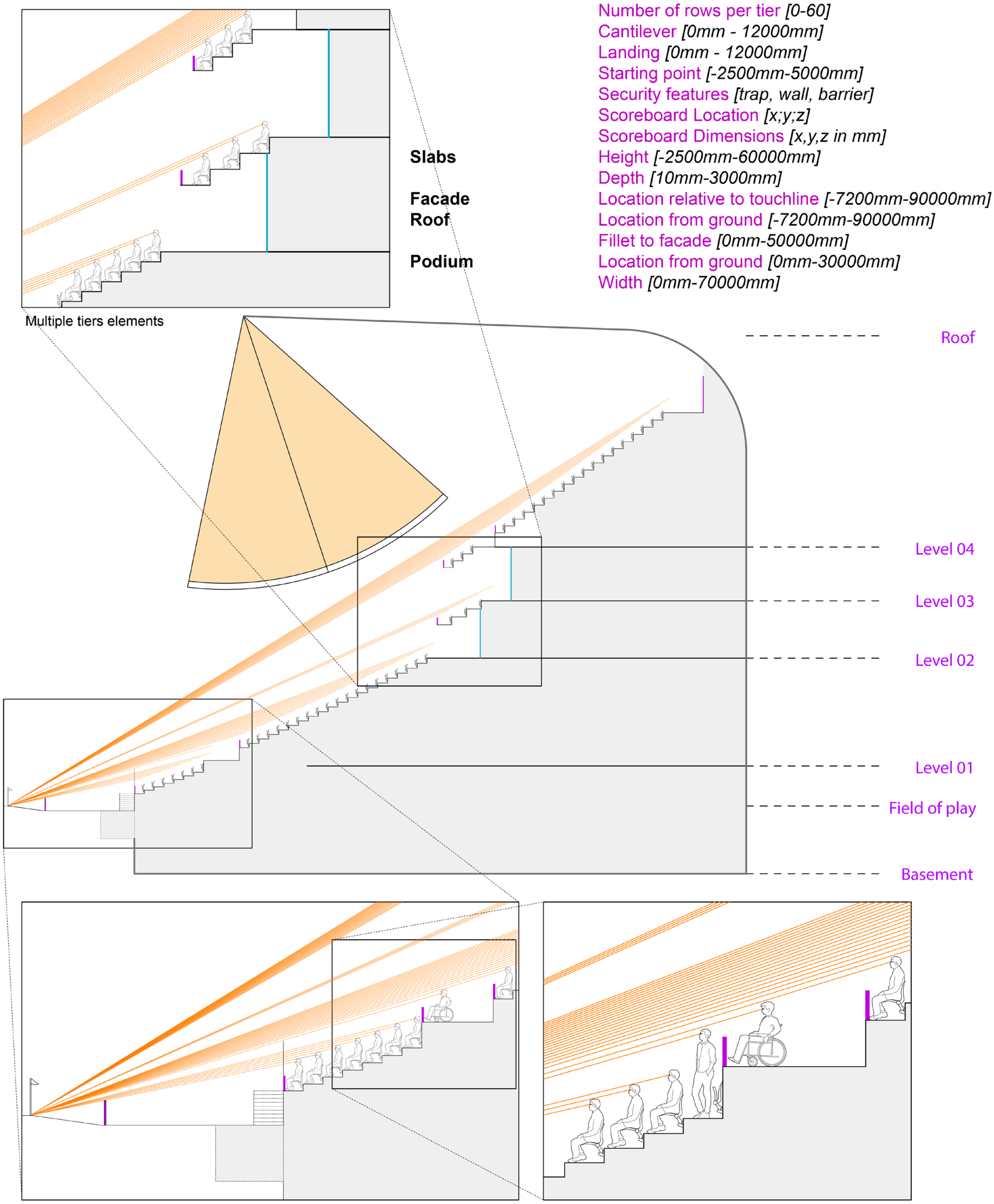
#### 4.5.1.3 Outputs

The data generated from this scale is exported as a set of lines, which is based on the type of structural elements and their relationship to the rest of the building: seating bowl, interior, and envelope. In terms of the optimisation of the module, this is done through the evaluation of the lengths of the different segments and the development of a design space aimed at improving sightlines, bringing the spectator as close as possible to the performance, and satisfying the legal constraints on the slope of the stands. Another primary optimisation objective is the relationship between the number of rows and the building’s footprint, as more tiers result in higher building cost but also result in lower building depth (John et al., 1981)

## 2d Section



| | |
|---|---|
| **Field of play** | Type *[natural - artificial - hybrid]* |
| | Height *[-500mm - 1500mm]* |
| **Advertising boards** | Location relative to touchline*[1500mm - 3500mm]* |
| | Building level *[-5 – 10]* |
| **Seats** | C-Value *[0 - ∞]* |
| | Depth *[400mm - 500mm]* |
| | Location on row *[back - mid -front]* |
| **Rows** | Depth *[700mm - 1200mm]* |
| | Superiser *[0-1]* |
| **Tiers** | Number *[0-10]* |
| | Number of rows per tier *[0-60]* |
| | Cantilever *[0mm - 12000mm]* |
| | Landing *[0mm - 12000mm]* |
| | Starting point *[-2500mm-5000mm]* |
| | Security features *[trap, wall, barrier]* |
| | Scoreboard Location *[x;y;z]* |
| | Scoreboard Dimensions *[x,y,z in mm]* |
| **Slabs** | Height *[-2500mm-60000mm]* |
| | Depth *[10mm-3000mm]* |
| **Facade** | Location relative to touchline *[-7200mm-90000mm]* |
| **Roof** | Location from ground *[-7200mm-90000mm]* |
| | Fillet to facade *[0mm-50000mm]* |
| **Podium** | Location from ground *[0mm-30000mm]* |
| | Width *[0mm-70000mm]* |




Parabolic section and safety features

Super risers and accessibility

*Figure 4.12. Parametric representation of 2d Section modular scale*

### 4.5.2 Bay scale

The structural bay scale was identified through the historic study of modularity in the early phases of the development of the practice-focused aspects of this research. It is a feature that is unique to modular stadium and arena design as it originates in the distribution of repeated structural units organised centrally around a playing field. This research uses this scale from a typological perspective by developing an ideal design that features all the characteristics of the final solution, with the exception of the final morphology. The reason for this approach is the distortion created by the overall shape of the stadium. While the characteristics of the units repeat, each unit is adapted to fit into the specific location around the playing field. This scale is influenced primarily by the type of construction deployed and can facilitate the selection of a structural approach.

#### *4.5.2.1 Input parameters*

The bay scale originates in the section generated by the 2D scale and adds depth to the design. The user inputs are based on the type and thickness of the seating bowl, slabs, and building envelope. This scale allows the construction type to be selected and enables the division of the volumes for the allocation of BIM families in platforms such as Revit. The scale also establishes the basis of the structural grid and identifies the relative position of the structural elements. In addition, this scale identifies the types of structural system used, and the volumes defined serve to coordinate between the architectural design and engineering solutions such as minimum surface topology optimisation.

#### *4.5.2.2 Relationships and effect on modularity*

This scale is key to modular stadium design and representation because it is the stage where all the structural systems are identified and the locations of all the building elements and volumes are developed. The parametric nature of the BIM families enables their adaptation for the final design once the module is used to populate the full design.

#### *4.5.2.3 Outputs*

The output of this scale is a set of placeholder volumes that are allocated to the specific slots on the stadium structural grid. The process is computationally efficient and allows for the subsequent superimposition of the internal circulation, functional layouts, and seating arrangements.

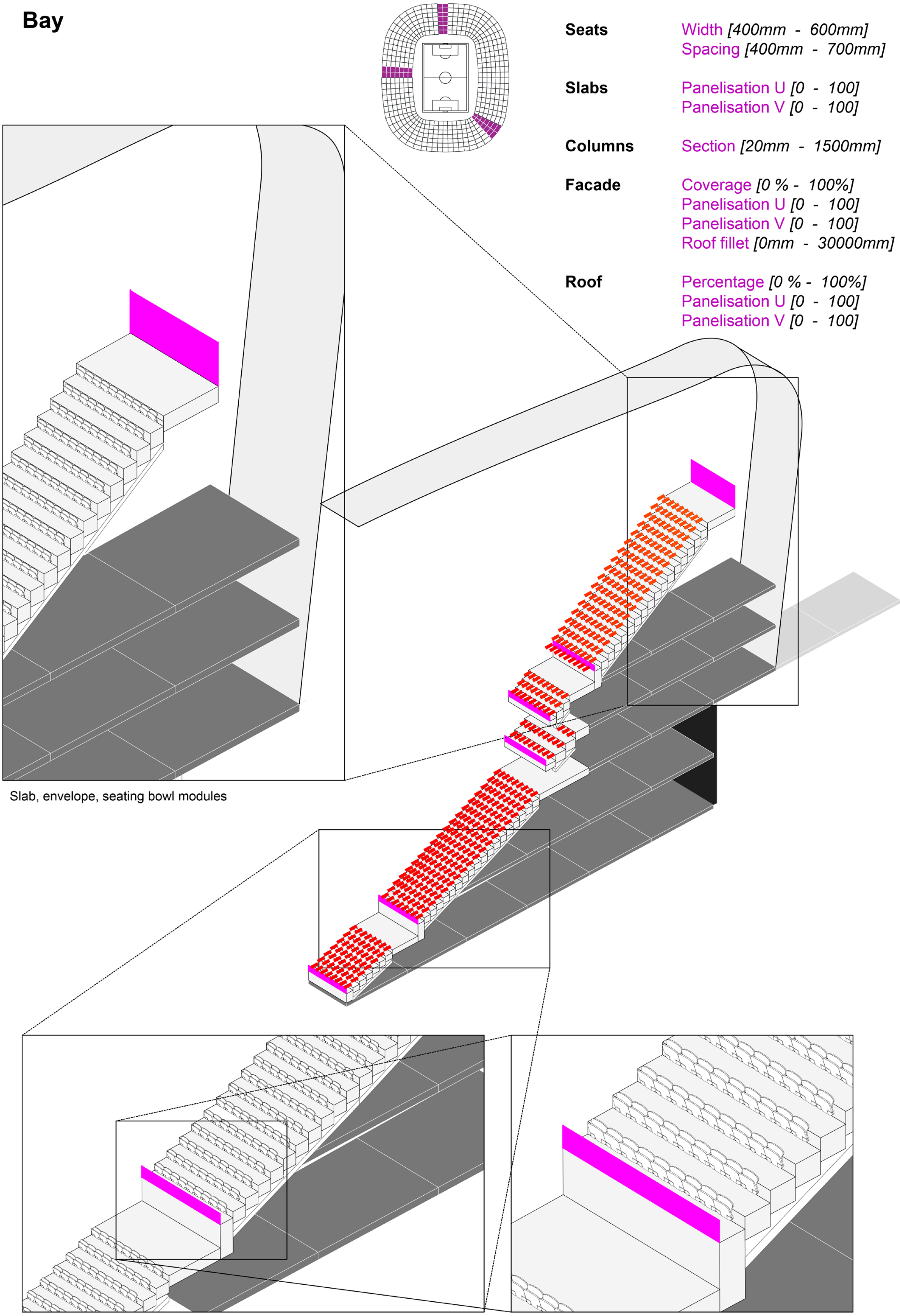



*Figure 4.14. Parametric representation of Bay modular scale*

### 4.5.3 Sector scale

The focus of this scale is the organisation and distribution of functions in the internal layout of the stadium. This scale covers both independent stands and stands that are part of a continuous seating bowl design. As a continuation of the previous two modular scales, this level of design development is based on the assembly of bay units derived from user input or a computer-generated pattern. The units' grid cells are split into four sub-cells each and functions, based on the findings from the typological study, are assigned to each sub-cell. The concourse cells are then joined together and the centre of each cell is used as a reference for the development of a circulation grid within each concourse. The circulation grid is developed for each level and the vertical circulation is based on the locations of the sub-cells that have been assigned to it. The limitations in the calculation of the travel distances can be found in the measurement of the vertical distances, as the script calculates floor-to-floor distances rather than the full circulation distance on the stairs. The reason for this choice is the proportional relationship between the two measurements: greater floor-to-floor distances result in more steps, which in turn increases the travel distance. The isovist floor plan analysis is based on the outline of the concourse and each centre of sub-cell is used to generate the isovist analysis rays.

#### *4.5.3.1 Input parameters*

The primary input value for this scale is the 3D bay type as a number for each lateral division of the stand. This allocation results in a list of numerical values equal to the number of bays resulting from the structural grid. The functions are also input as numerical values and cover the provision of the concourse and the commercial, sanitary, hospitality, storage, and players' spaces. The input is structured based on the bay number and the concentric functional grid row.

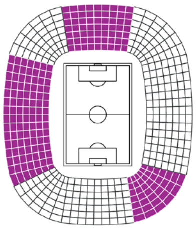
#### *4.5.3.2 Relationships and effect on modularity*

This scale quantifies the layout and circulation of modular stadium design. Each functional unit is considered as a replaceable modular unit and can be allocated to any cell in the functional grid. This approach was selected because the inputs work well within the parametric model and can serve as a basis for the optimisation workflows. As they originate in the typological analysis that identified the primary stadium design drivers, these functional types can also be used for comparative analysis and benchmarking.

### *4.5.3.3 Outputs*

This scale generates performance data covering both layout and circulation. In terms of layout, the primary elements taken further into the machine learning analysis workflows are the areas, frontage, and locations of the different functional types. This data enables the identification of distribution patterns, the optimisation of shop frontage, and the analysis of legal compliance in terms of the provision of sanitary spaces and their location with reference to circulation paths. The circulation representation offers a high level of detail in the circulation analysis in terms of the distances from each individual seat to internal functions, exits, and masterplan entrance points. Later, the script also evaluates the travel distances between functional and safety locations. Finally, the output of the isovist analysis has a direct relationship to the wayfinding design, as the output of this analysis is a set of ray lengths which describe the ability of a spectator to see further into the building. This analysis is based on ray lengths and densities and gives information about potential risk in terms of egress and overcrowding of stadium circulation zones.

## Sector



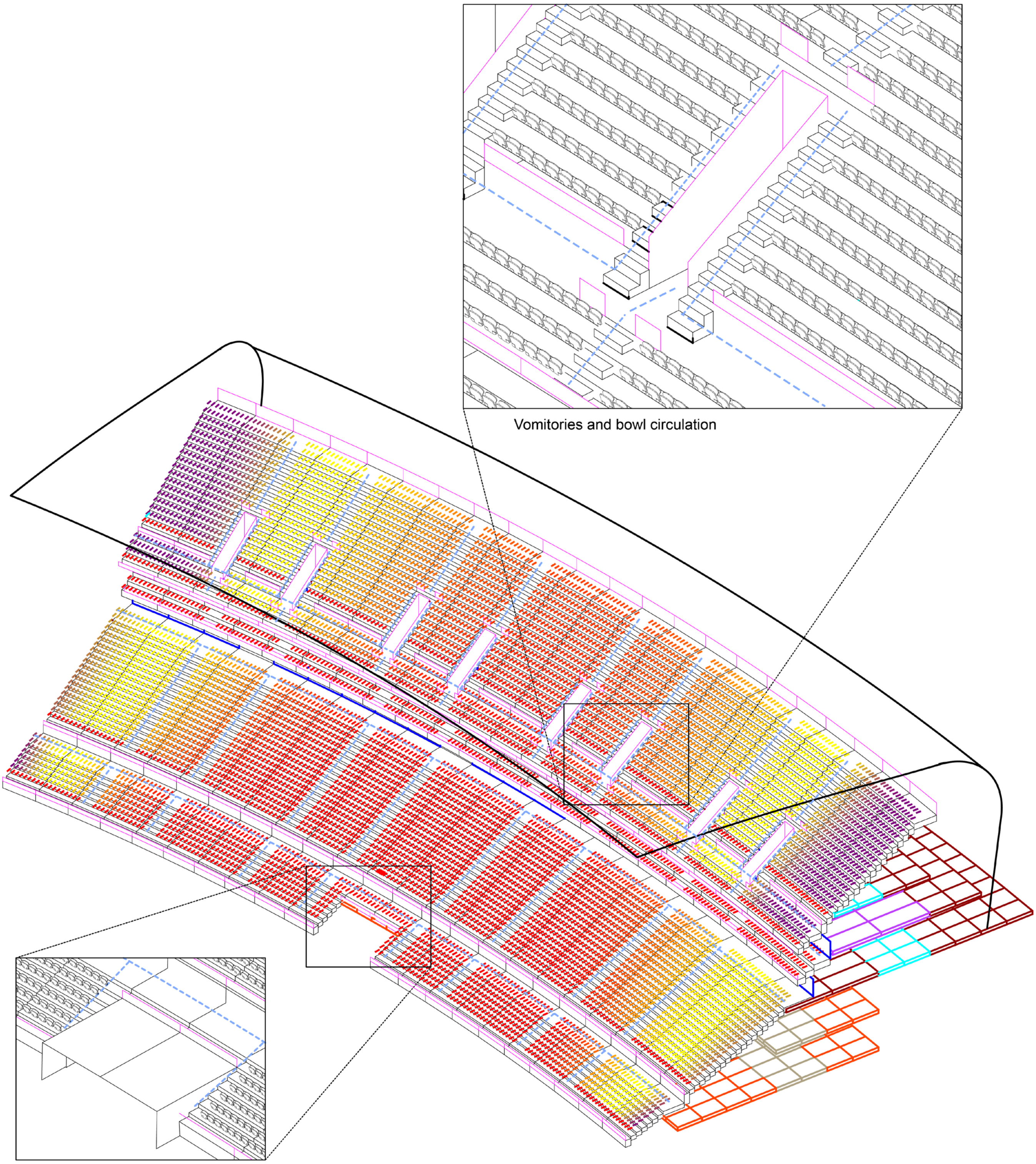



*Figure 4.15. Parametric representation of bowl elements included in the Sector modular scale*

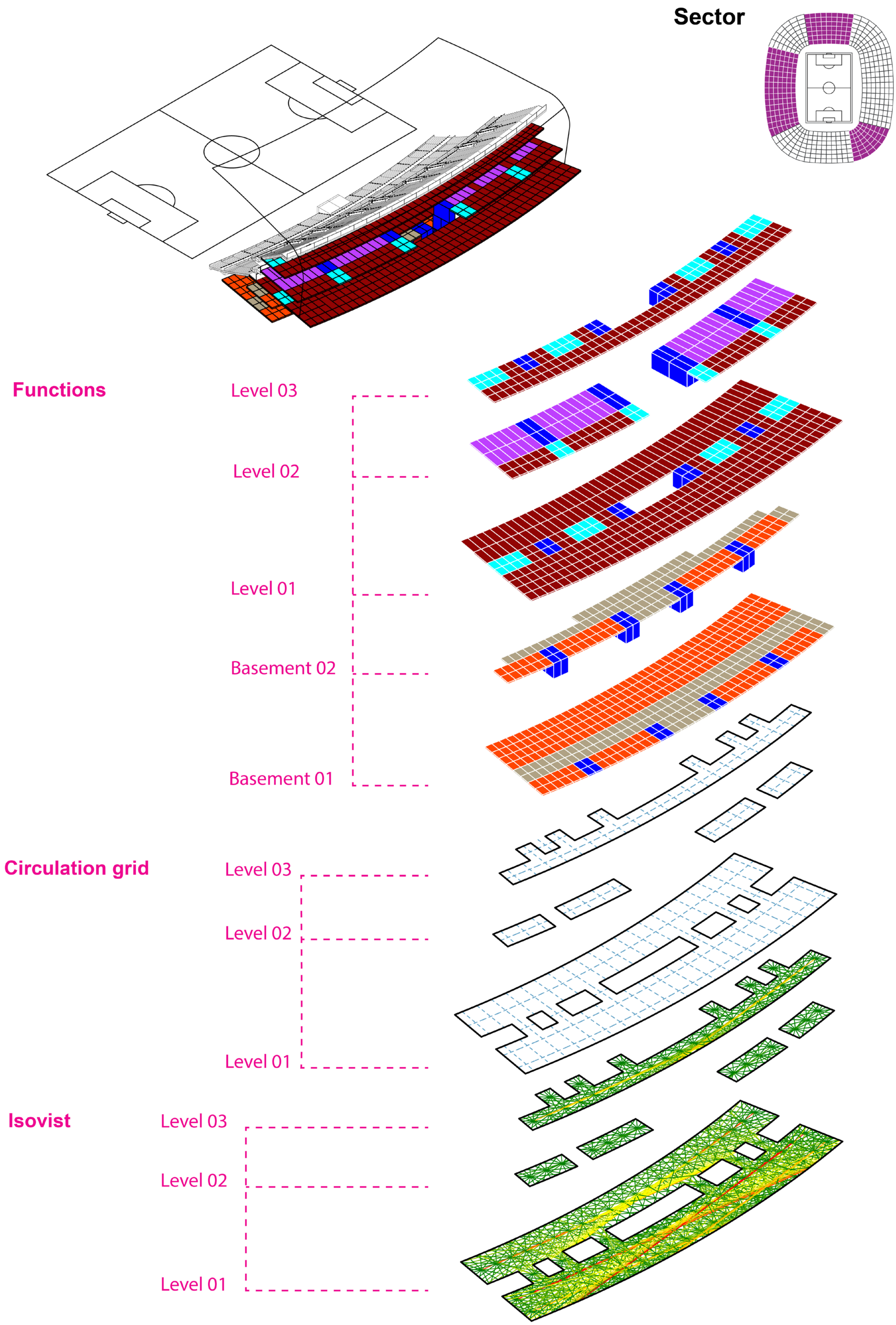



*Figure 4.16. Parametric representation of internal layout and circulation elements included in the Sector modular scale*

### 4.5.4 Stadium scale

Along with the 2D section scale, the stadium scale is one of the most widely used formats to represent stadium design. As mentioned in the legislative requirements for stadium design, one of the primary aspects of the design is the creation of a sequence of concentric zones that define the external and internal planning of this type of sports facility. The stadium scale corresponds fully to this comprehensive representation of the design, covering all the stadium stands and the external approaches to the building. This is the scale that captures the overall morphology of the building. The parametric model assembles the stands into a full building model and defines the external envelope and masterplan access points.

#### *4.5.4.1 Input parameters*

The parameters that control this scale are based on the type of curves that define the seating bowl outline, the building outline, and the masterplan outline. In combination, those three curves define the structural grid and the overall morphology. The curve types are derived from the typological analysis of stadium forms and follow the basic stadium morphology. The model also accommodates asymmetric designs, in which one or more stands are larger than the rest. Another important input is the location of access points, which are related to the existing urban infrastructure.

#### *4.5.4.2 Relationships and effect on modularity*

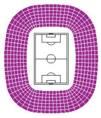
This scale focuses on a more conceptual reading of modularity, aimed at exploring the relationship between different buildings in an urban context. The case study in Chapter 03 of two stadiums in Kansas City designed for different sports sharing a common parking space is a great example of this type of critical reading of the design.

#### *4.5.4.3 Outputs*

The output of this scale is the comprehensive representation of a design within the constraints of the parametric model. This scale informs the masterplanning and overall morphology of the designs.

| | |
|---|---|
| **Masterplan entries** | location relative to centre of playing field |
| | Level *[0 -∞]* |
| **Orientation** | Relative to North *[-22° - 22°]* |

**Stadium**



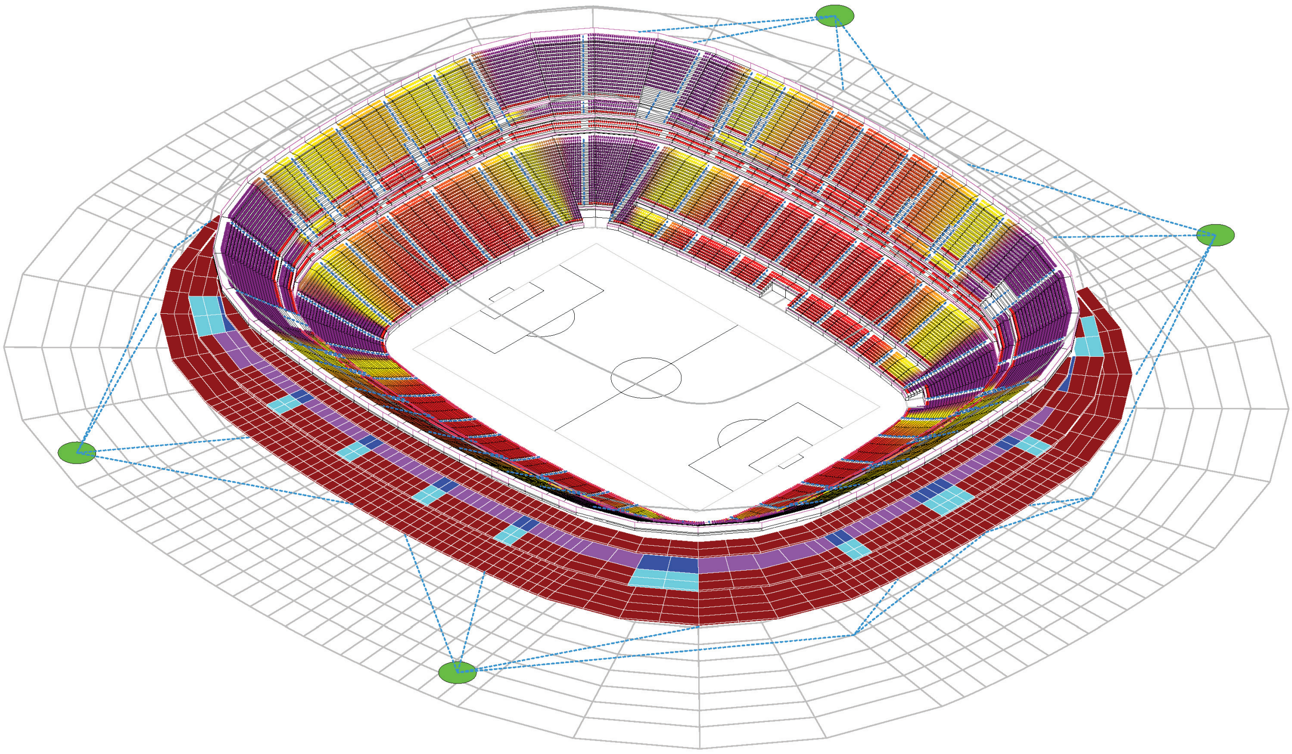


*Figure 4.17. Parametric representation of Stadium modular scale*

## 4.6 Scale in 3D analysis workflows

The construction of the parametric model for the encoding of the spatial data of a stadium is based on the relationships emerging within and across the design scales, which Carpo (2011) defines as 'traditional.' Even if not fully described in the technical literature, the 2D section, bay, sector, and stadium scales have been a set of semi-independent design domains since the construction of ancient Roman theatres and amphitheatres, as illustrated in Chapter 03. Each of these scales explores design elements that have specific spatial properties and requirements. One of the essential contributions of this research is the representation of these sets of scale-related design features and the relationships between the individual scales within a holistic parametric model. Hudson (2007) also proposes a parametric stadium representation but he stops short of bringing the characteristics of each scalar design domain into the parametric model and represents the generic stadium as a combination of elements rather than design fields. The approach proposed in this study allows for a comparison across case studies at the input level of the parametric model, unlike Hudson's (2007) approach to individual project-specific building zones.

Another useful aspect of Carpo's (2011) definition of the traditional scale is the two-dimensionality of the design scales. Apart from the bay scale, the other three scales are essentially parametrically represented in flat construction planes – the same way of structuring stadium design knowledge and ideas as in the pre-digital period. In addition, the bay scale is an extrusion of the sectional scale and the 3D representation is based on 2D information with depth, which is also inexpensive computationally. Defining the scales in this way allows the numerical input and detailed control of the parametric model, and the 3D representation is achieved through the relationships between the scales, rather than the scales themselves. In reference to BIM modelling (Eastman et al., 2018; Lai, 2021), the 3D model enables the analysis of sightlines, circulation, and layout organisation performance criteria, which result in the construction of additional analytical dimensions.

### 4.6.1 Increasing complexity as result of scale and linearity of design process

The methodological approach of this research to the overall stadium design process offers a hybridisation of the design process of fragmentation identified by Jones (1992) and Hudson (2008), with the modularity scales identified in the historical review in Chapter 03. The primary difference from the traditional design process lies in the translation of the thematic and zonal design dominant in current practice (Department for Culture, Media and Sport, 2008) and a focus instead on resolving the design scales semi-independently. The resulting design complexity is based on the same process of fragmentation and detailing of different building elements, but the design features are simulated as sets of spatial relationships within a holistic typological parametric model and then optimised with machine learning algorithms. The overall aim of the process is to optimise the design performance within a simplified model and increase the level of detail at later stages in order to supplement the overall project delivery.

### 4.6.2 Relationship between modular scales and legislation

The legislation in the United Kingdom related to stadium design is organised in two main ways, by function (Department for Culture, Media and Sport, 2008) and by building features ('Building Regulations and Approved Documents index', 2022). This duality of interrelated legal constraints is commonly accepted in practice and rarely questioned. In contrast to the current state of legislation, this study reconstructs the accumulated knowledge of stadium design in a form that is closer to a parametrisation of the rules, regulations, and standards that can be taken further for machine learning analysis. As such, there is a full overlap between the elements of the existing regulation, but these are organised in such a way that they can be represented in a parametric model, and the inputs and outputs of this model can be compiled into datasets aimed at training the analysis, optimisation, and generation of machine learning algorithms. The parametric inputs section later in this chapter describes in full the definition of the parameters and their limits, based on legislative requirements. Examples of the utilisation of pre-trained machine learning algorithms used for testing compliance with legal requirements can be found in Chapter 05.

## 4.7 How this model can create different stadium types – typology

As described in Chapter 02, the typological study aimed at identifying the design drivers for modular stadiums served as a framework for the development of a parametric model. The design characteristics and rules that emerged from this study enabled the construction of a detailed representation within the shared modular characteristics that span the most common stadium types with rectangular or athletics playing field. Those relationships also allowed for the expansion of the model to cover hybrid designs that carry the characteristics of more than one primary type. The focus on modularity also allows the assembly of whole sections of stadium designs that do not use the same organisational pattern. This enables the analysis not only of holistically designed stadiums such as the Allianz Arena in Munich, but also of significantly more complex designs that have developed over lengthy periods of time, such as British cricket grounds or football stadiums such as Chelsea F.C.'s at Stamford Bridge in London. The focus on the multi-objective optimisation of stadiums based on sightlines, circulation, and layout limited the parametric model towards the design drivers that affect those performance criteria – morphology, layout, and circulation.

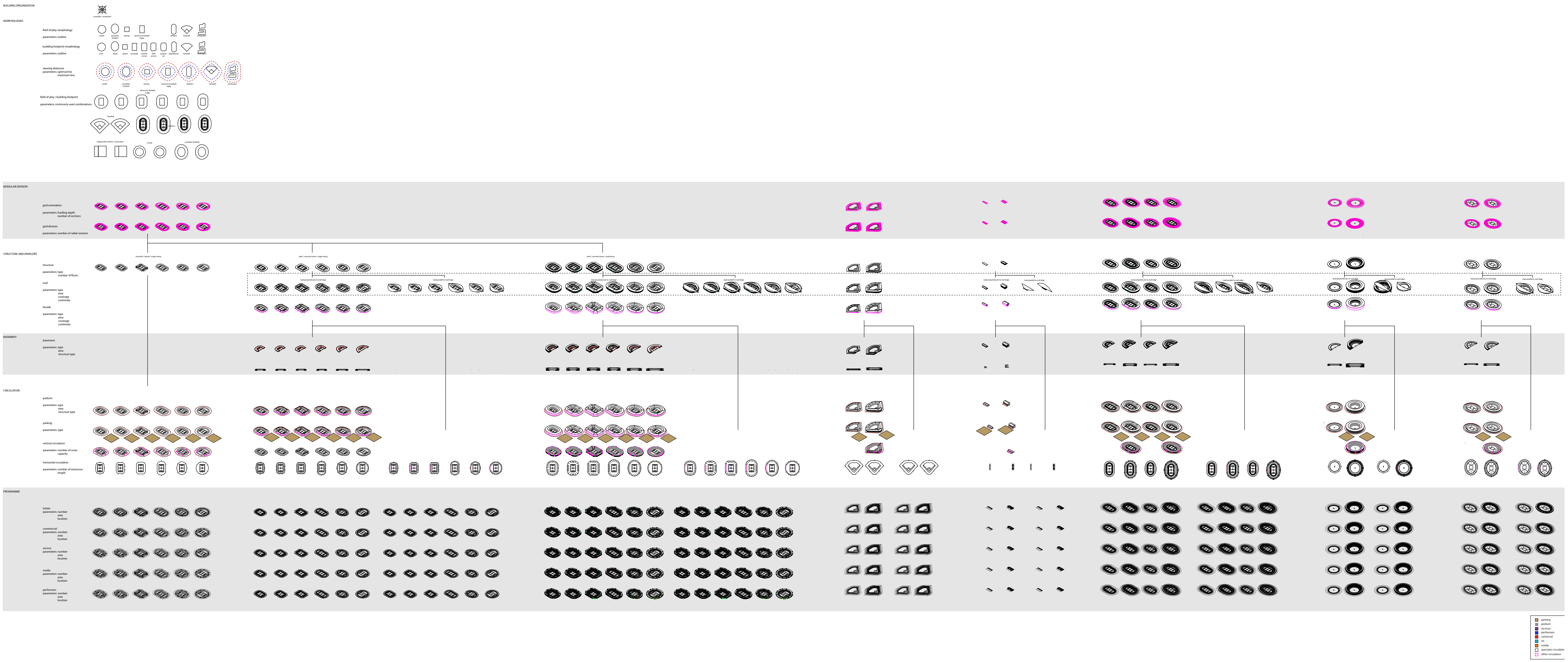


*Figure 4.18. Parametric model primary morphological and organisational types (high resolution image)*

### 4.7.1 Morphology

#### *4.7.1.1 Stadium bowl section*

The reason for selecting the 2D section as a modular scale for optimisation is the significant impact it has on the overall design (John et al., 1981). As evident from the historic review of the evolution of stadium design drivers, the multiple-tier configurations of the stadium bowl are a feature associated with the modern stadium. The reason for the historical dominance of single-tier types can be found in the construction technology challenges associated with cantilevering stands with varying live loads (Culley and Pascoe, 2009). Nevertheless, the impact of multiple tiers on sightline quality and the overall spectator experience is well documented in the existing literature (John et al., 2013). The parametric model is limited to up to four-tier configurations, as the typological study did not find a substantial number of precedents with more than four tiers. Another important characteristic in developing a range of types of stadium bowl configuration is the difference in row width provision for the various levels of hospitality provision. The parametric model allows an extensive range of options in terms of the bowl configurations for diverse types of spectator experience.

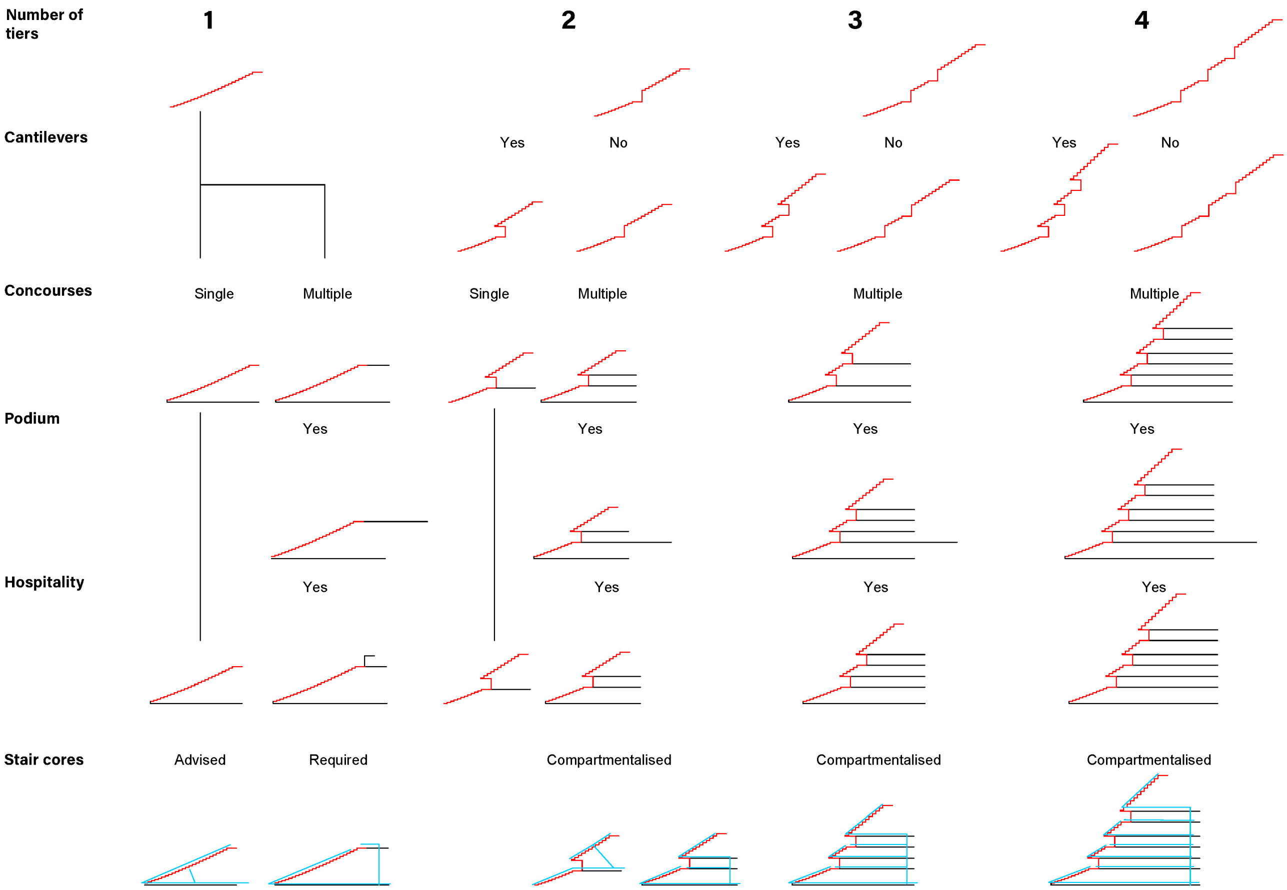


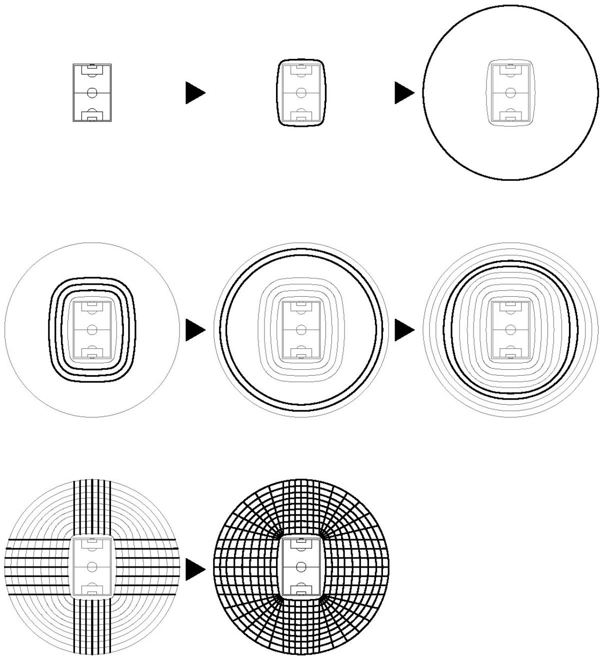

*Figure 4.19. Types of 2D sections included in parametric model based on provision of seating bowl features*

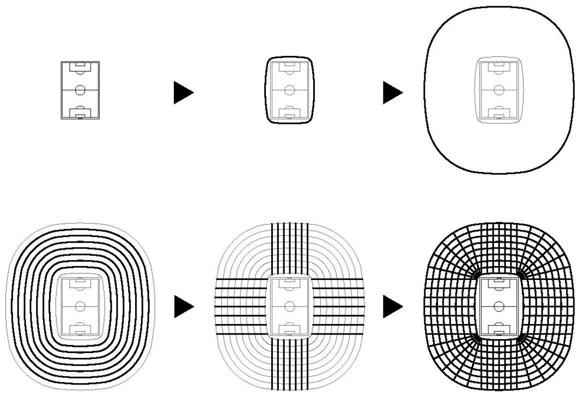
### 4.7.1.2 Shape grammars

As described Chapters 02 and 03, shape grammars play a foundational role in the development of the parametric model. The starting point for this set of relationships is the shape and size of the playing field – the model is optimised for use as a rectangular playing field sports, baseball, Australian football, cricket, athletics, and concert mode. Once the playing field is identified, the model can cover all the major building morphologies identified in the typological study – circle, hippodrome, independent stands, elliptic, tangent arc, various types of corners, and rectangular. Further on, the shape grammars enable the creation of hybrid designs with blends of different morphologies and the superimposition of one type on another. In terms of maximum viewing distance, the model is flexible and trims the outside of the seating bowl based on user input.

### 4.7.1.3 Modular assembly

The modular assembly of the structural bay units is key to the ability of the parametric model to represent a large section of existing stadium designs. The independent development of the bay units enables the assembly of configurations that are limited only by the number of bay types and the number of structural grid bays. There is no limit to the options of configuration, and the distribution patterns can be applied to the stand and stadium scales.



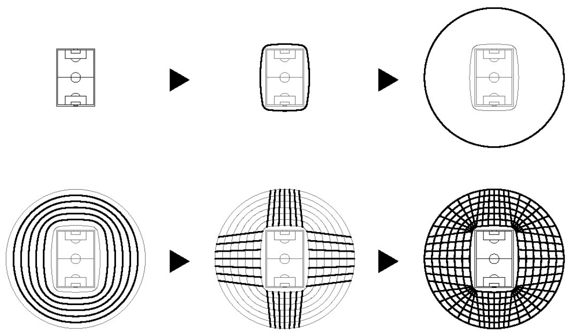




*Figure 4.20. Structural grid shape grammars*

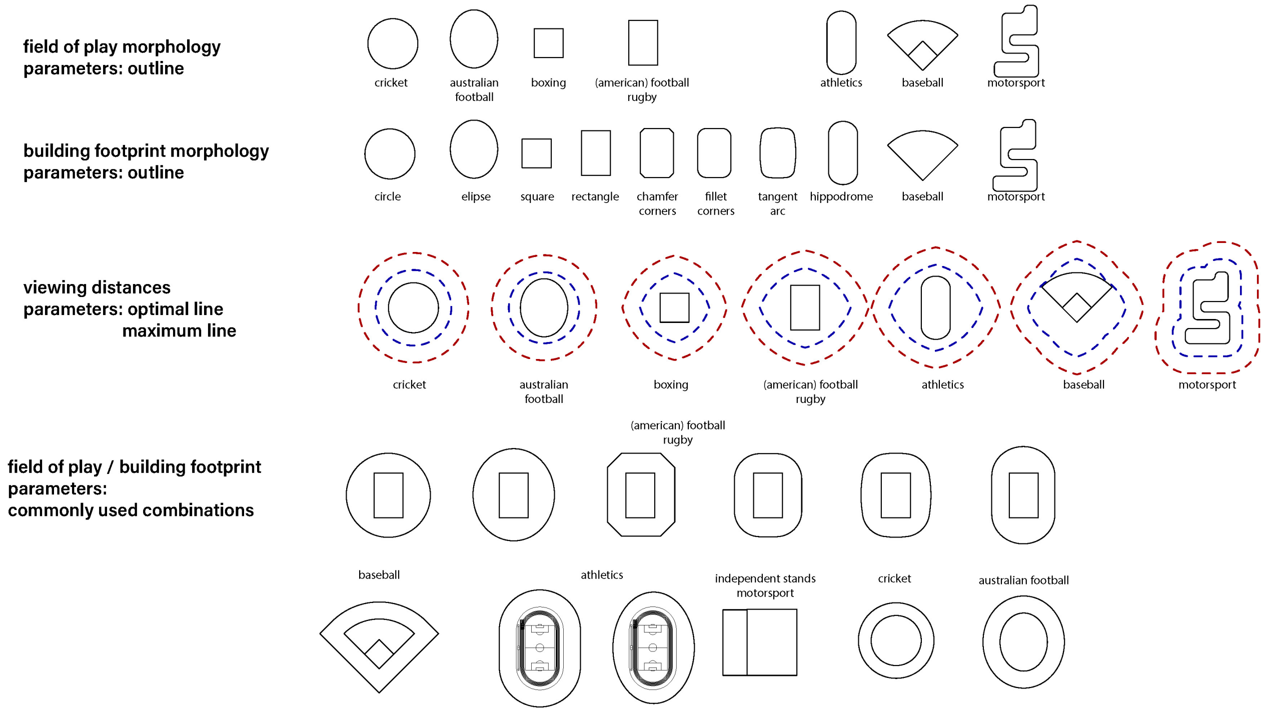



*Figure 4.21. Morphologies included in the parametric model*

#### 4.7.1.4 Envelope

The stadium envelope has less critical importance than the envelope in other building types, but the parametric model still attempts to capture some of its characteristics. The roof coverage representation is based on the structural typologies identified for the design of the stadiums for the FIFA World Cup in South Korea and Japan, where the load is transferred along the roof edge or across it (Shin et al., 2008). In terms of the façade, the typologies are based on whether there is one present and, if so, the area covered.

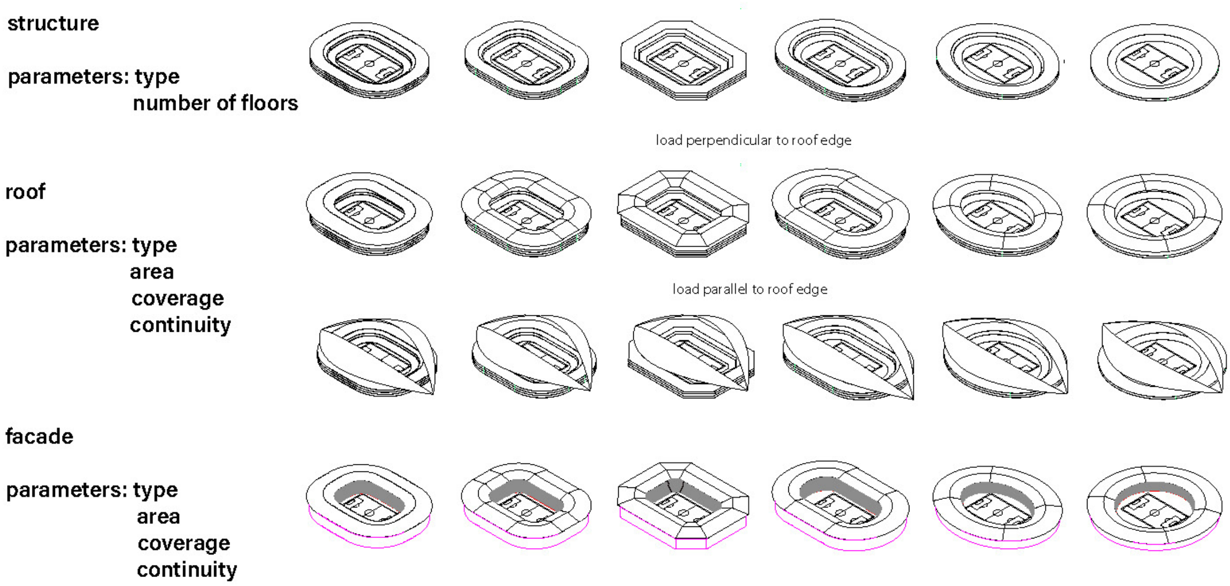



*Figure 4.22. Parametric model envelope elements*

## 4.7.2 Layout

The programmatic distribution within internal layout in the parametric model is captured based on the characteristics identified in the typological study in Chapter 02, as is the relationship of the concourse to the other building functions. The basic types investigated are as follows: the allocation of programmatic elements conjoined with the seating bowl; programmatic units completely surrounded by the concourse; programmatic elements aligned with the external envelope, and all the hybrid solutions. As previously described, the spatial planning is based on assigning a function to sub-grid cells, which produces a comprehensive analysis of all possible solutions. Further on, this approach allows for the machine learning algorithms to explore new solutions through the identification of new distribution patterns based on project-specific benchmarking.

## 4.7.3 Circulation

The parametric model maps the horizontal and vertical circulation of the seating bowl, the internal layout, and masterplanning. The model also includes exterior elements such as the podium and parking. As such there are infinite number of possible types explored the optimisation

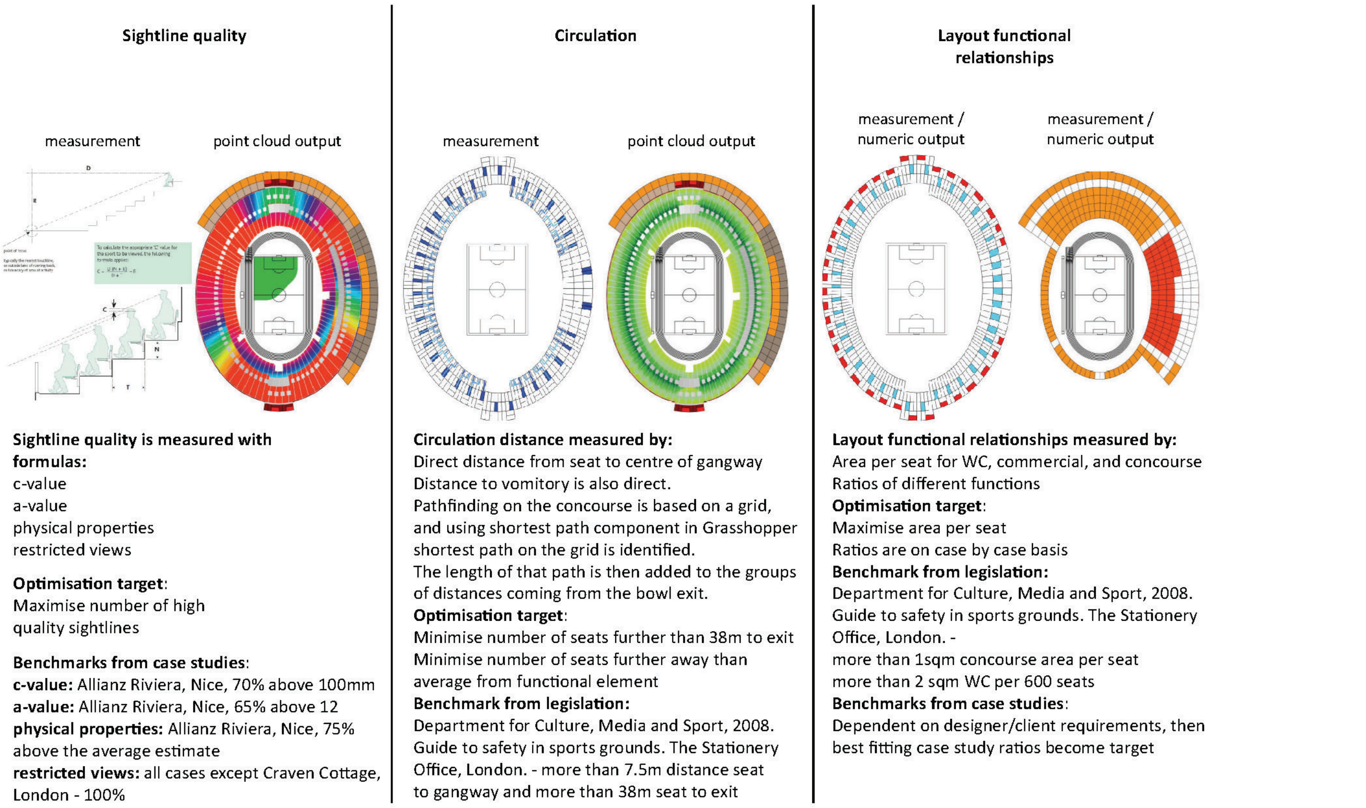



*Figure 4.23. Example of measurement approach to the parametric representation per optimisation targets*

algorithms. In terms of the stadium bowl, these are based on access – either via the vomitory or from above. The stadium bowl types are also defined by the presence of a super riser (*diazoma* - horizontal circulation within the stadium bowl) and the various safety and players' tunnels linking the interior with the playing field. The model also covers stadiums with or without horizontal or vertical internal circulation.

## 4.8 How this model is used to create different types of multi- use stadiums, using different optimisation parameters performance and benchmarking

### 4.8.1 Performance benchmarks

Performance benchmarking is an approach found in the work of all the previous researchers analysed, with the exception of Challiou (2019a, 2020). Initially this project evaluated more than 150 different performance benchmarks through simulation with a parametric model of a set of existing case studies and a set of parametric variations of the basic case study designs. These were later reduced to the performance benchmarks relevant to the basic stadium functionality – quality of sightlines, relationship between internal functions, and circulation distances. A similar approach has been deployed by Turrin (2014; 2016, 2012, 2011, 2011; 2018), Nourian (2018), and Pan (2021; 2020) in their studies. Each case study produces a set of performance values which are recorded and then compared across different case studies. This approach enables a set of maximum and minimum values to be established across the case studies and subsequently analysed.

### 4.8.2 Benchmark analysis methodology

Each of the performance benchmarks is based on the quantification of the performance of the case study in terms of sightlines, circulation, and layout. Each case study is represented through two datasets – the input values to the parametric model and the measurements output by the parametric model. The input values were selected after an extensive typological analysis and the identification of design drivers. These were also cross-referenced with the design drivers described in the literature. As such, these elements reflect the design characteristics shared by the case studies. On the other hand, the performances measured after the generation of the parametric representation of the individual cases studies are based entirely on the work of previous researchers and existing legal requirements.

The input elements are either distances, enumerations, or morphological types, while the output performance is also evaluated as the relationship proportions of areas of the programmatic elements and distribution maps of individual seat performance. The resulting dataset is entirely numeric, and this allows for the evaluation of the performance of the different machine learning algorithms and the selection of the most effective type of machine learning library for the specific analytical, optimisation, or generative task.

### 4.8.3 Rationalisation of choices

The research uses a multi-layered approach to achieving the research aims and objectives. Architecture, structural engineering, and computer science have well-established and extensively developed analysis methodologies and the utilisation of the methods selected for this research facilitates a link with the rest of the research in the field. Another major issue that arises from the complexity of the parametric model representation is the blurring of the focus of the study due to the multiple perspectives. A further level of complexity can be identified within the type of research itself – whether it is qualitative or quantitative. As discussed in the previous chapters of this thesis, stadiums originate in the quantitative definition of a space, and their entire design development has been strictly related to geometric and spatial relationships. Later, the function of these buildings is to host a performance or match, and there are two major design rules that emerge from this: i) a maximum distance for the performance to be visually appreciated and ii) the spectators have to be able to gather in order to see the performance. Those design conditions and the relevant legislative requirements establish the basis of a building type whose design principles are almost entirely dependent on quantified spatial relationships.

The data produced by the parametric model developed by this research comprehensively encompasses these analytical areas. In terms of methodology, the selected set of approaches are applicable across a number of other building types and can inform a new way of understanding buildings as a set of relationships within the domain of data.

## 4.9 Optimisation

### 4.9.1 Data input and analytical categories

The data input section of the parametric model is the driving force behind both the analysis and optimisation sections. Each case study is defined by a unique set of values which are recorded and compared. The inputs are based on the design drivers identified through the typological study and structured within each modular scale.

The areas of analysis link the data input and the optimisation. The overarching concept is that the designs can be evaluated and improved based on the elements that were identified in the typological study and translated to the parametric model. Each modular scale has a specific set of analytical categories which are grouped based on the location of the element analysed within the modular scales. These streams produce a new dataset of values which is used for performance benchmarking and optimisation. All the performance data is based on measurements from the parametric model. The full set of input data and performance analysis categories is available at the end of this chapter.

### 4.9.2 Implementation of data science in architecture

A quantitative understanding of space has been an inseparable part of the development of architecture, but it was only with the development of computational technology that architects began to fully understand the implications of performance-based design. Stadiums have been in the forefront of this process, but until now no work has been done to understand the limits and opportunities of this approach to design for this type of building. The primary challenge facing the research was to bring the work done by Hudson (2008) to machine learning. The basis of the methodology originates in the work of Mueller (2014), Turrin (2014), and Pan (2021), as described in Chapter 03, and focuses on developing design space and reducing the number of possible solutions with machine learning. This research expands their approaches to a new building type, brings several additional interconnected layers of analysis, and introduces modularity as the generative and driving force behind the creation of unique designs. The research expands the existing theory further by developing and testing evolutionary optimisation, supervised, semi-supervised, and unsupervised workflows for the reduction of design space and the selection of well performing solutions across multiple objectives.

### 4.9.3 Multi-scale modular design

Modularity at different scales has not been explored previously, either in academia or purposefully in professional practice. The research explores these in juxtaposition and in sequence rather than with the traditional understanding of the building as one coherent unit. This approach is aimed at improving the process of construction and fabrication, reducing construction time by increasing the number of prefabricated repeated elements. In addition, modularity is examined at a conceptual level – repeated organisational patterns that can facilitate construction and that can also be examined with machine learning.

### 4.9.4 Multi-objective optimisation

As described in Chapter 03, the problem of performance-based design improvement is covered extensively in the literature. The basic issue emerges when two or more often conflicting parts of the design are being improved simultaneously. This results in a compromise – a design that does not perform optimally in either direction but performs better as a whole.

Black box optimisation involves a condition where there is no linear relationship between the inputs and the outputs. The approach to the parametric model creates this type of condition for the practice side of the research. The use of machine learning is the best possible solution for this problem, as it does not rely on predefined relationships.

The focus of this phase of the research is digital representation and simulation – the construction of a model that captures all these characteristics and is capable of generating a large set of possible variations of design solutions. The research builds on previous studies, but for first

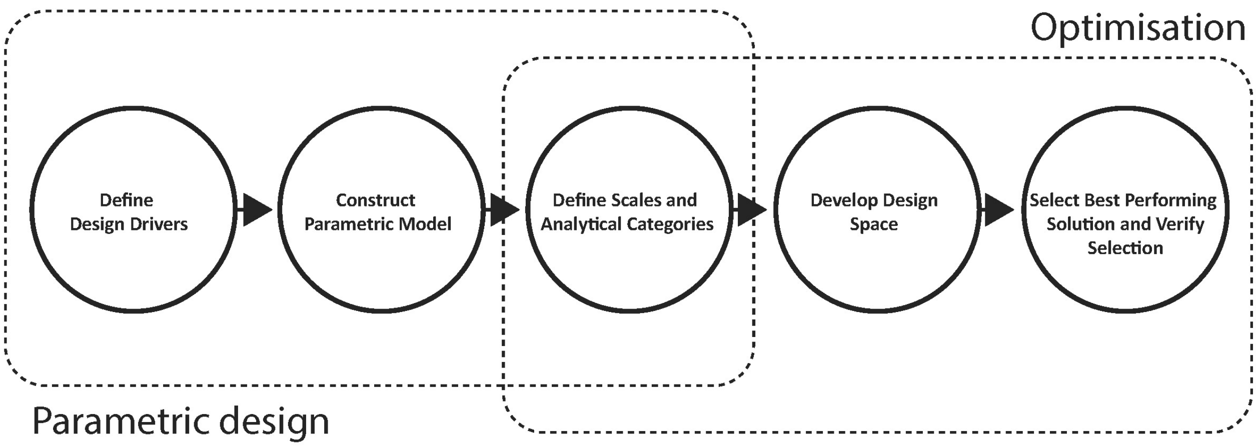



*Figure 4.25. Machine learning workflow structure*

time introduces point clouds as a means to evaluate stadium performance beyond sightline quality. The ability to produce many performance dimensions per seat makes possible, for the first time, the setting of performance benchmarks based not only on averages or extremes but also on densities and distributions.

The reduction in the number of possible design solutions in this research has been explored through three distinct machine learning pipelines. These workflows are aimed at automating conceptual studies in the early design phases, supplementing the process of identifying methods of construction throughout the design cycle, and testing for legal compliance. The fully automated workflow based on evolutionary optimisation with Octopus is deployed for cases with a narrow design space, where the set of variations is based on a limited number of input parameters. The more explorative semi-supervised pipeline based on a k-means unsupervised clustering algorithm and NN models is utilised for exploration  of previously unattainable solutions. The supervised pipelines with NN models are deployed for targeted optimisation based on specific aims while reducing a large design space and simultaneously testing for legal compliance. The optimisation

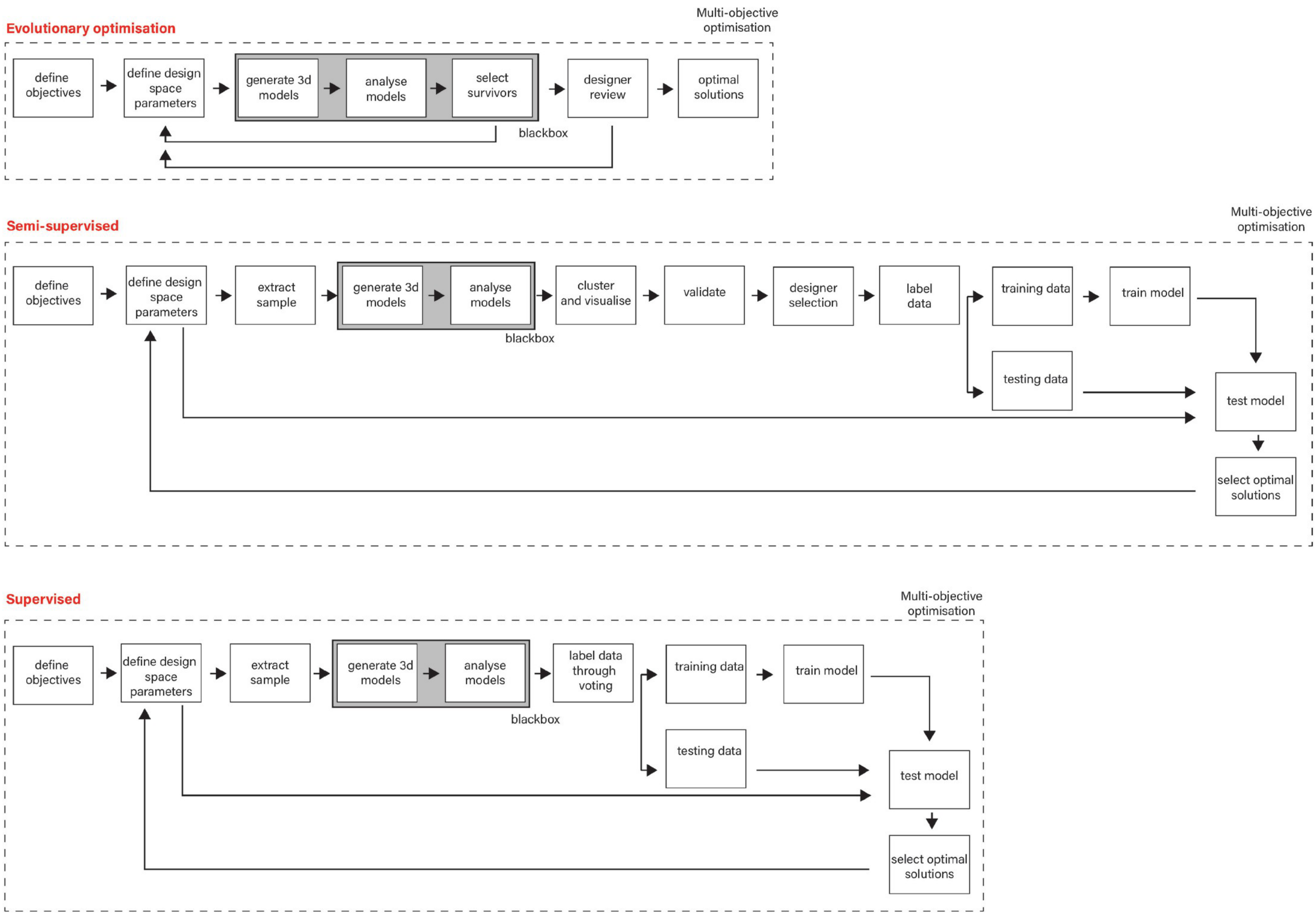



*Figure 4.26. Machine learning pipelines deployed in optimisation phase*

objectives are task specific, based on the requirements of each project development phase – they can be singular or a multiple set of features within the research focus on sightline quality, distances to specific programmatic features, and the proportional relationship between areas of programmatic features. Those features are measured within the parametric model through multiple performance metrics which are identified through the typological study and literature review. The full list of design space parameters, analytical categories, and benchmarks can be found in the Appendix. The Fitness functions of the NN models in both supervised and semi-supervised pipelines were evaluated as an average of the performance metrics. Utilising a NN model for this evaluation was also considered but the more traditional approach was selected due to the ease of interpreting the data for the specific design processes. As described in Chapter 03, there is long tradition in parametric stadium design of combining values algorithmically to produce performance ratings that capture a number of the analytical aspects, such as Buro Happold's Venue Performance Rating (Pottinger, 2021).

The fully autonomous pipeline is based on evolutionary optimisation. The input is definition of the parameters limiting the design space and the optimiser sequentially seeks better performing solutions within the set of typological variations. The tool used is Octopus, the only fully multi-objective optimiser available for Grasshopper in Rhino 7 at the time of writing. The focus was sightlines, circulation and layout and it managed to identify solutions which perform well in all categories as seen in those slides. The optimiser generates thousands of solutions and progressively identifies sets of solutions where the objectives converge. The limitations of this process is that the designer does not have input in the optimisation but only defines its parameters. As a result this pipeline outputs solutions only based one type of input and changes cannot be made through the process.

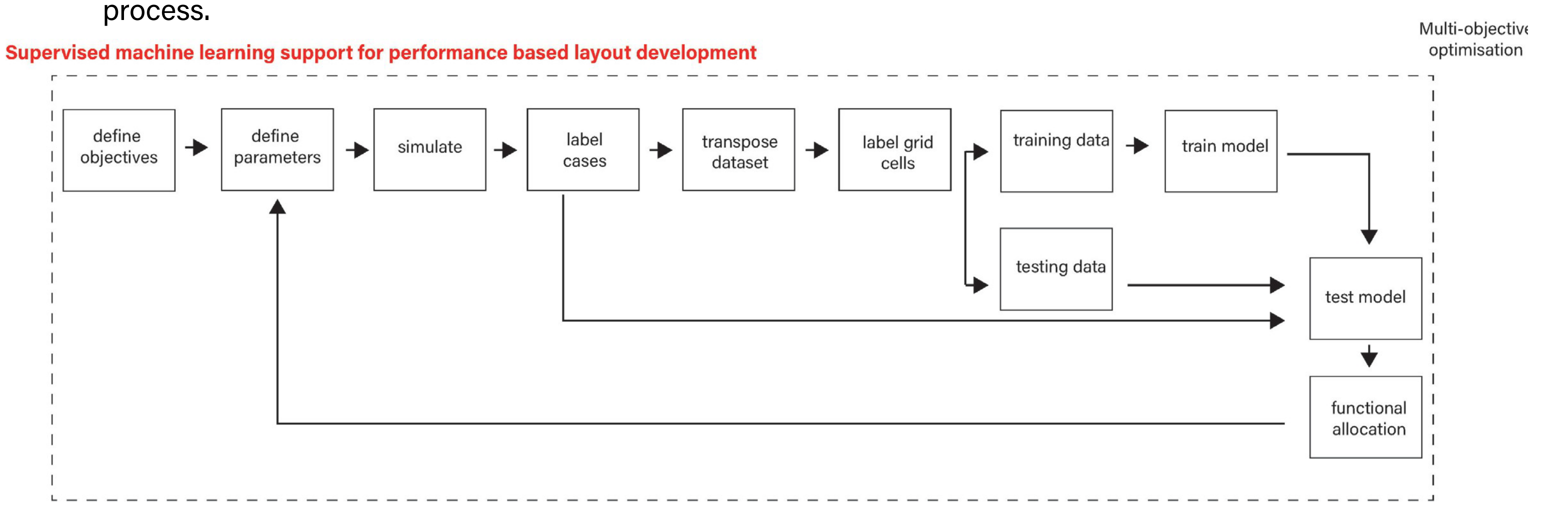



*Figure 4.28. Machine learning pipeline for performance based layout development*

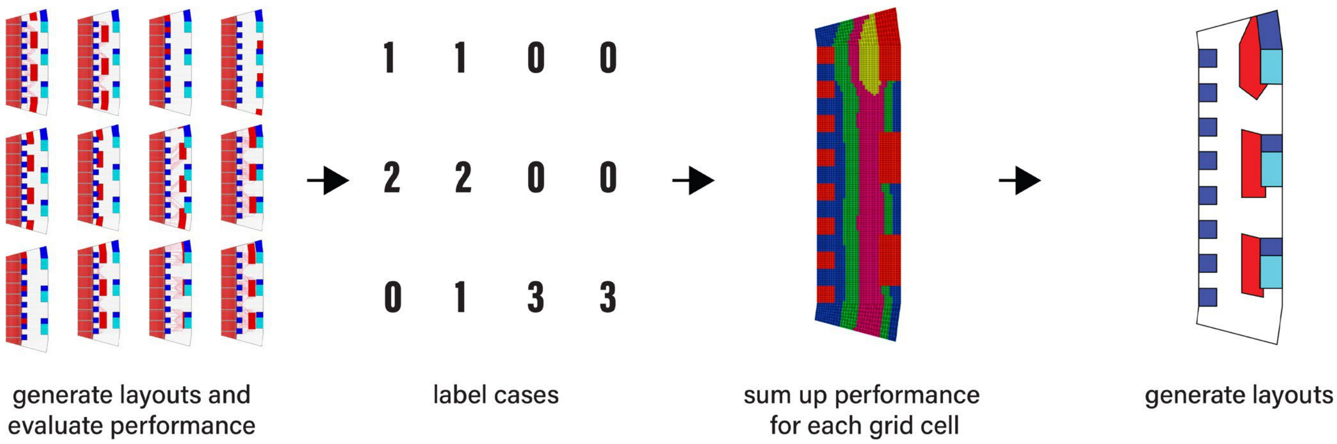



*Figure 4.31. Workflow for performance-based layout development*

The research approaches the layout analysis and optimisation through an expansion of the NN supervised machine learning pipeline. This is a special case in the application of this method, due to the many potential design solutions. The objective is also different – the informed allocation of functions based on multiple performance metrics, as opposed to the direct selection of well-performing solutions. The process is the same up to the point at which the data is labelled – a design space of possible layout solutions is simulated, and their performance is evaluated. At that point each simulated design solution is assigned a set of labels. In contrast to the NN supervised pipeline, this method then transposes the dataset so each grid cell is assigned a label based on the

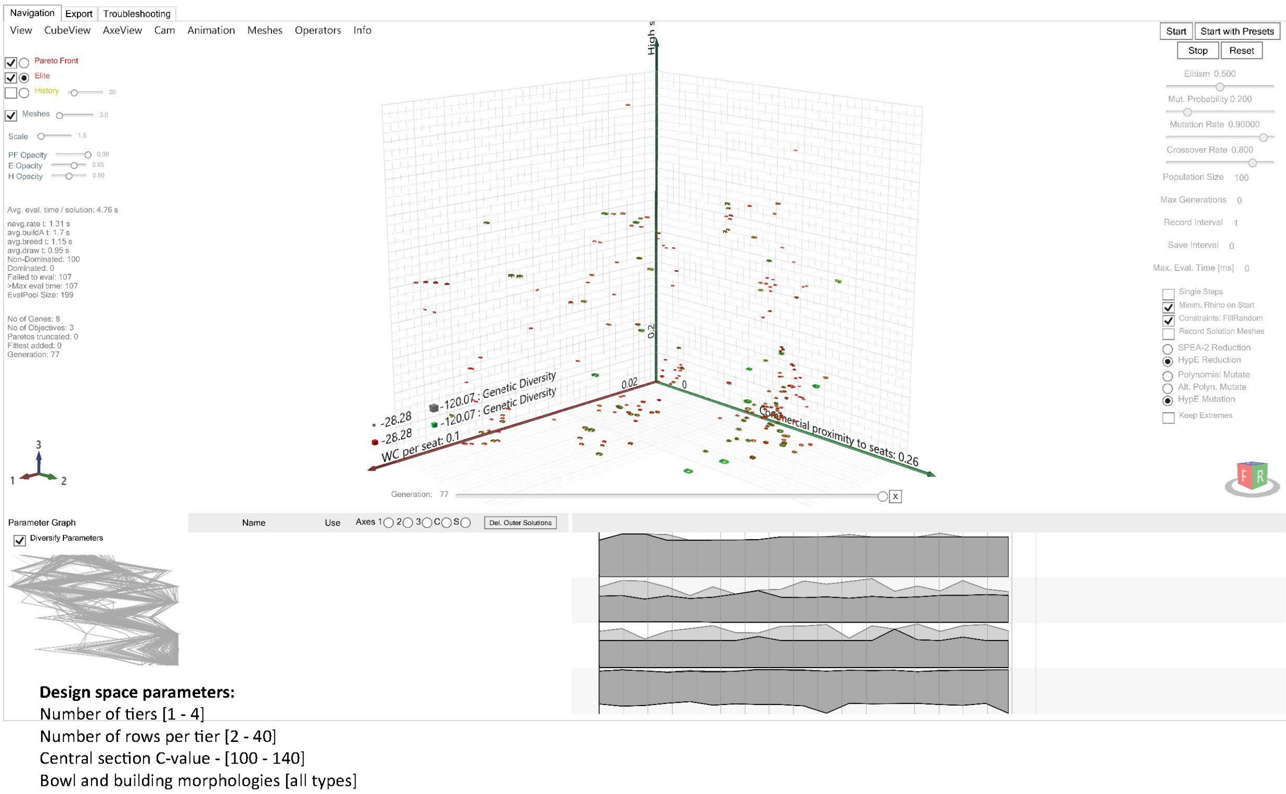



*Figure 4.29. Evolutionary optimisation with Octopus*

performance of the cell across all the case studies. As with the Fitness functions of the supervised and semi-supervised pipelines, this cell-specific performance rating is based on the sum of the labels from the design solution evaluation and then normalised in the domain of 0 to 1. This new data is used to generate performance heat maps and, using a NN algorithm, the grid cells are classified into different zones. These zones enable informed decisions to be made about the internal spectator facilities layout during the manual development of plans by the designer, or the automated generation of plans. This research is limited to the exploration of the possibilities presented by the application of machine learning to the optimisation of the internal layout based on programmatic provision and organisation, and it stops short of generating plans.

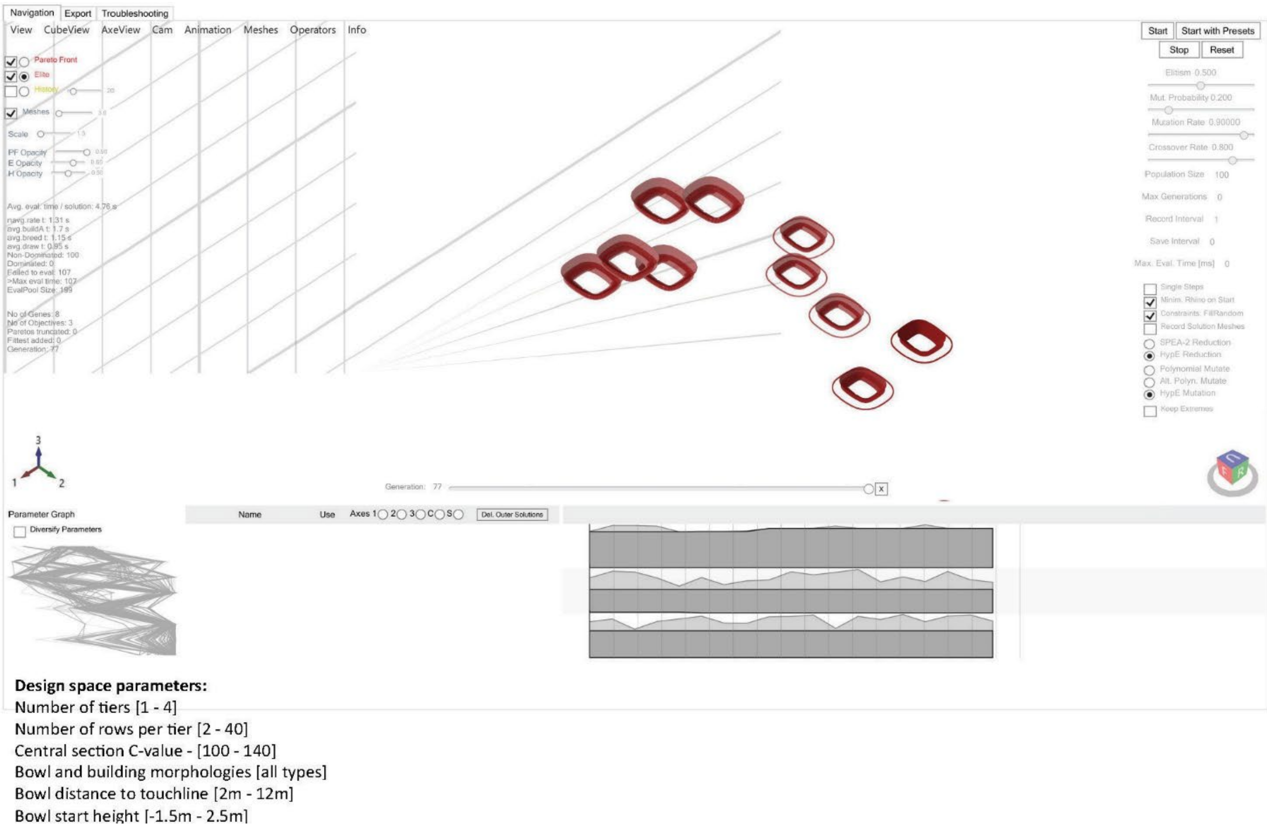



*Figure 4.32. Evolutionary optimisation 3D model possible solution evaluation*

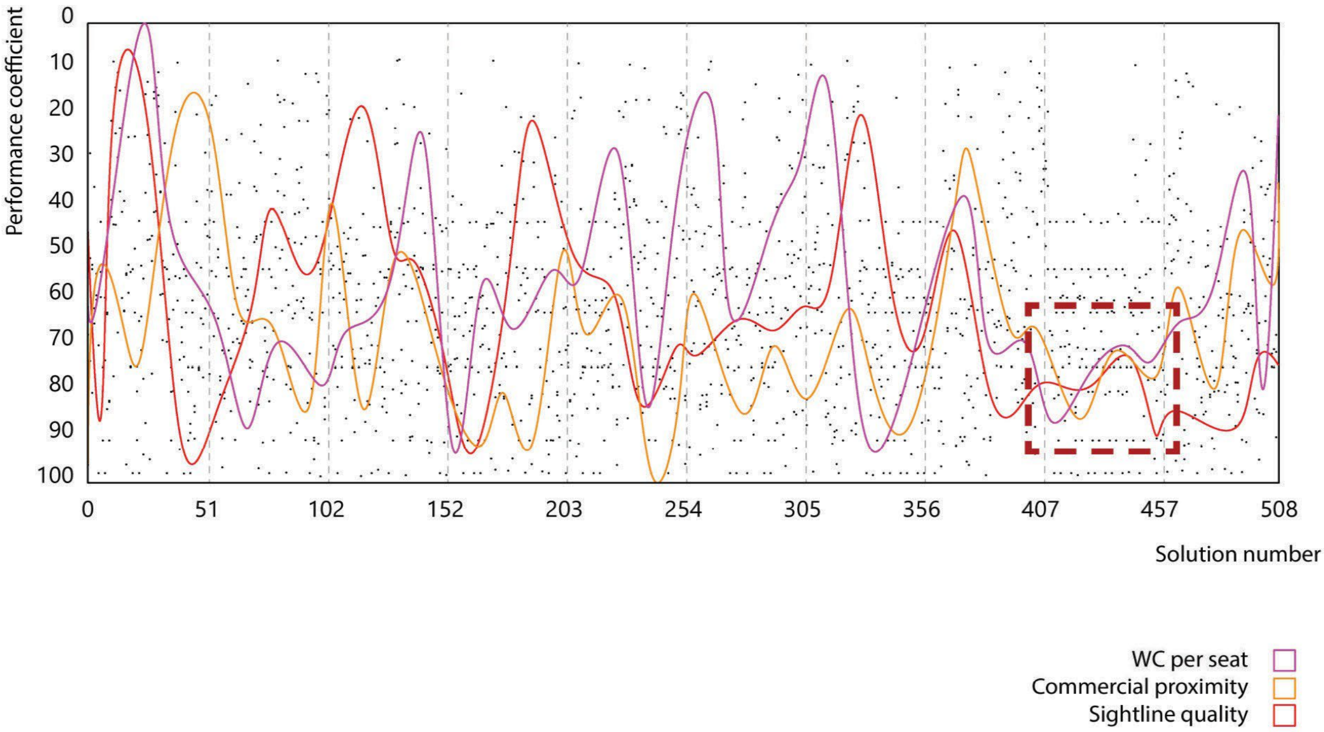



*Figure 4.33. Evolutionary optimisation graphic evaluation of possible solutions, optimal solutions in red square*

The deployment of the evolutionary optimisation pipeline is based on identification of the specific design objectives and the design space parameters by the designer. The research proposes the utilisation of this method within the later design stages for the reduction of a set of possible solutions for a specific area of the building, such as the number of rows or tiers. The reason for this approach is that the increase in the number of design space variables greatly increases the number of possible solutions, and thus the time and computational power required to find optimal solutions. Once those aspects are defined, the next task is to define the settings for the evolutionary process – elitism, mutation rate and probability, population size, type of reduction and mutation. Following this step, the optimiser automatically starts generating potential solutions.

Once the optimiser reaches a set of potential solutions in which the objectives are satisfied, the task for the designer is to evaluate the output and decide on whether the solution, or set of solutions, fits the overall objectives of the design. This can be done through visual inspection of 3D models of design solutions or through the graphic evaluation of a plotting of all the possible solutions and their relationships to the objectives. If the proposed solution is accepted, the parametric inputs of the solution are added to the parametric model and the solution is taken forward in the design process. On the other hand, if the solution is not satisfactory, the designer must re-evaluate the parameters and their limits in the definition of the design space, along with the settings of the optimiser. In cases where no solution is found, the designer can return to the original definition of the objectives and identify more feasible aims.

The semi-supervised method focuses primarily on design exploration and the identification of solutions that could potentially have been omitted in a traditional workflow. The starting point is the same as that for the evolutionary workflow – the definition of the objectives and the design space. Nevertheless, this pipeline is a lot more interactive, as it relies on validated unsupervised *k*-means machine learning models from the Accord Framework for the clustering of the cases, the manual selection of the best-performing group by the designer, and the subsequent labelling of the data for training a NN-supervised classification algorithm again from the Accord Framework. The semi-supervised approach is widely discussed in academia and its benefits can be found in the properties of both unsupervised and supervised approaches – it is a fast and convenient way to reduce the design space and identify well-performing cases with classification. However, there is one major drawback – as the initial clustering is done through an algorithm, there is bias associated with the results. This bias is potentially amplified by the unsupervised learning algorithm, the structure of the dataset (Brøndum et al., 2021), and the designer's choices.

The unsupervised method deployed in the typological study in Chapter 02 was based on the identification of groups in the dataset through clustering, as the data is not labelled. Taking this approach to optimisation tasks presents an interesting condition – the training dataset is structured, but the data is not labelled, and the output is categories rather than numbers. Finley describes this condition in his exploration of utilisation of *k*-means for supervised learning (Finley, 2008; Finley and Joachims, 2005). Finley's rationale (2008) for the focus on *k*-means is that this algorithm is one of the most widely used, effective, and best-understood clustering methods. Later, when the input dataset already has the desired partitioning, the data segmentation provides a distance measure that is proportional to the properties of the clustering task (Finley, 2008). In terms of this research this means that the clustering algorithm is

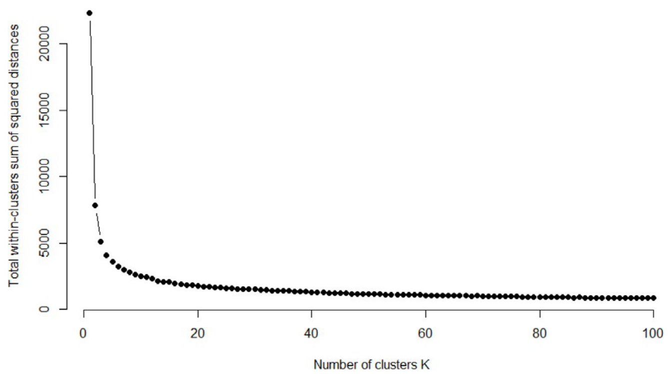



*Figure 4.34. Fidelity of k-means clustering in refence to number of clusters – the lower the distance, the more diverse the cases in each cluster (Migge, 2019)*

forced to evaluate the inputs in a weighted manner that captures the complexity of specific elements. The weight of each dataset feature is relative to its group size, and the groups have equal weights.

*K*-means clustering was selected because of the widely available performance data of this algorithm and its applications in existing research. In statistics and machine learning, *k*-means clustering is a method of cluster analysis which aims to partition *n* observations into *k* clusters in which each observation belongs to the cluster with the nearest mean (Accord Framework, 2017). The first aspect considered was the computational performance of the algorithm – there are several existing studies, such as those by Na (2010), Migge (2019), and Ahmed (2020). *K*-means clustering is based on the distances between all the data points, which are iteratively distributed into groups (Ahmed et al., 2020; Bekarian, 2020; Finley, 2008; Na et al., 2010; Yang and Sinaga, 2019). After a comprehensive empirical survey of varying *k*-means Migge (2019) determined that the fidelity of the clustering begins to decrease rapidly in cases with less than four clusters, while there are no significant changes for clustering above that number.

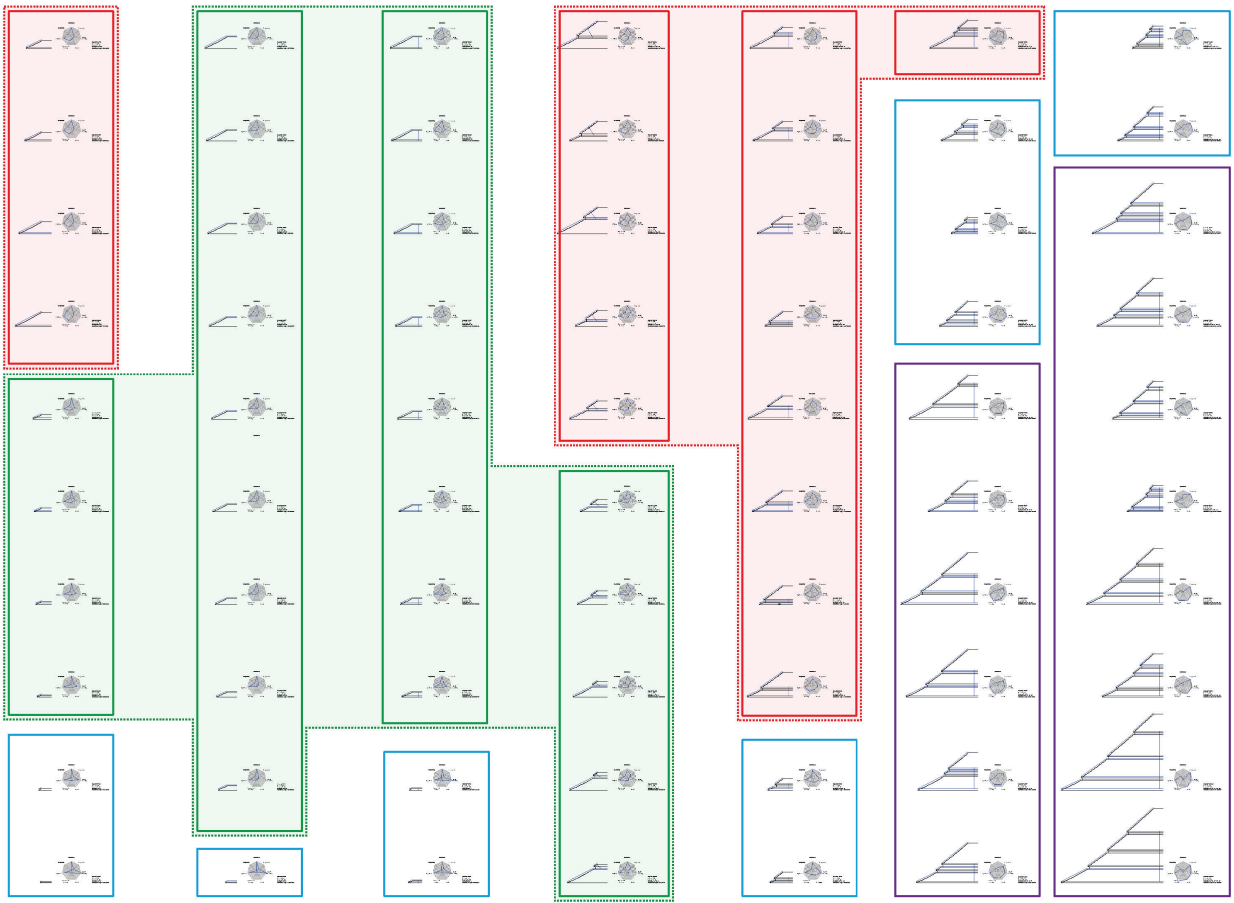


*Figure 4.35. K-means performance groupings at 2D section modular scale*

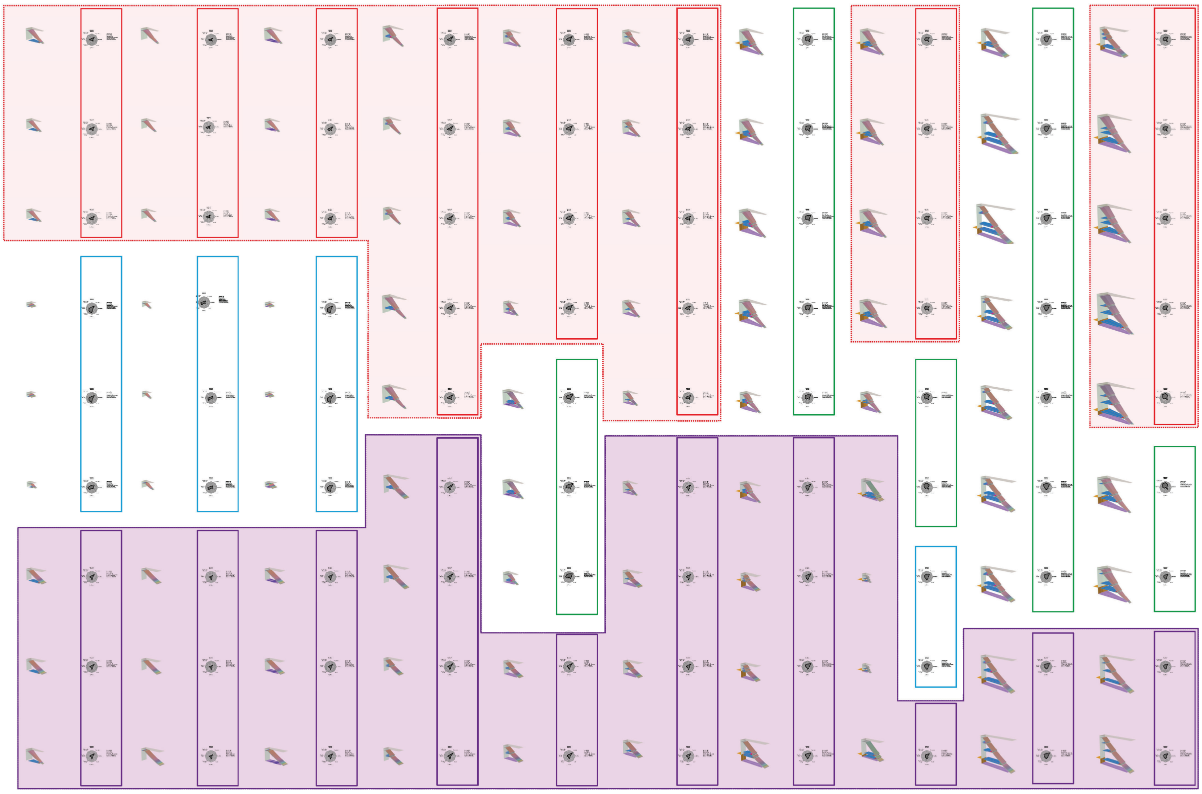


*Figure 4.38. K-means performance groupings at bay modular scale*

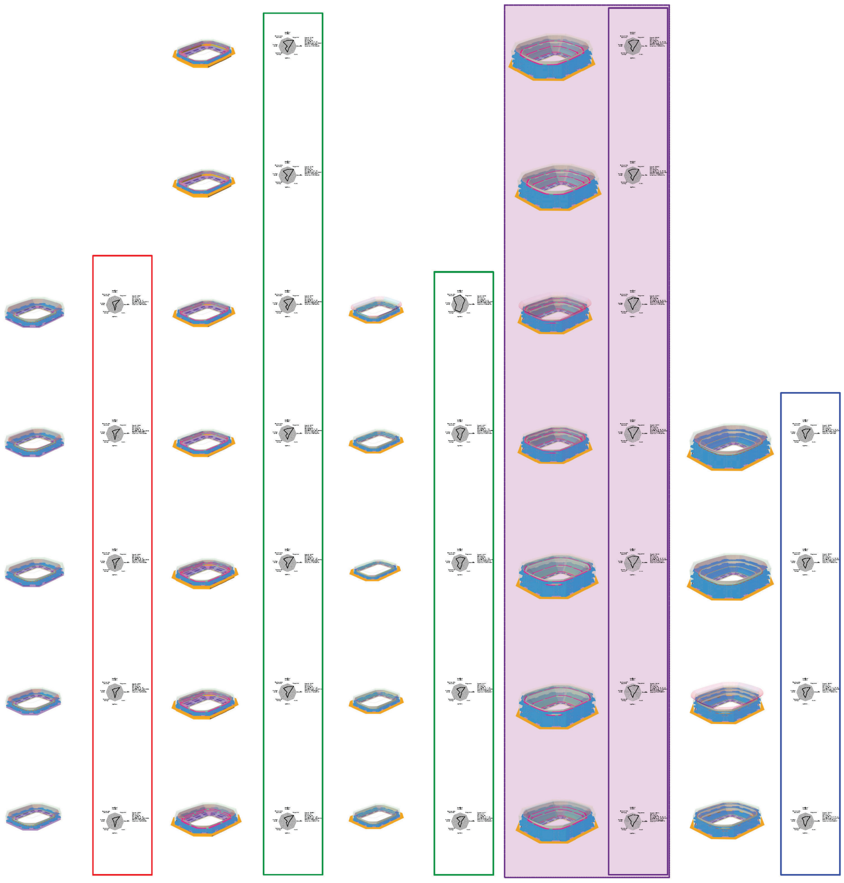


*Figure 4.37. Neural Network reduction of design space at stadium scale based on designer decisions*

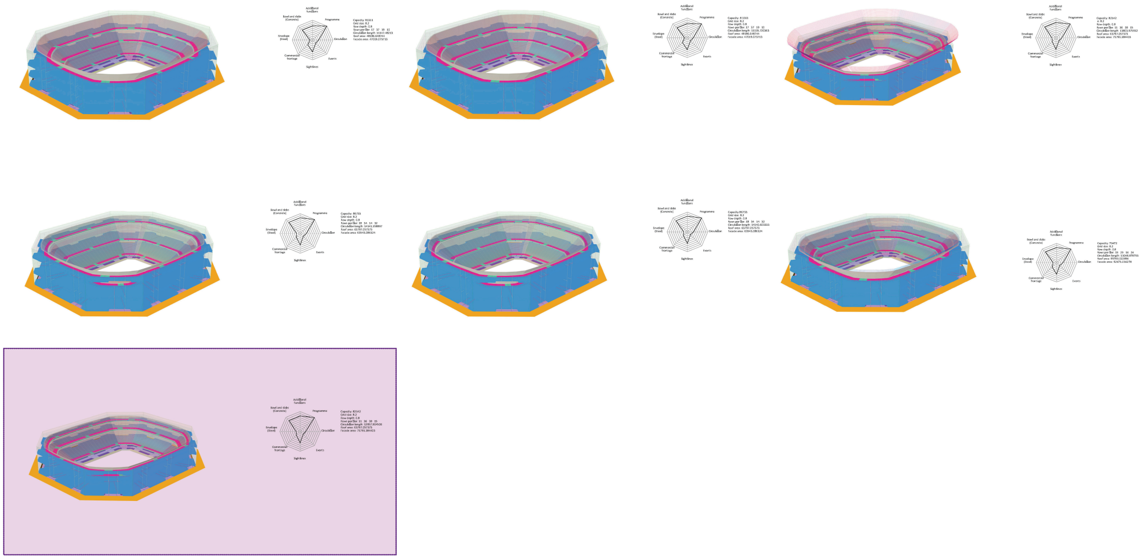


*Figure 4.41. Final Neural Network reduction of design space at stadium scale based on designer decisions*

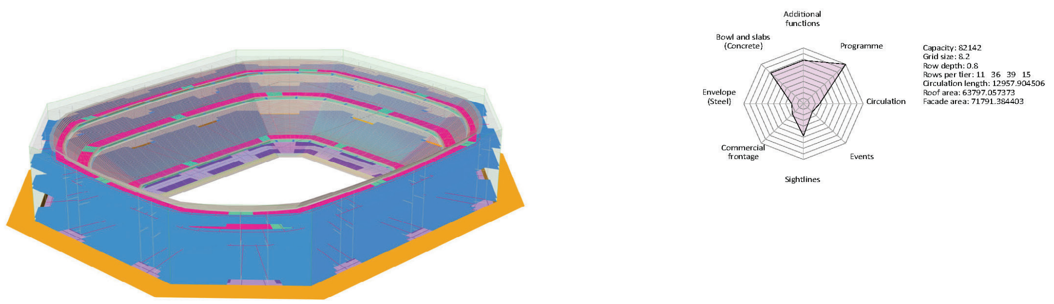



*Figure 4.39. Neural Network identification of best performing solution*

Kassambara (2018) proposes several methods for the retrospective validation of the number of clusters in *k*-means. His primary approach is based on the definition of the algorithm – compute solutions with different number of clusters, evaluate the data point distances, and select the final *k*. However, this approach is expensive computationally and requires time. His second approach is also based on the generation of a full set of cluster variations, but the consequent analysis is based on maximising the average silhouette over a range of possible values for *k*, as described by

Kaufman and Rousseeuw (1990). This method takes silhouette width and approximates the number of clusters based on the highest value. Again, it is a time-consuming and computationally expensive process. Kassambara's (2018) third approach is based on Tibshirani's (2001) gap statistic method, in which the total within the intra-cluster variation for different values of k is compared with their expected values under null reference distribution of the data. In terms of the current research, all three methods are valid – currently the research implements Tishirani's (2001) methodology for validation of number of clusters, as it requires the generation of a limited set of solutions rather than many solutions.

An example of a similar approach to optimisation tasks is the method developed by Pan (2021), in which a sample set is extracted from the design space with SOM (Kohonen, 1990) and data is labelled. The labels are then used to reduce the design space. The difference between Pan's approach and this research is the visualisation within the parametric model rather than through the SOM map. The reason for this alternative method is that it involves the organisation of the layout based on design drivers and modular scales, instead of a holistic approach to the design solution.

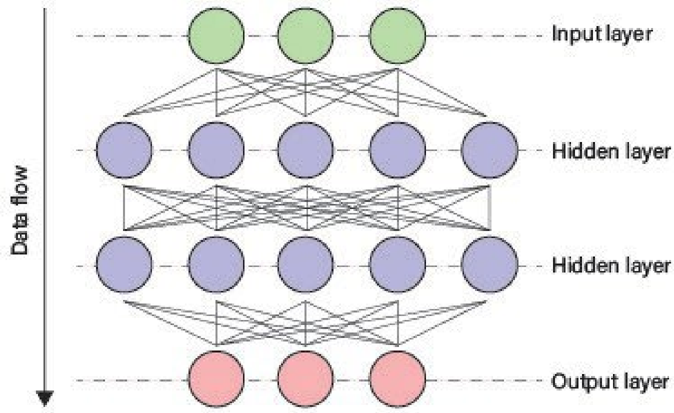


*Figure 4.43. Two hidden layer NN data flow BM (2021)*

The supervised multi-objective optimisation pipeline is based on the direct application of an NN algorithm for the reduction of the design space. The NN algorithm was also selected due to the large application in existing research and widely available performance data (Aggarwal, 2018; Bishop, 2006, 1995; Goodfellow et al., 2016; IBM, 2021). In essence, this type of machine learning algorithms are based on the utilisation of layered interconnected nodes that simulate the way the human brain works (AWS, 2023). The data is introduced in an input layer where it is analysed and processed. Then it is passed on to a series of hidden layers that categorise it further based on patterns identified by the algorithm. The final result is generated by the output layer in the domain. NN algorithm from the Accord Framework requires the values to the be remapped within the domain of -1 to 1 and its outputs are also within the same numerical range.

The start of the workflow is the same as for the previous two solutions – the identification of the objectives and design space parameters specific to the design development stage. A sample from the design space is extracted, simulated, and analysed. The research then makes full use of the abilities of the parametric model to produce performance data and labels for each objective, based on either legal requirements or performance benchmarks from case studies. Those labels are then combined based on voting. The labelled dataset is then split into training and testing sets. The validated model is then used to reduce the initial design space.

| Category | C-value | A-Value | Distance | Angle 01 | Angle 02 | Score | Rank |
|---|---|---|---|---|---|---|---|
| **Case 01** | 5 | 4 | 5 | 5 | 4 | 28 | 2 |
| **Case 02** | 5 | 5 | 5 | 5 | 5 | 30 | 1 |
| **Case 03** | 2 | 2 | 2 | 2 | 2 | 10 | 5 |
| **Case 04** | 2 | 3 | 3 | 2 | 1 | 11 | 4 |
| **Case 05** | 1 | 1 | 2 | 1 | 1 | 6 | 6 |
| **Case 06** | 3 | 3 | 3 | 4 | 4 | 20 | 3 |

*Figure 4.45. Voting system based on clusters, rank is the final label*

Voting is a method for assembling machine learning models (Kyriakides and Margaritis, 2019). Traditionally this method is used to find a specific solution based on the training of several different algorithms on the same dataset, but Demir (2017) expands the scope of this method to all setups including the same algorithm and different datasets. The basic aim of the implementation of this technique in terms of the practice side is to select well-performing cases across multiple metrics. Based on work by Brownlee (2021), the reason this approach was selected is that the best-performing cases have to be identified, the performance of the machine learning models is similar, and they are structured in exactly the same way. The objectives are selected manually by selecting a set of the analytical categories which are more detailed than the ranges specified in building standards and regulations. Both Kyriakides and Margaritis (2019) and Brownlee (2021) define two principal types of voting – hard and soft. Hard voting is based on adding up the labels produced by the machine learning models, and the case with most votes wins. On the other hand, soft voting is based on adding up the probabilities for a label, and the case with the highest probability wins. (Brownlee, 2021) This research relies on hard voting, which is currently conducted within the parametric model. Approaching the research with his tool enables a large design space and an efficient labelling process. The reason for the subsequent utilisation of the NN algorithm is to identify previously unattainable solutions.

### 4.9.5 Validation of the outcomes

This research is grounded in its empirical approach to gathering data, as a result the validation process for the outputs of the study is based on the standard scientific method discussed widely in the literature (Popper, 2005). The overall aim is to ensure that the results are reliable, accurate, and useful. Depending on the stage of the research process and specific workflow, the approaches adopted for this process ensure replicability through empirical testing, data validation, methodological rigour, model validation, cross-validation, external validation, peer review, and a review of the real-world implementation of comparable models. The models are continuously validated as more data is added, to ensure that the models are accurate and relevant throughout the research process.

The overarching approach to the validation of the data and models involved in this study is the aim for replicability in the process and findings. The entire research has been designed and documented so others can reconstruct the study and reach identical results by following the steps described in this thesis. The parametric and a selection of pre-trained machine learning models are available on GitHub (Milev, 2023b) for free download. The research is also based on the critical reassembling of widely accessible approaches, models, and data that allow this process to take place independently. Looking ahead, the potential of increasing the complexity of the parametric model is infinite, and future studies can expand both the detail and objectives of the workflows. The image data generated from this process can also serve as a basis for the development of other workflows based on different machine learning and artificial intelligence studies, with generative models such as Stable Diffusion (Rombach and Esser, 2023). Machine learning libraries are also freely available and the research specifies the exact versions to enable others to replicate the study.

The process of data validation is essential, and multiple sources have been cross-referenced in order to verify the quality and accuracy of the data. As the research relies heavily on the intermediate translation of 2D plan and section data to 3D models through the parametric model, each case study has been input separately and the resulting model compared to the 2D data. The results of the sightline analysis of the case studies have been compared to available sightline studies of similar morphologies and designs such as the studies by Hudson and Westlake (2015), Fenwick Iribarren Architects (2018), Morales and Sykes (2019), and Hudson (2020). Where no studies were available, the comparison was conducted based on the results of studies of the same morphological type. Overall, the objective of the research is to train and test the machine learning models with data that is both accurate and representative of the real-world conditions simulated.

As described in Chapter 03, the machine learning model validation is based on established practices in the field and is specific to each workflow. The unsupervised algorithms are tested through various statistical measures to evaluate the specific distribution of the classification cases, while the NN supervised algorithm is tested by splitting the data into training and testing sets. The aim of this step for the supervised models is to ensure that they fit the training data well and generalise to new data. The split proportions for testing vary across cases, but the overall objective follows the standard approach of using between 10% and 20% of the dataset.

To validate the machine learning models' robustness and the way they interpret the data, the research utilises cross-validation to test the reliability of the models. This process involves splitting the datasets into multiple subsets and training and testing via alternative potions of the available data. This process is in place to ensure that the model does not depend on the way the data is split.

The final quantifiable validation of the machine learning models is based on bringing external data and evaluating the results as benchmarks. This is done by carrying out testing on new data from case studies that have not been previously analysed. The assessment of the performance of these designs is then compared to similar case studies.

The methodology of research was peer-reviewed by established authors and practitioners in the field, such as Geraint John. The workflows and overall research structure were subsequently presented at a research conference and published as a research paper (Milev, 2023b).

## 4.10 Input parameters

The tables in the Appendix summarise the parameters that control the algorithmic model per modular scale. There are more than eighty different features that can serve as a basis for the development of a design space. As described earlier in this chapter, the parameters in the 2D section scale define the sightline quality, the sector scale focuses entirely on layout, and all the scales affect the circulation. The tables are structured based on the location of the features within the scale and building design: the second column displays the list of parameters in the specific area and their limits as identified in the legislation and reference literature, the third column displays the legal reference documents, and the fourth column displays the reasoning for the inclusion of each feature, its accuracy, and its measurement unit.

## 4.11 Analytical categories

The identification of optimisation targets is based on the analytical categories from the typological study in Chapter 02 refracted through the concept of modularity in stadium design described in Chapter 03. Due to the quantitative nature of the research, the aim is to optimise the design elements which define the output of the analytical categories. The focus on modularity enables the selection of such elements related to the three major sections of stadium type – stage, auditorium, building – across the four modular scales. Breaking down the analysis to these major categories enables the efficient extraction of information and also forms the basis of the structure of the parametric model. This strategy enables the development of an approach to the creation of a design space based on parametric variation within specific areas of the stadium. It can also take advantage of the performance benchmark studies and enable the development of a strategy of parametrically translating specific well-performing elements from one building to another. The selection of the metrics is made by the designer at the beginning of each optimisation workflow, based on the specific requirements of the task.

The typological analysis, along with a literature review, resulted in a set of more than 140 analytical categories. These were reduced to the most important features that were relevant to the requirements of the RIBA design development stages. The final analytical categories for this study are divided into sightlines, circulation, and layout groups. The sightlines group utilise the 'C' value formula to evaluate performance based on the current legal framework. The sightlines are further analysed based on physical properties such as restricted view, field of view, and distance to the touchline. The circulation analysis is based on principles derived from Space Syntax and is based on distances between programmatic features. The layout analysis is based on programmatic provision and organisation.

The tables in the Annex summarise all the analysis categories evaluated in the final model. The first column shows the research theme reflected in the analysis and the type of analysis. The second column displays the feature that is measured, the type of data, and range of output values. The third column displays the objective of either maximising or minimising the value. The fourth column displays the process of measurement, while the fifth column displays the relevant references from the literature. The sixth column summarises the measurement, evaluation, and accuracy of each feature.

## 4.12 Benchmarks

The establishment of stadium design drivers and analytical categories opens up the possibility of identifying case study performance benchmarks. Working within the parametric model, the resulting dataset of sightline, circulation, and layout information needs to be analysed and the best-performing case studies identified.

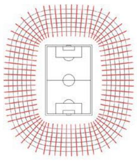
The full sets of performance metrics were analysed with *k*-means in order to identify groups based on performance per analytical category. Based on the performance objective for each category a median and best-performing case study were identified. The best-performing case study was also identified based on the performance objective and highlighted with a magenta square in the top right-hand corner of the visualisation of its metric. The full set of benchmarks can be found in the Appendix.

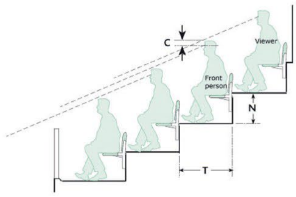
### 4.12.1 Case studies

*Table 4.1. Benchmark case studies*

| **Name** | **Location** | **Capacity** (executive suites) | **Playing field size** | **Built** (renovated) | **Cost** (million) | **Architect / Renovation architect** |
|---|---|---|---|---|---|---|
| Olympiastadion | Berlin, Germany | 74 475 (65) | 105m x68m | 1936 (2004) | €297 (2004) | Werner March/ Albert Speer (1936)/gmp (2004) |
| Estádio Nacional Mané Garrincha | Brasília, DF, Brazil | 72 788 | 105m x68m | 1974 (2013) | € 660 | (gmp) |
| Arena da Amazônia - Vivaldo Lima | Manaus, Brazil | 44 300 (68) | 105m x68m | 2014 | € 200 | gmp |
| Allianz Riviera | Nice, France | 36 178 | 105m x68m | 2013 | €250 | Jean-Michel Wilmotte |
| Olimpiyskyi National Sports Complex | Kyiv, Ukraine | 70 050 (14) | 105m x68m | 1923 (2011) | €150 | L. I. Pilvinsky (1923) / gmp (2011) |
| London Stadium | London, UK | 60,000 | 105m x68m | 2011 (2022) | £ 760 | Populous (2011) / KSS (2022) |
| Craven Cottage | London, UK | 19,359 | 100m x65m | 1896 (2022) | £ 120 | Archibald Leitch (1896 / … / Populous (2022) |
| Allianz Arena | Munich, Germany | 75 024 (106) | 105m x68m | 2005 | €340 | Herzog & de Meuron |
| Merkur Spiel-Arena | Düsseldorf, Germany | 54 600 (27) | 100m×70m | 2004 | €240 | JSK Architekten |
| RheinEnergie Stadion | Cologne, Germany | 50 000 | 105mx68m | 1923 (2004) | €117.4 | gmp |
| Japan National Stadium | Tokyo, Japan | 68 000 | 107m×71m | 2019 | €1250 | Kengo Kuma |

# 4.13 Full set of analytical dimensions Allianz Arena, Munich

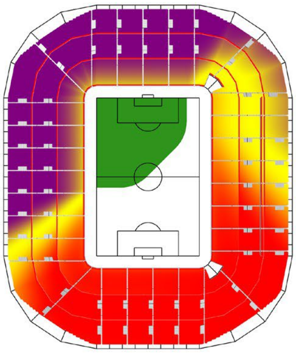





Cvalue

*Department for Culture, Media and Sport, Guide to Safety in Sports Grounds (London: The Stationery Office, 2008)*

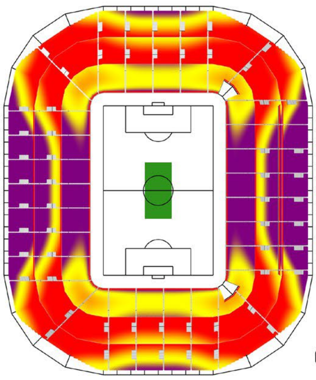
**C-value football**



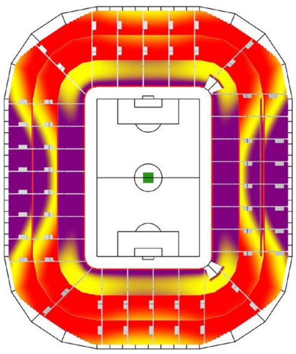
Point cloud of seat locations with individual sightline quality value based on the unobstructed view above the head of the spectator on the lower row. The sampling is based on the full capacity of the stadium and each value is based on the spectator looking towards the closest point on the field of play touchline.

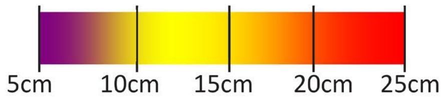
**optimisation target - higher values**

**C-value baseball**



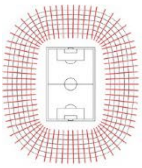
**C-value tennis**

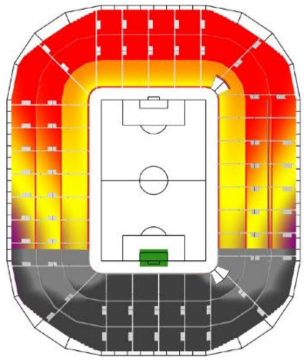





**C-value boxing**

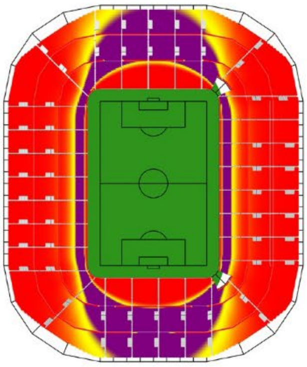
*Figure 4.46. Full set of analytical dimensions based on Herzog & de Meuron (2005)*





*
Greyed out seats are excluded from final calculation

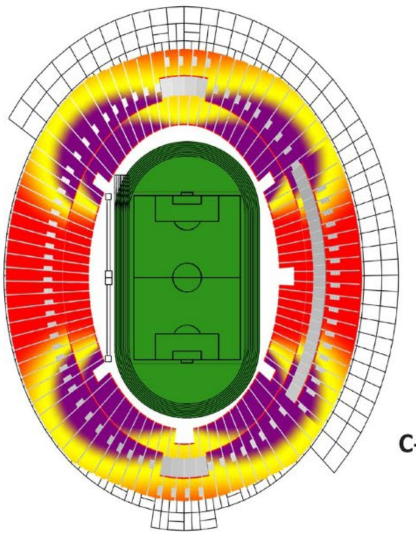
**C-value concert**



*
The calculation is for an athletics track that goes under the seating stand.

Below you can see the London stadium in athletics configuration.

**C-value athletics***



**C-value athletics**

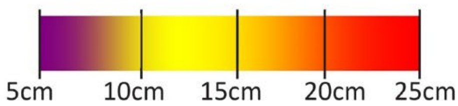



*Figure 4.48. Full set of analytical dimensions based on Herzog & de Meuron (2005)*

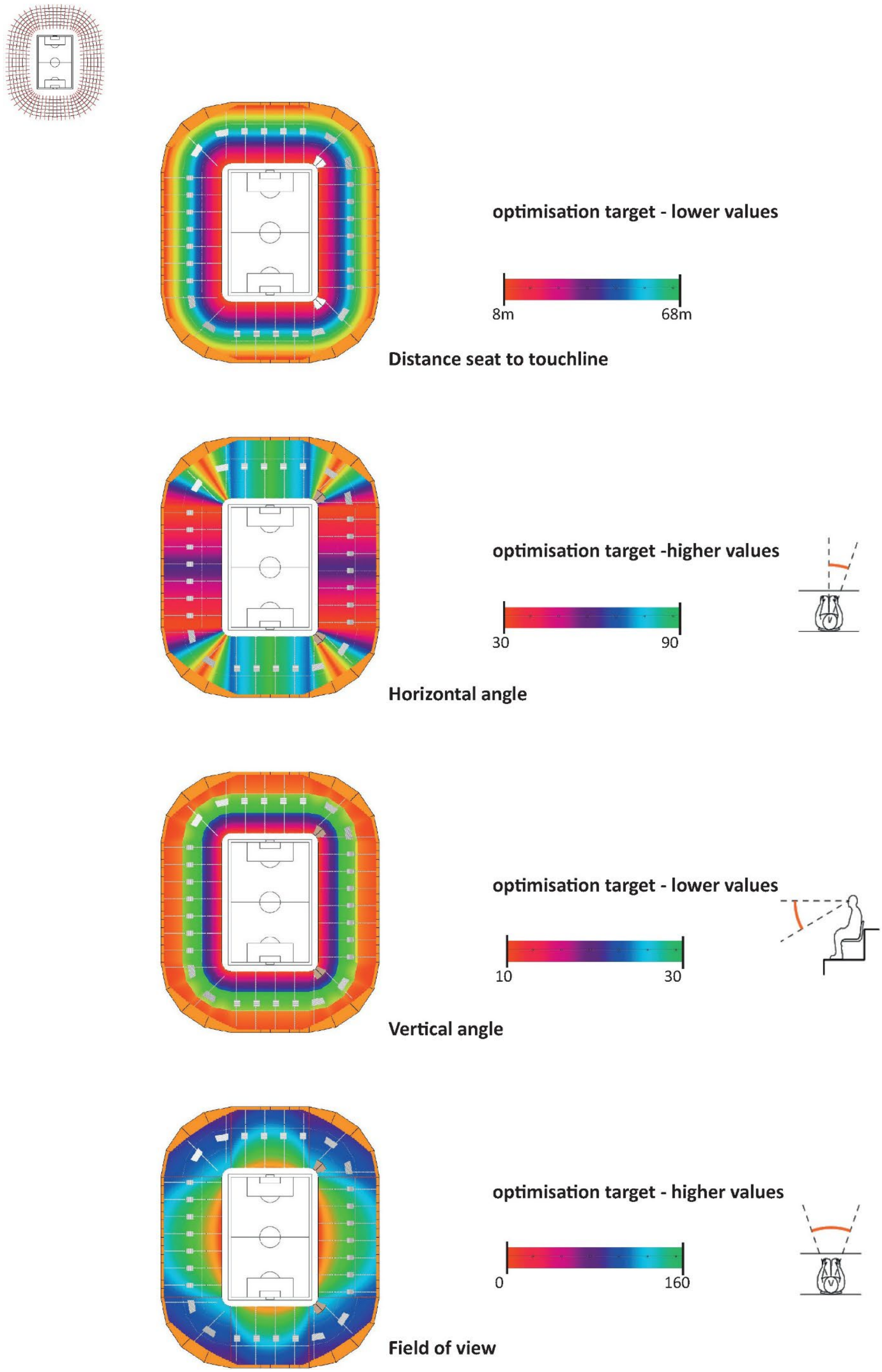



*Figure 4.49. Full set of analytical dimensions based on Herzog & de Meuron (2005)*

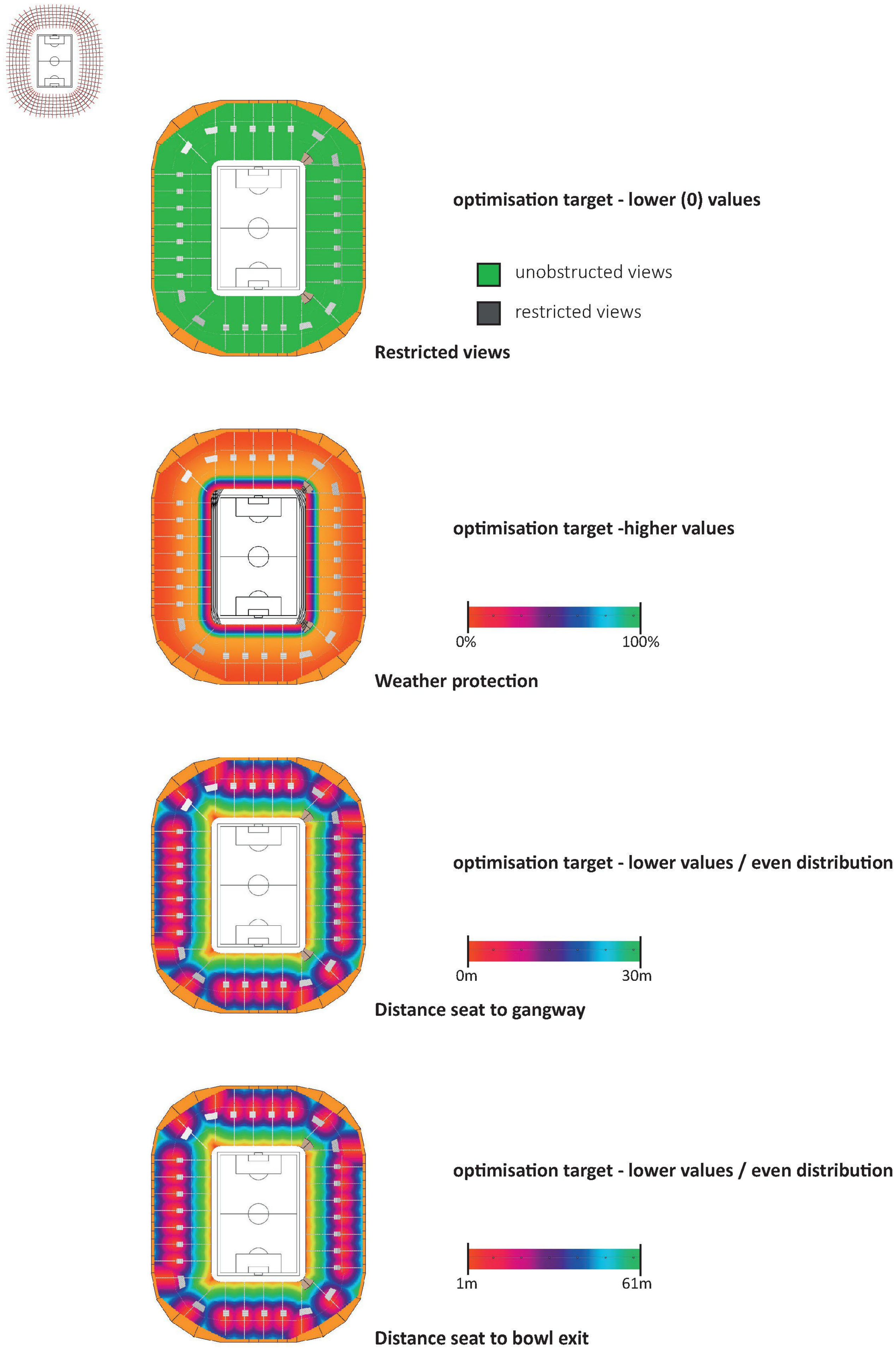
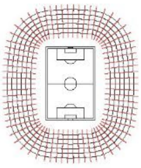
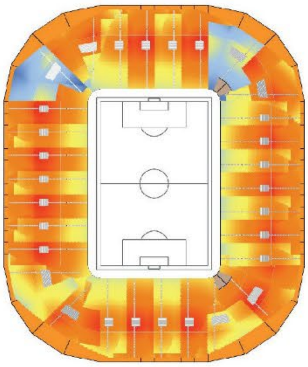



*Figure 4.51. Full set of analytical dimensions based on Herzog & de Meuron (2005)*

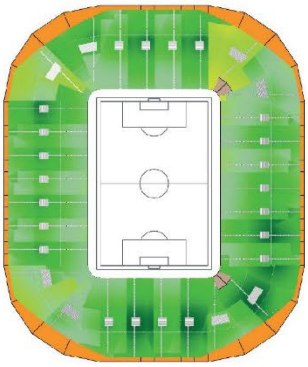




optimisation target - lower values / even distribution

40m 130m

Distance seat to vertical circulation



optimisation target - lower values / even distribution

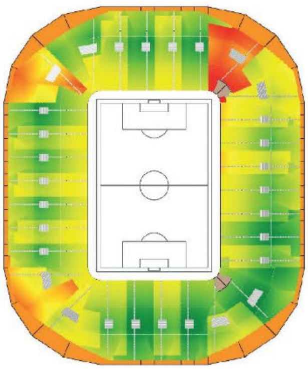
49m 163m

Distance seat to stadium entrance

optimisation target - lower values / even distribution

0m 27m

Vertical distance seat to main entry level

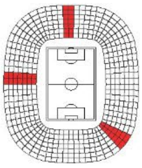


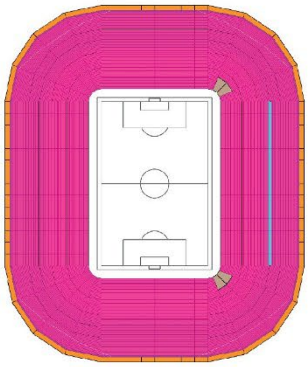
optimisation target - lower values / even distribution

150m 300m

Distance seat to masterplan entry

*Figure 4.53. Full set of analytical dimensions based on Herzog & de Meuron (2005)*

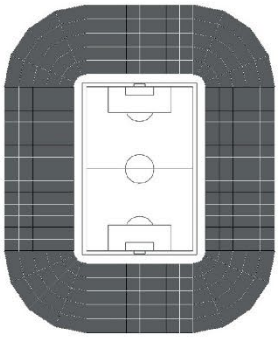




**optimisation target - same values**

0.3m 3.5m

**Row depth**

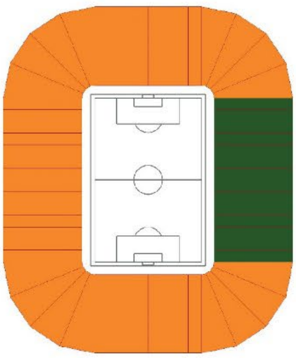


**optimisation target - frame**

monolith

frame

**Frame / monolith**



**optimisation target - less dispersal**

**Module type**

**Numerical data:**

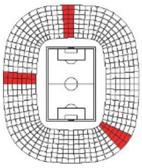
**Moving elements area** = 0 sqm

**Moving elements number** = 0

**Rows maximum number** = 73

**Steps total** = 8672

*Figure 4.54. Full set of analytical dimensions based on Herzog & de Meuron (2005)*



**Rakers total** = 60

**Bowl area** = 33369.707645 sqm

**Bowl material volume** = 10010.912293 m3

**Seats rail total lenght** = 32917.405569 m

**Gangway total area** = 2336.07505

**Gangway total number** =246

**Vomitories total area** = 1452.483497

**Vomitories total number** = 76

**Frame monolith ratio** = 1

**Number of columns total** = 324

**Columns length total** = 5263.649914 m

**Slab on ground total area** = 23646.068102 sqm

**Slab on columns total area** = 91823.067082 sqm

**Primary vertical circulation cores** = 30

**Vertical circulation area total** = 12699.597987 sqm

**Basement area total** = 41272.659197 sqm

**Basement walls area total** = 8550.432296 sqm

**Facade_area_total** = 31115.368927 sqm

**Facade height** = 30.56794 m

**Facade openings area** = 1.238e-11 sqm

**Roof area total** = 69806.892608 sqm

**Roof span** = 99.616322 m

**Roof number of divisions** = 60

**Podium area total** = 10496.434079 sqm

**Podium height** = 8.4 m

*Figure 4.55. Full set of analytical dimensions based on Herzog & de Meuron (2005)*

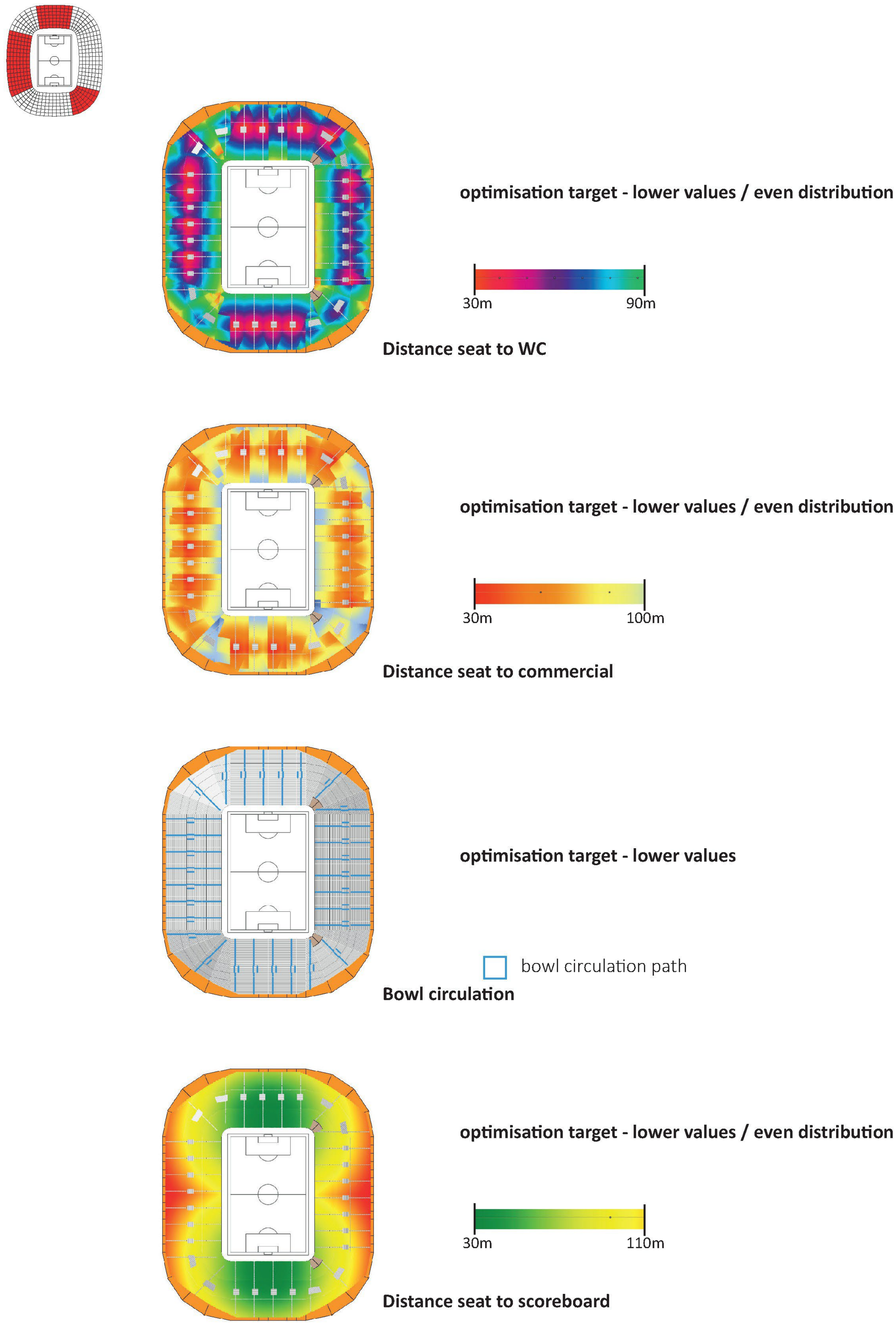
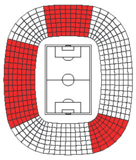
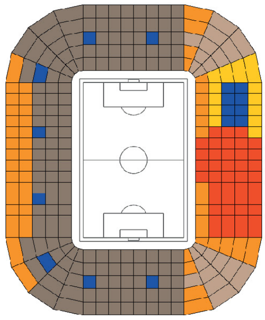


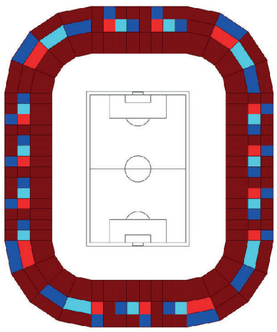

*Figure 4.57. Full set of analytical dimensions based on Herzog & de Meuron (2005)*





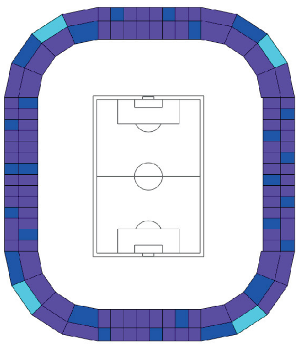
plan basement

parametric representation



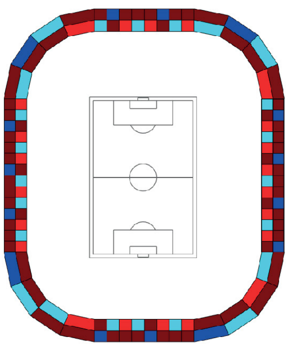
plan level 00
general admission concourse

parametric representation



plan level 01
hospitality

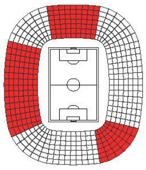
parametric representation

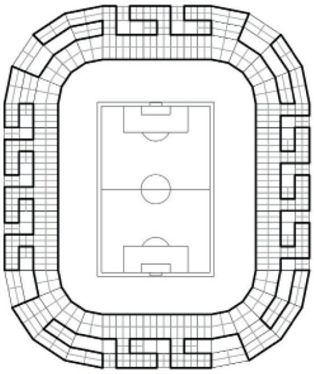



plan level 04
upper concourse

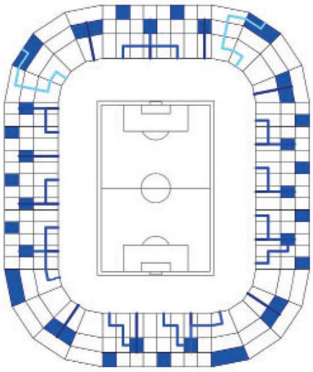
parametric representation

*Figure 4.59. Full set of analytical dimensions based on Herzog & de Meuron (2005)*





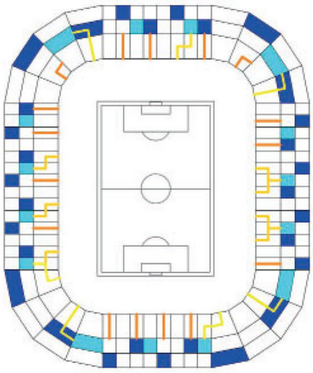
Concourse circulation analytical grid



optimisation target - lower values / even distribution

15m 30m

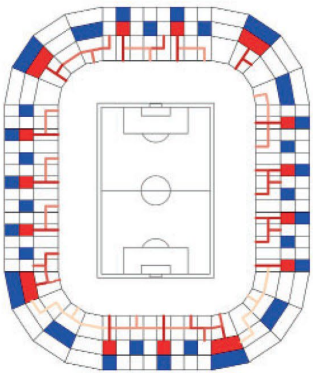
Vomitory to vertical circulation paths



optimisation target - lower values / even distribution

15m 30m

Vomitory to WC paths

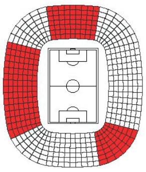


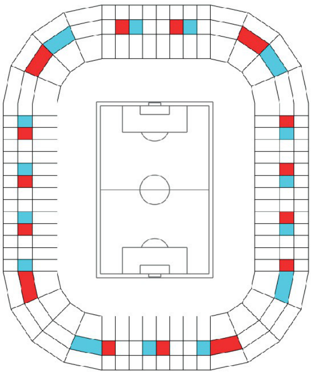
optimisation target - lower values / even distribution

15m 30m

Vomitory to commercial paths

*Figure 4.61. Full set of analytical dimensions based on Herzog & de Meuron (2005)*



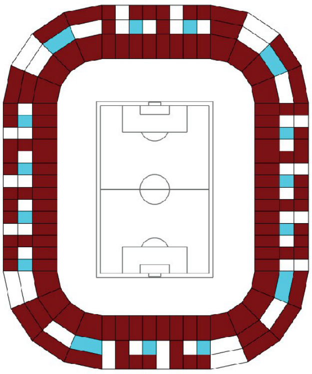


**optimisation target - even distribution**

WC

commercial

**Spatial relationships WC - commercial**

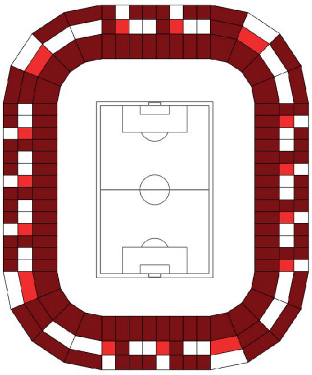


**optimisation target - even distribution**

WC

concourse

**Spatial relationships WC - concourse**

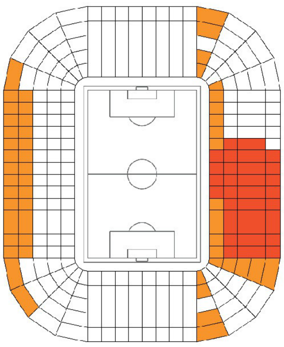


**optimisation target - even distribution**

commercial

concourse

**Spatial relationships commercial - concourse**



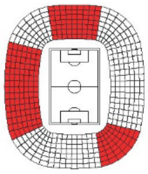
**optimisation target - even distribution**

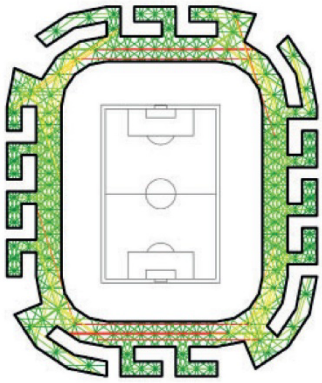
performers

service

**Spatial relationships service - performers**

*Figure 4.63. Full set of analytical dimensions based on Herzog & de Meuron (2005)*





optimisation target -higher values / even distribution


Isovist main concourse

**Numerical data**

**Distance changing room to field of play** = 5.6 m

**Concourse area per seat** = 0.367828

**Vertical circulation to concourse area** = 0.637609

**Topological distance number of turns from bowl to vertical circulation = 1.466667**

**Angular distance angular change from bowl to vertical circulation** = 14.20364

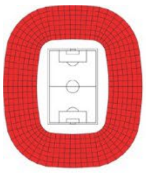
**Average metric distance, Euclidean distance from bowl to vertical circulation = 34.588757**

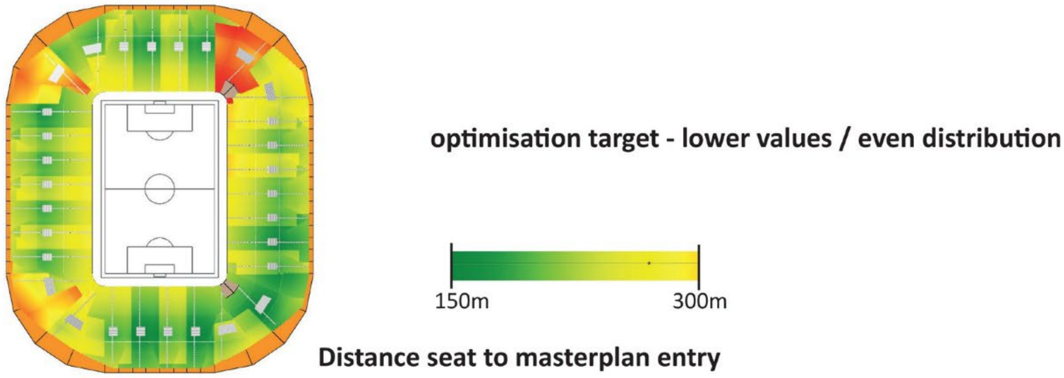
**Concourse visibility isovist average lenght** = 12.22707

**Isovist rays above 50m ratio** = 0.027222

**Other horizontal circulation area** = 2259.724061 sqm
**Vertical circulation area** = 12699.597987 sqm
**WC area** = 4362.79534 sqm
**Commercial area** = 14376.172132 sqm
**Service / Store area** = 15770.50389 sqm
**Performers** = 2866.2961 sqm
**Hospitality area** = 17701.291461 sqm
**Media area** = 4089.569339 sqm
**Other area** = 21425.644933 sqm
**Internal parking area** = 19917.53994 sqm
**Concourse area** = 193397.372146 sqm

*Figure 4.65. Full set of analytical dimensions based on Herzog & de Meuron (2005)*






**Numerical data**

**Number of stadium entrances = 16**
**Number of masterplan entry points** = 4
**Distance podium entry to stadium entry** = 8
**Distance commercial to mastreplan entry** =
186.125029 m
**External programme variation** = 4

*Figure 4.67. Full set of analytical dimensions based on Herzog & de Meuron (2005)*

## 4.14 Typological parametric variations

As described earlier in the thesis, there are only a small number of full stadium plans available to examine. In order to resolve this problem, the research has to focus on the development of parametric variations – a method that allows the generation of hybrid design solutions based on averaging input values in the parametric model of the best-performing case studies. The aim is the generation of a second dataset that not only reflects the case studies but also benefits from the properties of the parametric definition of the stadium – as all the case studies are translated as a set of input values, these values can be averaged and thus create new design solutions. In addition, those values can be controlled in terms of the weight of each design parameter – only a select subset of the values can be utilised in the optimisation process and thus improve the performance of specific area of the design. The tables in the Appendix show the same analysis as the benchmark studies but for parametrically generated design space based on the designs of Brasilia's Mane Garrincha Stadium by gmp and Allianz Riviera by Wilmotte. These two cases were selected because they performed best in terms of exit distance and sightline quality. The variation is based on averaging the base morphology, number of tiers, number of rows per tier, and internal layouts.

# Chapter 5 Application: Deployment of Machine Learning Supplemented Workflows in Stadium Analysis and Optimisation Within the

## 5.1 RIBA Plan of Work and its Data-driven Overlays

### 5.1.1 How can someone else use it?

Multi-objective optimisation of modular multi-use stadiums is an approach to a series of design problems that have implications that reach far beyond the planning of a single building type at all of the design development stages defined by the RIBA Plan of Work [PoW] (2020). Recent changes in legislation and UK government policy have challenged the traditional design and procurement model towards design automation and prefabrication. The long-established relationship between stadium design, engineering, and the development of construction technology have brought stadium design to the forefront of this transformation. The machine learning automated workflows within a modular parametric context presented in this thesis can potentially streamline the design process by automating large sections of repetitive work, exploring new design solutions, evaluating and developing design based on performance data, and expanding the accessibility of technically complex tasks to non-professionals.

## 5.2 State of practice and relevant design development stages in the UK, EU, USA, and globally

### 5.2.1 RIBA Plan of Work

Originating the 1960s, the RIBA (2020) PoW was one of the first formal attempts to structure the building design and construction process. The PoW is the project delivery schedule reference for most of the contractual relationships in the building procurement process in the UK, and has a significant impact on design development. Aimed at creating a framework for organising the activities required to deliver a successful project, the PoW was understood and developed as a process that progressively details an architectural solution to a client's problem (Jones et al., 2019). For fifty years, this linear process (Roly Hudson, 2008) started with the client's decision to build and concluded with the building being used. The RIBA framework was so efficient that corresponding

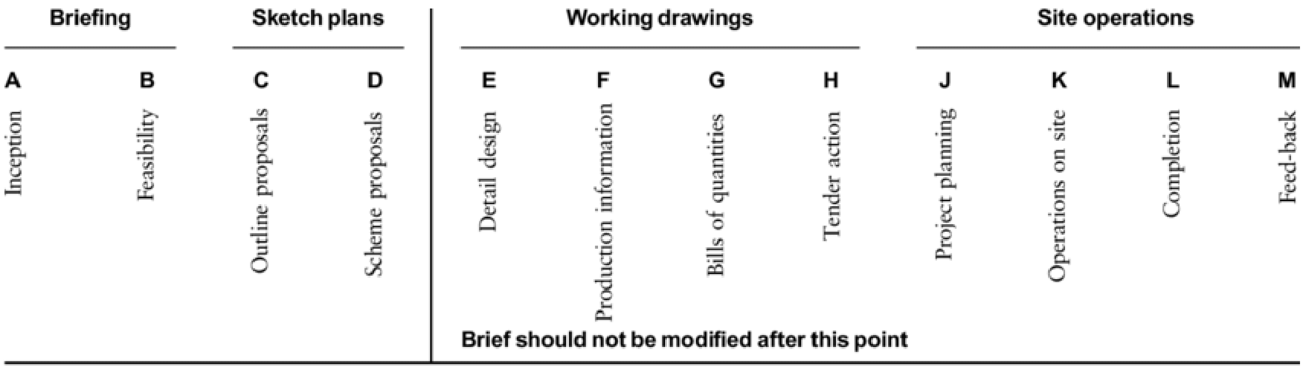



Figure 5.1. RIBA Plan of Work 1963

organisations in other countries, including the United States, Australia, and most European countries, adopted similar systems with comparable stages and deliverables. Three major factors, however, challenged the framework and exposed its inherent rigidity: the push towards sustainability (HM Government, 2021), an evolution of procurement methods (Sinclair, 2013), and the development of digital and manufacturing technology (Thompson, 2021). As a result, in 2011 the UK government published an outline *Construction Strategy* (Government Construction Strategy, 2011)


Figure 5.2. Critical symptoms of failure and poor performance of UK construction sector (Farmer, 2016)

which aimed to respond to these industrial and environmental developments. The RIBA followed suit and completely reconceptualised the PoW by separating the building performance analysis into two new stages – *Strategic Definition* and *In Use.* At the time, this was a paradigm change – the ability to learn from previous projects has always been the hallmark of experienced architects: nevertheless, the PoW forced architects and designers to learn from previous developments in order to define new projects strategically as part of the delivery process, with its contractual implications.

The revised PoW kickstarted a process of transformation that instantly started gaining momentum. The RIBA published a *Building Information Modelling* [BIM] overlay on the PoW (Sinclair, 2013) which built on its previously published sustainability targets (Gething, 2011) through the perspective of a digital delivery framework for the traditional design, procurement, construction, and utilisation process. As the PoW is the basis for the project delivery schedule, BIM became the norm, and increasingly clients and contractors demanded the delivery of designs as BIM models, along with the traditional drawing packages. The dramatic change in the procurement landscape exposed significant problems within the industry – low productivity and a lack of predictability, structural and leadership fragmentation, financial fragility, a dysfunctional training model, the unsatisfactory demographics of the workforce, a lack of collaboration and investment in innovation, and the generally poor image of the industry (Farmer, 2016). The situation was so dire that every stakeholder in the industry had to revaluate how and what they deliver within their part of the overall system (Thompson, 2021). The new delivery framework, the PoW 2013, brought a renewed focus on methods of construction and the value delivered by the construction industry. This resulted in an inquiry into existing approaches that were less commonly used in traditional construction, such as off-site manufacture and the quantification of the actual value that each approach and project deliver to society and the economy. Subsequently there was an inquiry by the Construction Leadership Council (2019) into the actual skills that would be required in the industry of the future and the adequacy of the existing labour skills in a design environment dominated by digital design and analysis.

### 5.2.2 The position of parametric design and machine learning in practice

The first researcher to define the role of the parametric designer in the stadium design project team was Hudson (2008), whose work was later developed by Turrin (2011), Zarei (2012), Mueller (2014), and Pan (2021). Hudson attempted to position parametric design in reference to the integration of algorithmic modelling with the reset of the design process. The dramatic changes in government policy and technological advancements shifted the balance of roles, and the position of the computational designer is shifting from an auxiliary role to one that is crucial for almost all aspects of the design process. In his review of the benefits and limitations of Buro Happold's Venue Performance Rating toolkit, Hines (2021) highlights the shift towards the early application of data-driven design in RIBA Stages 1 -3 and the increasing importance of professionals working in this field. In terms of its more general application in architecture, at Foster+Partners this role is defined as beneficial for improving our knowledge and understanding of design, the automation of repetitive tasks, and a push towards the limits of design through optimisation (Michlatos and Abdel-Rahman, 2021).

The primary uses of similar methodologies in practice can be found in several important design aspects. The use of computational tools for generative design is aimed at developing designs within a set of constraints and can help with the exploration of a wide range of design possibilities. The work of Nagy (2017) presents a link between the parametric generation of layouts and machine learning, while Mukkavaara and Sandberg (2020) systematise this process into a generative framework within the context of residential blocks. Machine learning has been traditionally used to simulate and analyse design performance in terms of crowd flow (Borja-Borja et al., 2018; Brocklehurst et al., 2005; Luque Sánchez et al., 2020; Mahmood et al., 2017; Song and Sheng, 2020; Torrey, 2010) and structural optimisation in the context of stadiums ("Modern Stadium Design Inspired by Topology Optimization," 2021). In this PhD, the primary objective of these processes is to set benchmarks and optimise the design based on quantitative data. Other applications of similar approaches in practice include the exploration of the possibility of design customisation to address specific environmental pressures, traffic management and predictive maintenance. In reference to Hudson's (2008) definition, those tasks can be summarised as translation and rationalisation, variation, analysis and testing, optimisation, communication, and fabrication.

### 5.2.3 Role of the human/designer in machine learning-supplemented design workflows and its limitations

Along with the rapid technological development and the re-evaluation of the entire design and construction model, the role of the human designer is transforming under significant economical and methodological pressures. As described by Culley et al. (2015) and Thompson et al. (1998), technology is the driving force behind stadium design evolution and the design workflows are inextricably connected to this progression. In reference to the work of the previous researchers and the findings from this thesis, the primary tasks that the human designer faces in the machine learning-supplemented workflows are the definition of the initial problem and constrains, the selection and curation of the datasets for training of the models, the selection and fine-tunning of machine learning algorithms, the interpretation and validation of the analysis results, and ultimately – the decision of whether a design solution will be implemented or not. Those tasks shift a large amount of the design process towards automation and increase human importance in the preliminary and post-design supervision related tasks.

The core of the importance of the role of the human designer in this new environment can be found in the process of quantification and translation of design properties and requirements into a machine learning-accessible format. Humans are still more capable to consider ethical and aesthetic aspects within social and cultural context. The human mind is still more adaptable to unforeseen circumstances and unique requirements that are difficult to translate as data. Finally, the designers are still better equipped to interpret the complex legislative environment into complex designs and to integrate machine learning solutions within overall design output.

The limitations of the human input in machine learning-supplemented workflows are strongly related to the designer's strengths. The potential for bias in the curation of the training datasets is extensively reviewed in literature. The human designer has limited ability and time to analyse the vast set of data generated by AI and machine learning. This problem is further amplified by the complexity of the models themselves – the designer is faced with the difficult task to understand both the design problem and the tool that proposes design solutions. This dialectic relationship has the potential to result in beneficial counterintuitive design solutions proposed by machine learning that are omitted because the designer could not fully comprehend the process or solution.

## 5.3 Application

### 5.3.1 Predesign - RIBA Stages 0 – 2

Since their introduction in 2013, the two preliminary phases in the RIBA (2020) PoW have set the goals of defining the strategic aspects of the project and consequently preparing the client's brief based on their strategic vision. The circular nature of the RIBA PoW is aimed at informing strategic decisions at these stages based on data and the lessons learned from previous projects. In this way, based on existing performance and legal data it is possible to question whether a construction project is the best solution to a client's problem (RIBA, 2020). This analysis, in conjunction with the identification of the project risks and an estimate of the budget, form the basis for the business case for a project. Further, RIBA Stage 0 is the phase during which all the design strategies defined by the PoW are considered, and most beneficial solutions are taken forward. This phase is led by the client, while the architect and other specialists can be brought in as consultants.

At RIBA Stage 1 the design brief takes the conclusions from the previous phase and structures them towards a document that lists all the client's considerations as design parameters. This stage is aimed primarily at preparing the information required for the design to begin, to test whether the client's spatial requirements fit the site, and whether the budget will be sufficient to achieve the client's aspirations (RIBA, 2020). This stage sets the foundations for the procurement method selected, the structure of the delivery team, and the information delivery system that is to be followed throughout the entire design and delivery process.

In the context of stadium design, those two project phases are defined in the work of John and Sheard (2013, 2007; 1997, 1994). As appendices to the multiple editions of their stadium design manual, these authors always include a client briefing guide that includes all the primary design considerations such as legal and administrative concerns, project objectives and parameters, site considerations, and those relating to spectators, participants, media, management, general services, and ancillary areas (John et al., 2013). This document aims to facilitate the work of both client and architect, and in terms of this research sets the basic reference for parameters to be included in the parametric and machine learning models.

### 5.3.2 RIBA Stage 0 - Strategic definition

The practice side of this research considers all the aspects highlighted in the RIBA PoW and automates a significant number of the tasks associated with this stage. As the architect's involvement at this phase is limited, the machine learning-supplemented approach can be deployed by the client or, in certain cases, the contractor. With limited technical knowledge, these stakeholders can develop their own understanding of the potential functional distribution in the future design and estimate the potential development of a business case. Based on the grounding in the typological study and the benchmarks developed, the preparation of the client's requirements can originate in the historic performance of previous projects adapted for comparison within the context of the project. With limited knowledge of stadium design this process can inform a general understanding of the financial estimate for a potential project and provide a range for the likely capacities and limits of functional provision, based on the building's footprint. Based on the same data, the preliminary analysis for the potential business case can inform the type of stadium developed – single or multi-functional – and provide a quantified estimate of the performance of those early studies. This phase is critical because the commitment to a project has a high economic and public value, the developer starts spending from the budget even before the project has begun, and the valuable time of design professionals is spent on speculating about projects that could have been easily filtered through an automated process. This information can also support the development of the project team and identify the different programmatic implications associated with the project in terms of specialist design, such as specific commercial or auxiliary facilities.

Another direct application of the machine learning workflows based on the analysis of the parametric model is the appraisal of potential sites. Due to the focus on circulation analysis and optimisation, the workflows enable the automatic audit of any site and its surrounding infrastructure. Rather than investing in an analysis of masterplanning options for a number of sites, the workflows allow the developer to analyse any potential site and estimate its suitability before bringing in any external consultants. This analysis is further enriched through an estimation of maximum capacity and various project risks associated with crowd flow per potential site. Taking this process further, the analysis can be automated to go through every potential site within a specific catchment area and even analyse the potential of merging sites. In addition, the client can explore potential morphologies that fit the site and use the optimisation tool to select the best-performing solutions.

This in turn can contribute to the potential identification of the best route towards construction and help to select the contractors and specialist advisors who will participate in the next stage.

### 5.3.2.1 RIBA Stage 0 Site appraisal - Data creation

The process of site appraisal is based on the requirements set out in the *Green Guide* (Department for Culture, Media and Sport, 2018, 2008) and the *FIFA Safety and Security Regulations* (2011a). The two primary aspects of the data curation for this analysis are the stadium orientation and the safety zones around the venue. The orientation is a critical consideration for this particular building type, due to its natural grass playing field and the requirements for TV broadcast (Department for Culture, Media and Sport, 2008; Fédération Internationale de Football Association, 2011a; John et al., 2013). The playing field requires continuous and balanced solar exposure for all areas to grow evenly and to have similar post-event recovery periods. As with Ancient Greek theatres (Leacroft and Leacroft, 1984), the main stand is orientated with the spectators' backs to the sun so that the quality of view for the holders of the more expensive tickets and TV broadcast is not impeded by glare from the setting sun (Fédération Internationale de Football Association, 2011a). There is no specific legal requirement for this design feature, but the research takes FIFA's recommendation for the range between -75° to +15° on the North-South axis (Fédération Internationale de Football Association, 2011a). For designs in the Southern hemisphere those values are reversed.

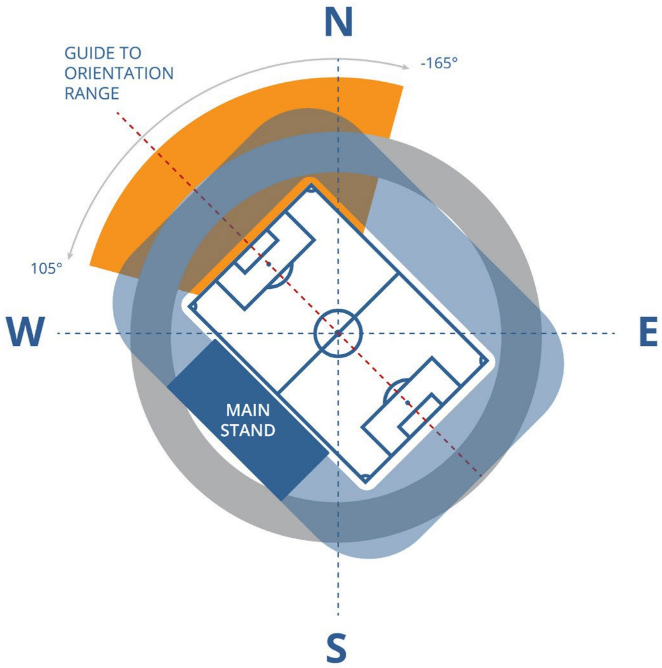



*Figure 5.3. Northern hemisphere stadium orientation (Fédération Internationale de Football Association, 2011b)*

The second element that defines the suitability of a given site is the external circulation. The *Green Guide* (Department for Culture, Media and Sport, 2008) identifies six circulation zones. In terms of site appraisal, the most important areas are the masterplan exterior, Zone Ex, the unsecured buffer, Zone 5, and the first area after security checks, Zone 4. The crowd flow in Zones

Ex and 5 is unmanaged, but spectators must be able to circumnavigate the territory, while spectators are segregated by seat and stand position in Zone 4.

The task of identifying site suitability is a classification problem that results in a set of solutions that have a higher or lower likelihood of belonging to a well-performing group. The required steps for a member of the client's team to start the site appraisal process are to load the parametric model and reference the masterplan entry points, the intended centre of playing field location, and the site outline.

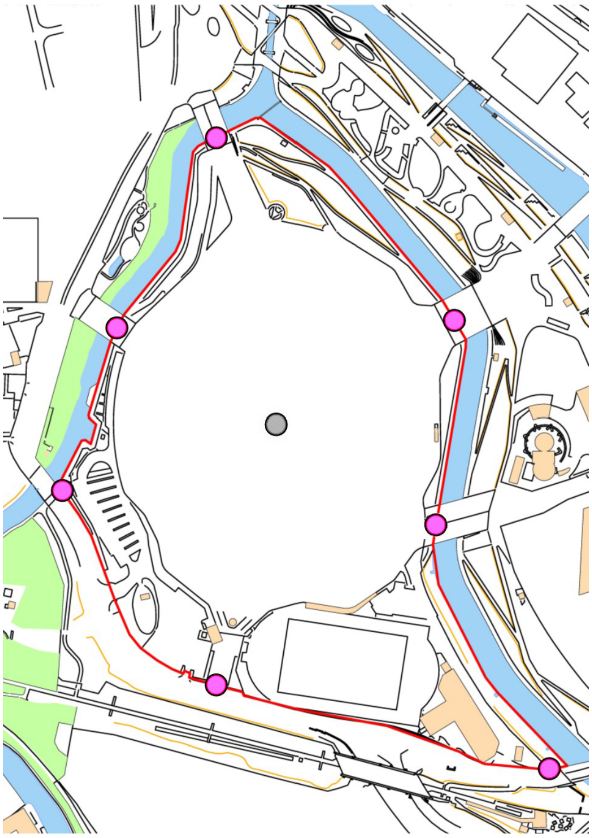


*Figure 5.4. Site of London Stadium by Populous Zone 4 entry points indicated in magenta (Milev, 2022)*

A practical example for this analysis is the review of the site of the London Stadium. The venue is located in a park and surrounded by a river. The simulation takes into account two additional entry points to the original design on the south and west, and the venue was initially designed as an 80,000-seat Olympic stadium.

*Table 5.1. Table showing RIBA Stage 0 site appraisal inputs*

| Features | Data | Input |
|---|---|---|
| Centre of playing field | longitude, latitude | 537658.0,184062.0 |
| Entry point locations | longitude, latitude | 537895.6,183737.1<br>537601.8,183815.0<br>537503.2,184153.6<br>537554.5,184257.2<br>537597.8,184333.8<br>537830.0,184159.4<br>537812.6,183970.3 |

### 5.3.2.2 RIBA Stage 0 Site appraisal - Data processing

The parametric model is based on the relationship between the centre of the pitch and the location of the entry points from Zone 5 to Zone 4. The model generates a design solution for each stadium morphology, each type of event, each 10° rotation, and a 10,000-seat incremental capacity. The circulation distance is measured from the masterplan entry points to the security screening at the border between Zones 4 and 3 as a direct distance. The internal paths to the seats are measured as shortest path based on the internal circulation grid and bowl circulation. Each seat is then assigned a total value of the accumulated distance to the closest Zone 4 entry point. The output of the data processing is a point cloud with seat to exit values and a Boolean value of whether the solution fits within the site area. The masterplanning of Zone 4 is based on the division of the area into smaller sections based on the number of entry points. The overall aim is to have an equal distribution of those areas per sub-zone and a difference as small as possible in the areas so that they can host equal number of spectators on the way to the stadium gates. The resulting dataset contains distances from seat to masterplan entry, Zone 4 area distribution, capacity, and an indication of whether the site outline and masterplan entry points allow enough space for the allocation of areas for safety zones.

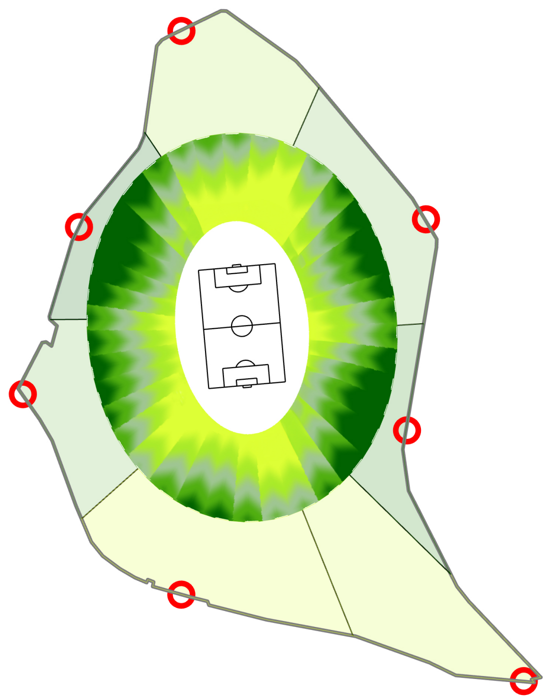


*Figure 5.5. Simulation of elliptic morphology with proximity of seat to masterplan exit and external circulation zones areas represented through green saturation*

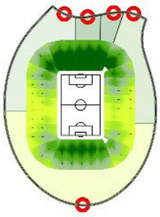
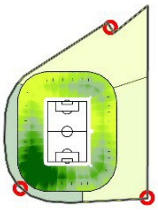
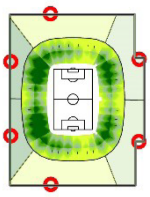
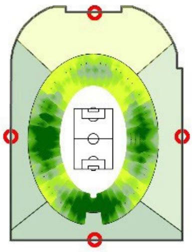
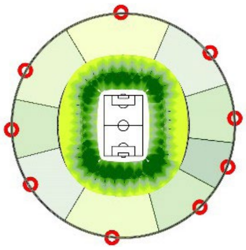
The model is intended to give a general idea about the suitability of the site and includes neither complex stadium bowl configurations nor programmatic features. Limiting the representation of the cases in this way offers a faster processing time and minimises the need for specialist knowledge about the design.

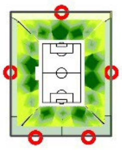
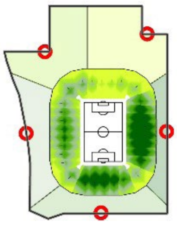
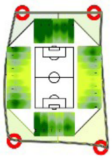
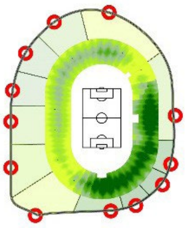
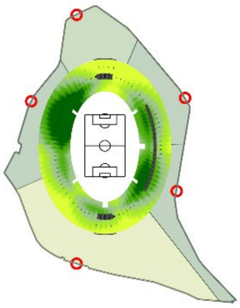
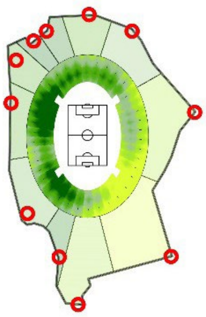
*Table 5.2. RIBA Stage 0 site appraisal NN training data entry example*

| **Analysis feature** | **Data type** | **Example** |
|---|---|---|
| Distance seat to masterplan entry | Average | 288.19m |
| Masterplan areas | Difference between largest and smallest external areas | 12335.35 sqm |
| Feasibility | Safety zones fit on site | 1 |
| Capacity | Total number of seats minus gangways | 91,972 seats |
| Morphology type | Shape grammar identifier | Type 6 |

### 5.3.2.3 *RIBA Stage 0 Site appraisal – Benchmarks*

*Table 5.3. RIBA Stage 0 site appraisal case study benchmarks*

| Case Study | Visualisation | Distance seat to masterplan entry | Masterplan areas difference | Feasibility | Capacity | Morphology type |
|---|---|---|---|---|---|---|
| Allianz Arena, Munich |  | 283.70m | 10435.994392 | 1 | 75024 | 2 |
| Allianz Riviera, Nice |  | 210.00m | 13953.241197 | 1 | 36178 | 2 |
| Arena da Amazônia, Manaus |  | 272.19m | 4396.694962 | 1 | 44300 | 7 |
| Olympiastadion, Berlin |  | 214.88m | 8248.377129 | 1 | 74667 | 6 |
| Mane Garrincha, Brasilia |  | 288.83m | 5568.024409 | 1 | 72788 | 7 |

| | | | | | | |
|---|---|---|---|---|---|---|
| heinEnergie Stadion, Cologne |  | 120.56m | 1051.026012 | 1 | 50000 | 1 |
| Merkur Spiel-Arena, Dusseldorf |  | 257.56m | 9682.936941 | 1 | 54600 | 2 |
| Craven Cottage, London |  | 137.61m | 3052.645073 | 1 | 22384 | 1 |
| Kyiv Olympic Stadium |  | 193.75m | 4746.088091 | 1 | 70050 | 4 |
| London Stadium |  | 288.19m | 12094.365711 | 1 | 80000 | 6 |
| Tokyo Olympic Stadium |  | 284.63m | 10435.994392 | 1 | 68089 | 6 |

### 5.3.2.4 RIBA Stage 0 Site appraisal - Data analysis and output

The data analysis is based on the supervised machine learning workflow, where a subset from the design space is extracted, labelled, and used to train a neural network from the Accord framework within Lunchbox in Grasshopper. The labelling is an automated process based on voting (Burka et al., 2022) in which each feature is assigned a label, the labels are added up, and groups are assigned a primary label. The reason that the NN was selected is the number of features analysed and the efficiency and integration with Grasshopper of the algorithm. Another reason for its selection is that the pretrained NN model can be used for the analysis of other cases utilising the same analytical categories.

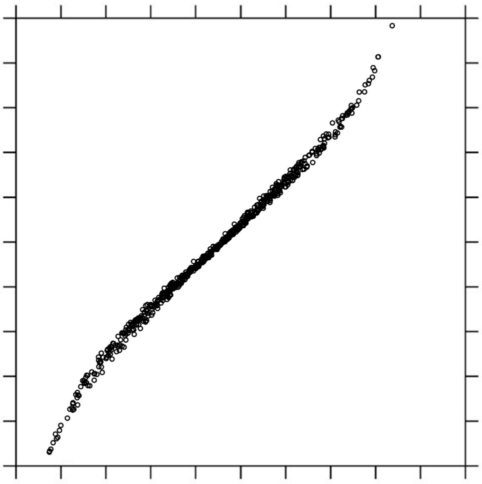


*Figure 5.6. Neural Network validation plot based on 326 training inputs*

Once the cases are processed, the model outputs a set of feasible ranges in terms of capacity, orientation, and morphology. Those are then validated by comparing them with the benchmarks. The model also outputs the best-performing cases and highlights the best-performing solutions per objective. This information can be further expanded to include functions, programmatic provisions, and the amount and type of elements to be assembled on site.

*Table 5.4. Neural Network hyperparameters and prediction rate*

| | |
|---|---|
| Learning rate | 0.1 |
| Network topology | Feedforward network |
| Type of hidden layers | Fully connected |
| Number of epochs | 500 |
| Sigmoid's Alpha | 1.0 |
| Number input neurons | 3 |
| Number of hidden neurons | 2 |
| Activation function | BipolarSigmoidFunction |
| Optimizer | ResilientBackpropagation |
| Momentum | 0.0 |
| Chromosomes | 100 |
| Regularization | False |
| Adjustment | 10 |
| Bayesian alpha | 0.1 |
| Bayesian beta | 1.0 |
| | |
| Accuracy of prediction | 85.12% |

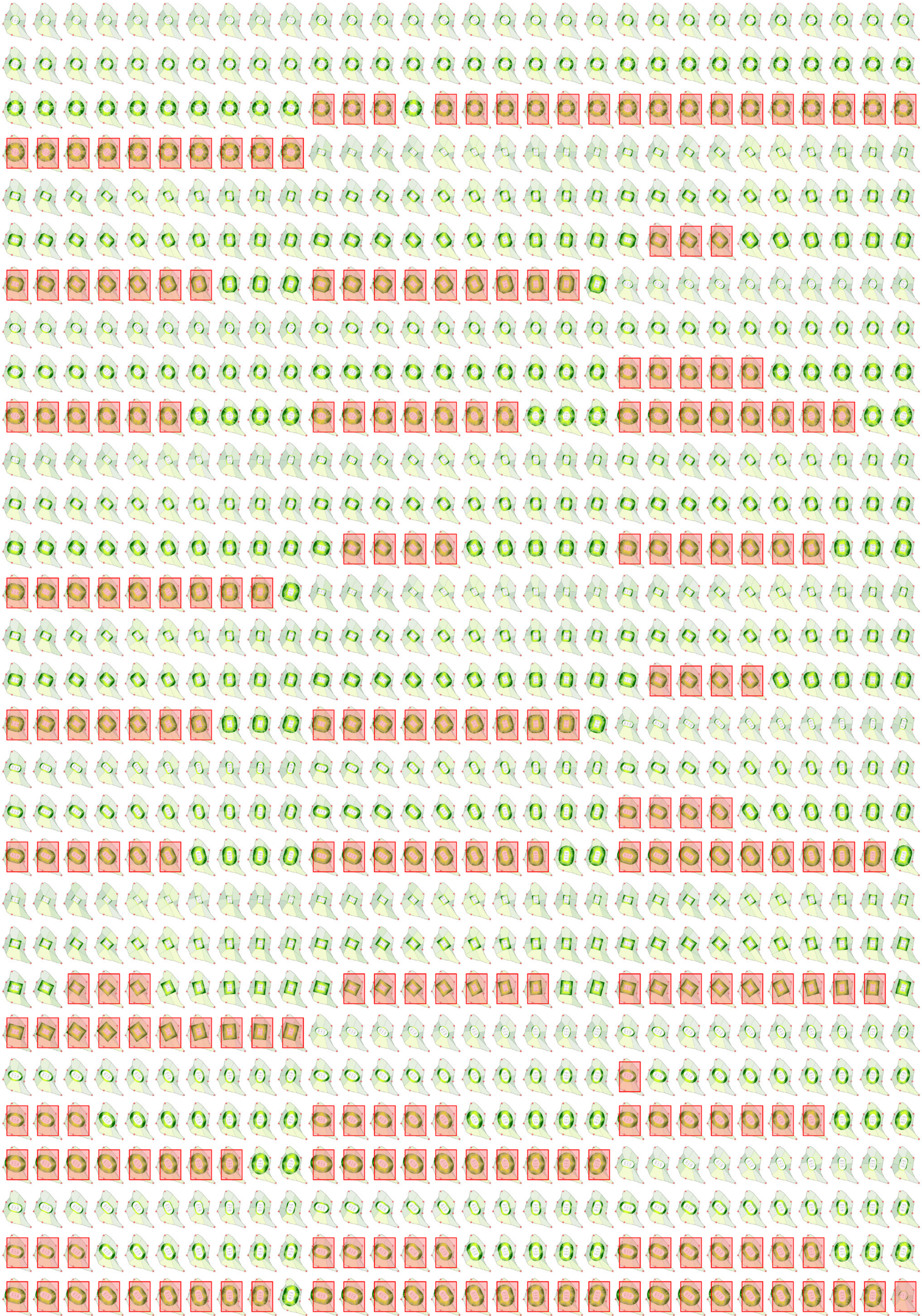


*Figure 5.7. RIBA Stage 0 site appraisal identification of unfeasible solutions*

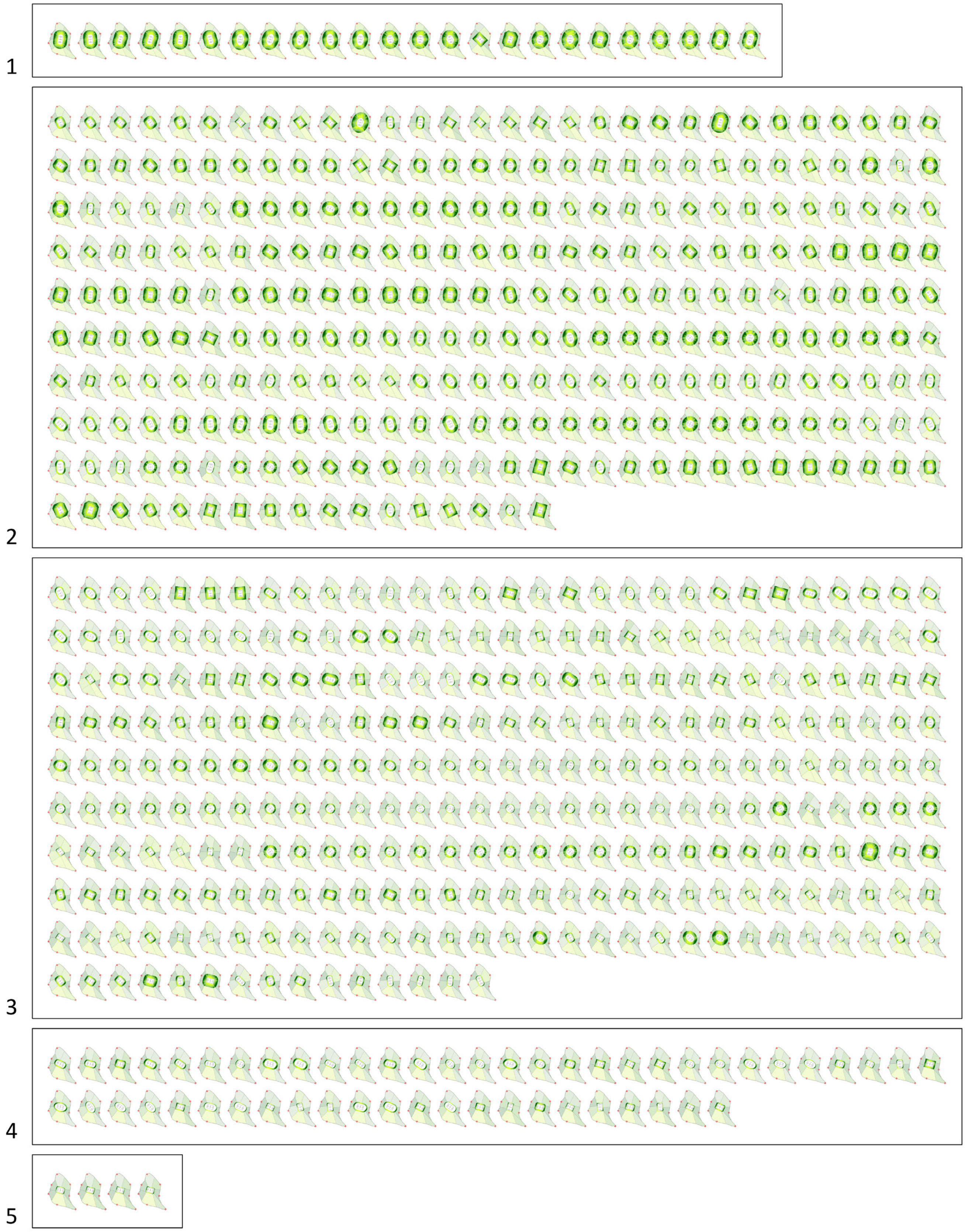


*Figure 5.8. RIBA Stage 0 site appraisal potential solutions classification*

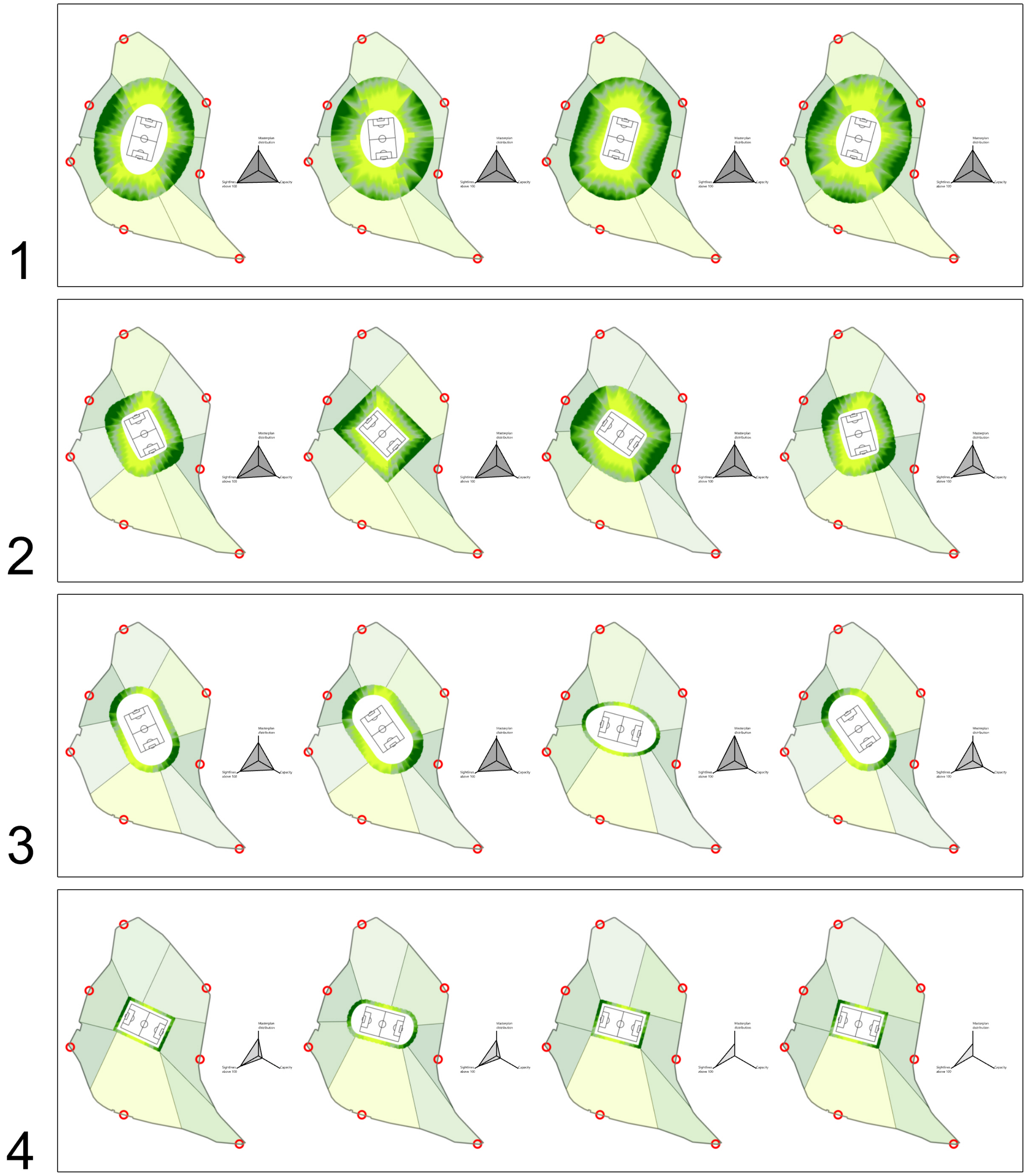



*Figure 5.9. RIBA Stage 0 site appraisal sample of potential solutions with performance indicator*

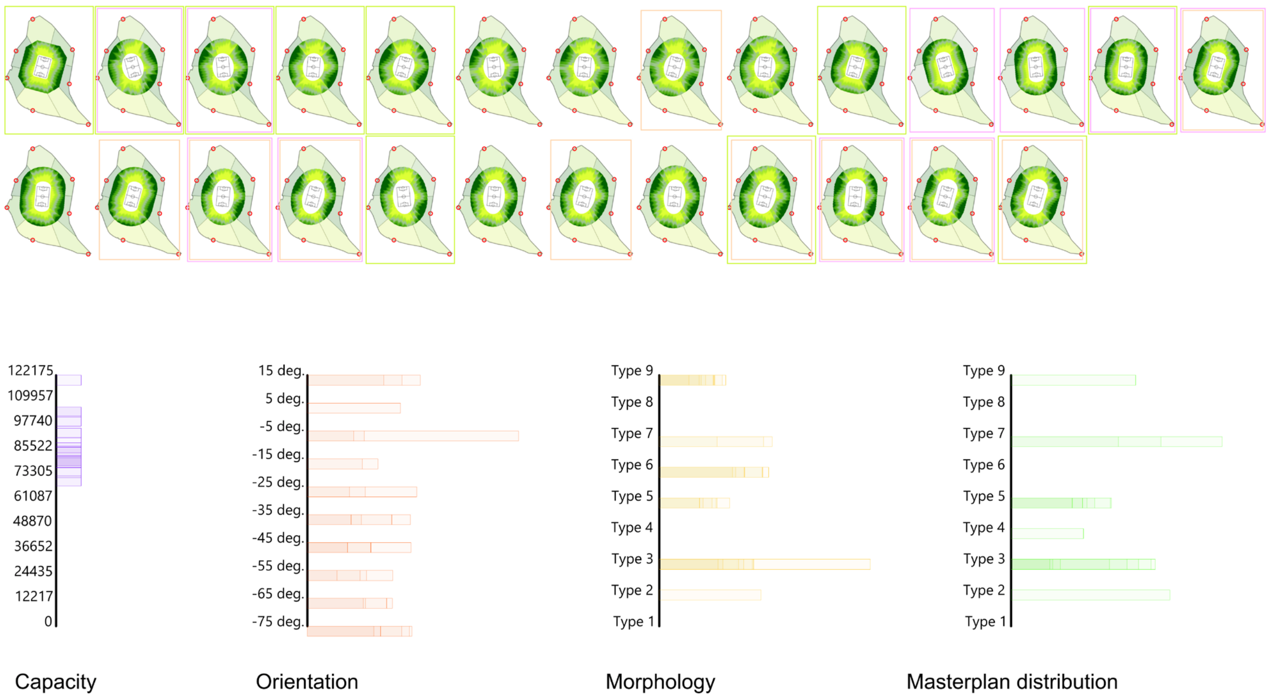



*Figure 5.10. Best performing group objective breakdown – the best performing solutions pe objective are highlighted with the objective colour and the ranges performance is visualised per category, note that oval morphologies perform best*

### 5.3.4 RIBA Stage 0 - Construction strategy

The development of a construction strategy can benefit greatly from automating the site appraisal process without the need to bring in external consultants. With a background knowledge of the off-site production capacity in the specific area, the workflows described enable the 'best fit' methods for a specific site to be identified and give an idea of the potential morphologies. Bringing these estimates at this early stage in the procurement process allows the design to be channelled towards a specific target and limits the number of options that need to be considered in the later design stages. This process challenges the overall function of the architect and streamlines a major section of the background work that must be done before embarking on a project of this scale. The potential advantage of bringing in the manufacturers and contractors at this early stage is that it also directs the design towards fabrication, which results in limiting the design to specific morphologies and solutions. Departing from the identification of the primary construction and structural systems during the phase of site appraisal by the developer, these workflows will significantly reduce the workload of all the disciplines involved in design and will also shorten the overall timeline of the project, thus reducing time and cost.

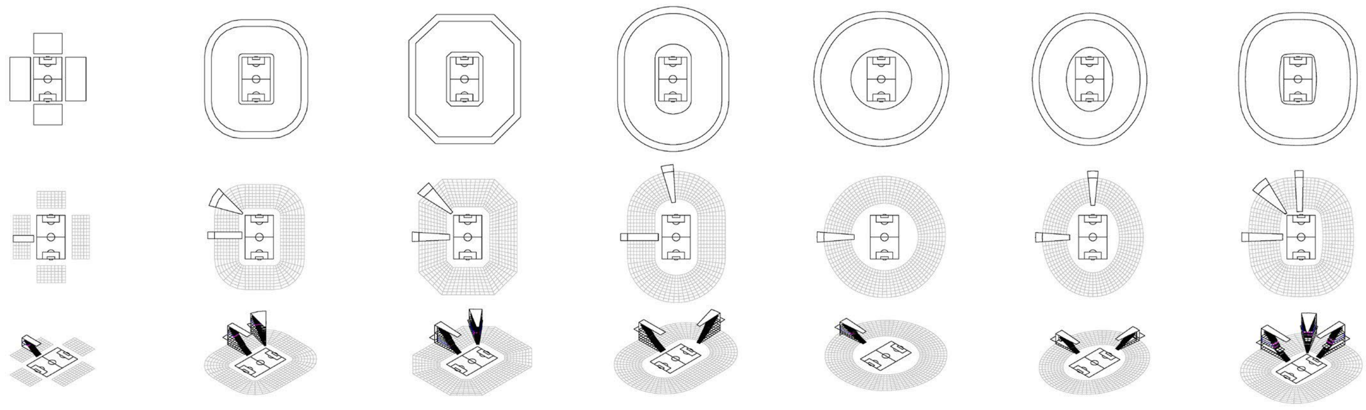



*Figure 5.11. Morphologies included in machine learning supplemented analysis*

The extended machine leaning model can accommodate additional design considerations such as the amount of material used per morphology, the provision of comfort (i.e. a roof), and noise and light pollution. This data-rich tool and set of workflows have the potential of streamlining this part of the design process and reduce the overall cost of the design and construction. Developers are not the only potential users of this tool and the workflows; they can be also used by design professionals to estimate whether or not to commit to a project based on site feasibility and client expectations, by local and national regulating bodies to estimate the level of compliance of potential projects with legal frameworks, by sports organisations to identify potential infrastructure development strategies, and by fan organisations to cross-check information released in the media against physical site conditions.

#### 5.3.3.1 RIBA Stage 0 Construction strategy - Data creation

The initial phases of this analytical pipeline require the same information as a site appraisal: masterplan entry points, location of the centre of playing field, the site outline. The complexity of the sections of the parametric model that simulate the design performance are also similar. There are no multi-tier seating bowl units, and the circulation is based on exits at the top of the gangways. The reason for this simplified approach is again because the tool is intended to be used by professionals with limited or no knowledge of stadium design who work for the client team, sports, fan, or legislation organisations, or any other type of government or municipal body. The focus of the simulation is primarily on morphology – different configurations of the basic stadium design are simulated on site across multiple orientations and capacities. The output data measures the number, length, area, and volume of the basic structural typologies identified by Culley and Pascoe (2015; 2009)– columns to support the floor slabs and seating bowl, precast concrete sections for the floor slabs, building footprint for the basement / ground slab, roof and façade areas. The aim of producing the data is to provide an indication of the approximate amount of building elements each feasible morphology and thus inform the range of the budget required.

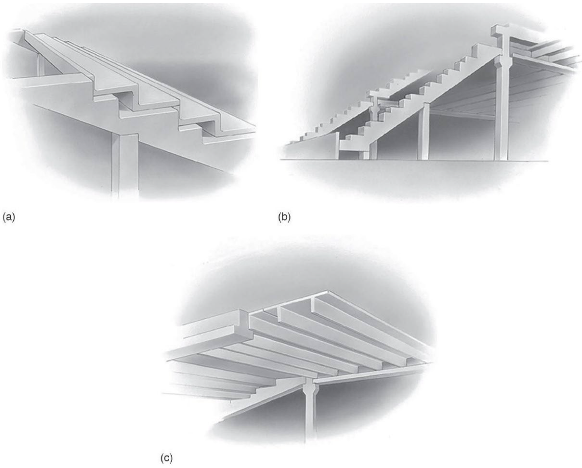



*Figure 5.12. (a) Precast seating risers with raker-beam supports. (b) Raker beams supported by precast columns. (c) Precast concrete double tee floor systems (Courtesy of the Precast/Prestressed Concrete Institute (PCI) cited in (Culley et al., 2015)*

*Table 5.5. RIBA Stage 0 construction strategy inputs*

| **Features** | **Data** | **Input** |
|---|---|---|
| Centre of playing field | longitude, latitude | 537658.0,184062.0 |
| Entry point locations | longitude, latitude | 537895.6,183737.1<br>537601.8,183815.0<br>537503.2,184153.6<br>537554.5,184257.2<br>537597.8,184333.8<br>537830.0,184159.4<br>537812.6,183970.3 |
| Morphology (optional) | Type | 0-9 |
| Capacity (optional) | Number of seats | 10 000 – 90 000 |

#### 5.3.3.2 RIBA Stage 0 Construction strategy - Data processing

The simulation with the parametric model follows the same process of generation, measurement, documentation, and validation as the site feasibility. The primary difference is found in the amount of information produced – the dataset of the feasibility study is based around distances from each individual seat to the masterplan exit points while this pipeline is aimed at identifying elements that are repeated. As a result, the output of the simulation is a list of the types and number of elements that have the same or similar spatial characteristics.

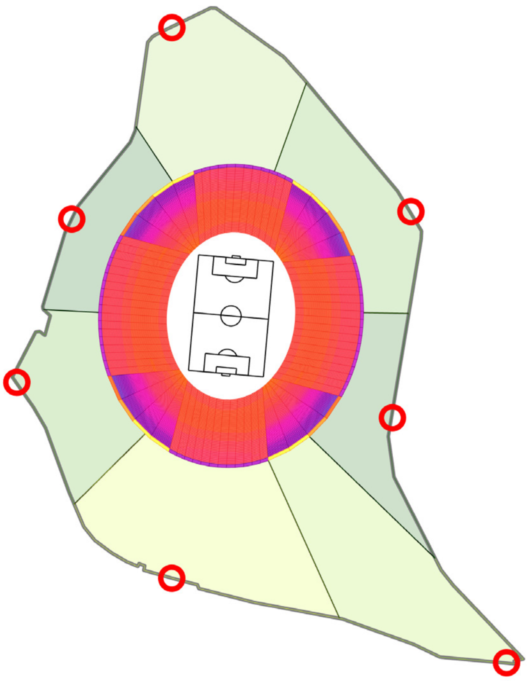


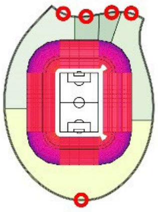
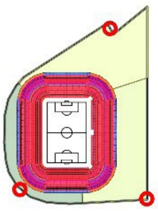
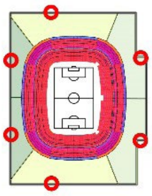
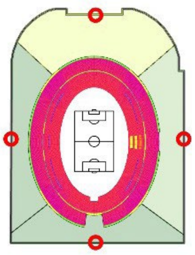
*Figure 5.13. Stadium seating bowl modular sections distribution, colours based on unit width*

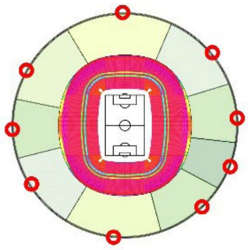
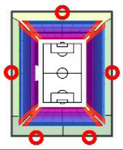
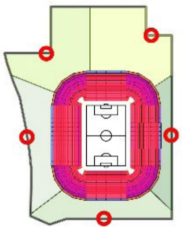
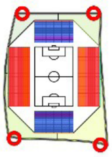
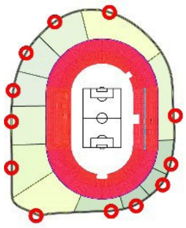
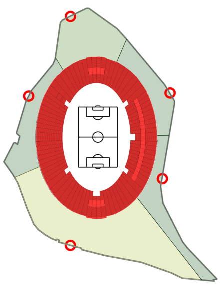
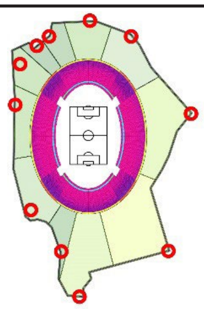
*Table 5.6. RIBA Stage 0 construction strategy NN training data entry example*

| **Analysis feature** | **Data type** | **Example** |
|---|---|---|
| Roof area | Building footprint minus oculus | 49812.69 sqm |
| Building footprint | Area | 57049.83 sqm |
| Number of seating bowl element types | Number of seating bowl horizontal element groups by area | 15 |
| Total number of elements | Total number of seating bowl horizontal elements | 6,840 |
| Capacity | Number of seats | 85,228 |

### 5.3.3.3 RIBA Stage 0 Construction strategy - Benchmarks

*Table 5.7. RIBA Stage 0 construction strategy case study benchmarks*

| **Case Study** | **Visualisation** | **Footprint** | **Element types** | **Elements total** | **Capacity** |
|---|---|---|---|---|---|
| Allianz Arena, Munich |  | 52936.04 | 16 | 10387 | 75024 |
| Allianz Riviera, Nice |  | 37887.41 | 21 | 4336 | 36178 |
| Arena da Amazônia, Manaus |  | 33255.44 | 22 | 4892 | 44300 |
| Olympiastadion, Berlin |  | 34087.42 | 22 | 4892 | 74667 |

| | | | | | |
|---|---|---|---|---|---|
| Mane Garrincha, Brasilia |  | 52936.04 | 16 | 10387 | 72788 |
| RheinEnergieStadio, Cologne |  | 38047.78 | 33 | 5848 | 50000 |
| Merkur Spiel-Arena, Dusseldorf |  | 38898.00 | 16 | 3164 | 54600 |
| Craven Cottage, London |  | 28186.29 | 4 | 3984 | 22384 |
| Kyiv Olympic Stadium |  | 48312.24 | 21 | 2800 | 70050 |
| London Stadium |  | 52217.88 | 23 | 5388 | 80000 |
| Tokyo Olympic Stadium |  | 47294.94 | 14 | 4844 | 68089 |

#### 5.3.3.5 *RIBA Stage 0 Construction strategy - Data analysis and output*

As with the site feasibility analysis, the problem can be defined as one of classifying the simulations based on their performances. The NN model is again trained on labelled extracts from the design space. Each performance metric is recorded as a preliminary label, and through voting (Burka et al., 2022) the labels are assembled into a primary label for each case. The model then outputs a range of possible design solutions and the number and type of repeating structural elements. The output is both numeric and visualised through colour mapping of the performance of the designs. Following this process, the client and the other stakeholder teams have an indication of how much of each structural system will be required and can approach manufacturers for quotes and timeframes for design and delivery. This approach is extremely useful for this part of the procurement team, as it reduces the requirement for specialist participation. The pretrained NN model can be used for the analysis of other cases that utilise the same analytical categories.

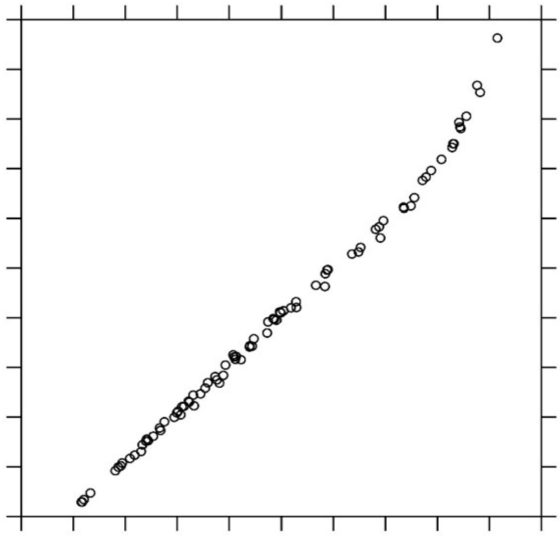


*Figure 5.14. Neural Network validation plot based on 230 training inputs*

*Table 5.8. Neural Network hyperparameters and prediction rate*

| | |
|---|---|
| Learning rate | 0.1 |
| Network topology | Feedforward network |
| Type of hidden layers | Fully connected |
| Number of epochs | 1000 |
| Sigmoid's Alpha | 1.0 |
| Number input neurons | 5 |
| Number of hidden neurons | 7 |
| Activation function | BipolarSigmoidFunction |
| Optimizer | ResilientBackpropagation |
| Momentum | 0.0 |
| Chromosomes | 100 |
| Regularization | False |
| Adjustment | 10 |
| Bayesian alpha | 0.1 |
| Bayesian beta | 1.0 |
| | |
| Accuracy of prediction | 88.75% |

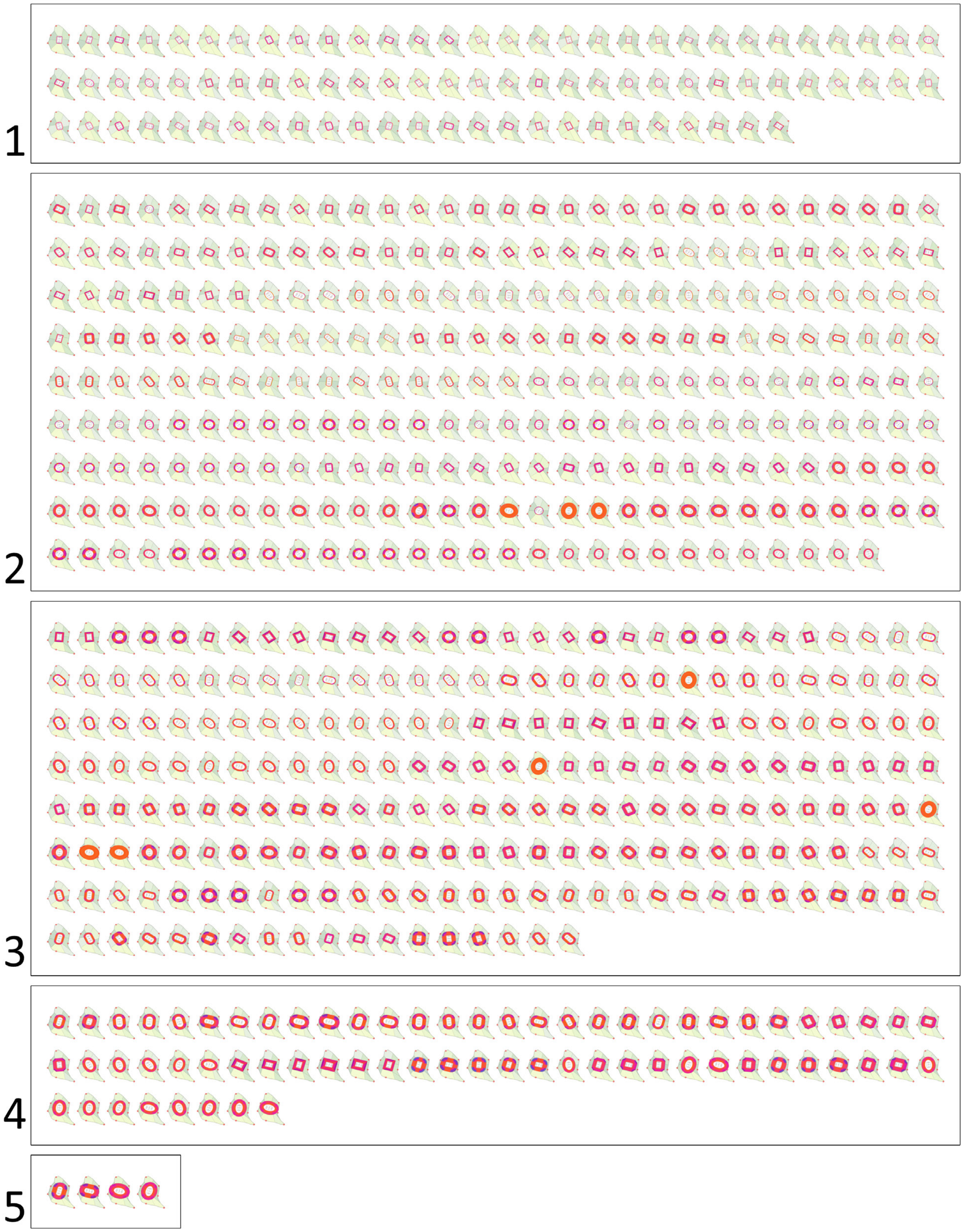



*Figure 5.15. RIBA Stage 0 construction strategy potential solutions classification*

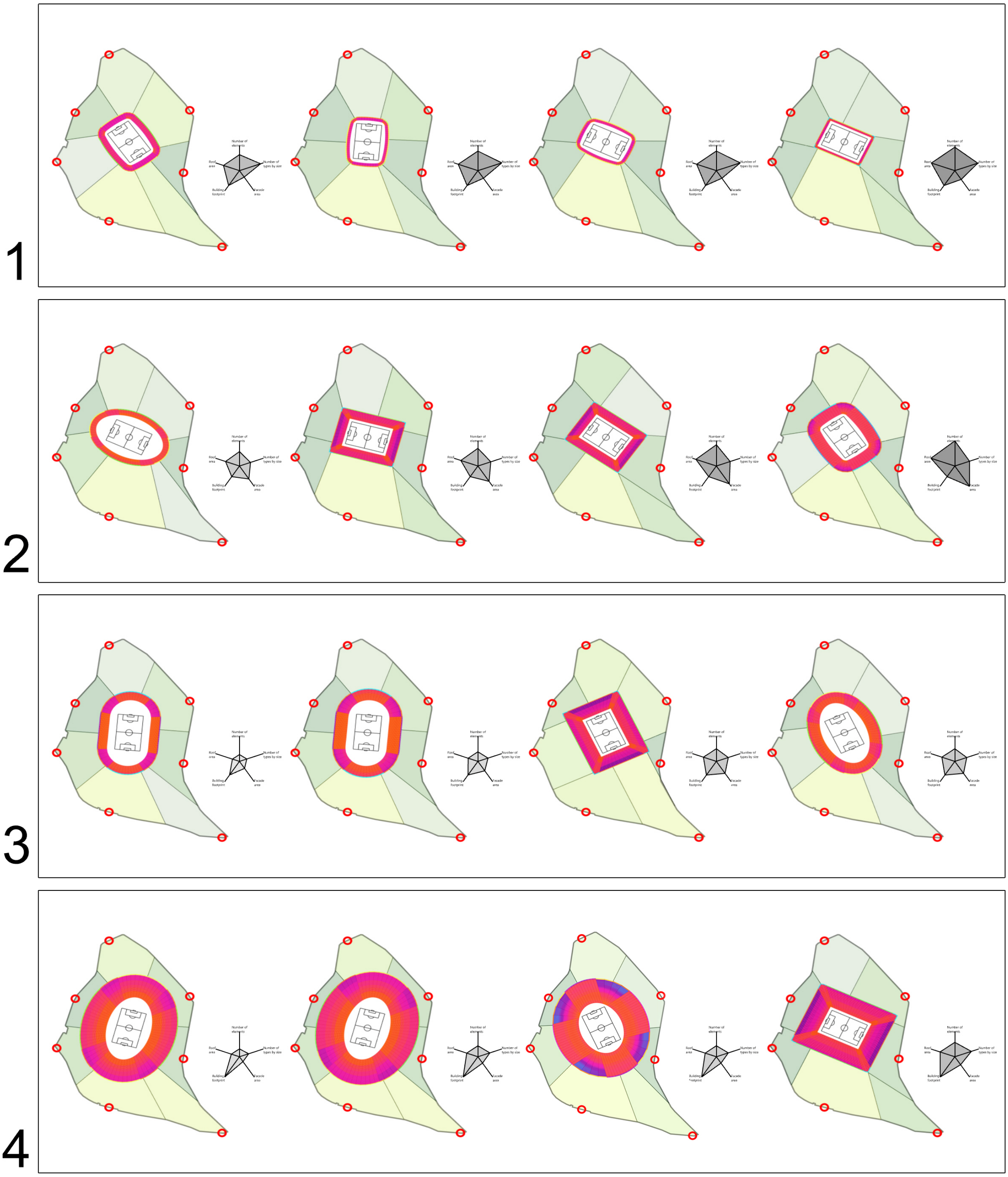



*Figure 5.16. RIBA Stage 0 construction strategy sample of potential solutions with performance indicator*

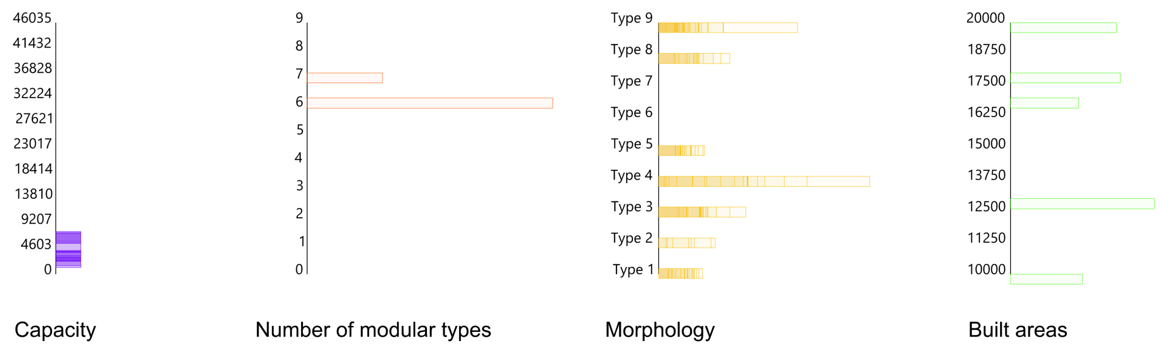



*Figure 5.18. RIBA Stage 0 construction strategy best performing cases and statistical analysis of performance distribution*

### 5.3.4 RIBA Stage 1 - Preparation and briefing

The first stage at which the architect is directly involved is essential in terms of establishing the direction for the development of the project. The preparation of the client's brief is a combination of the client's requirements, site considerations, and the architect's experience of working on similar projects (Sinclair, 2011). The machine learning-supplemented workflows are directly influential for a better understanding of the project's spatial requirements on site and the overall aspiration for building quality through the data-rich environment of the parametric simulation. In the hands of the architect, this tool allows for efficient and extensive feasibility study analysis. Nevertheless, the simplicity of the tool allows the rest of the stakeholders to verify the conclusions presented by the architect and to provide alternative solutions which the architect might have not considered. The tool enables an analysis of the crowd flow options available for the specific site, the overall volume of the stadium, and the properties of the structural system deployed. This in turn offers a detailed estimate of the structural system which will potentially be selected and the potential implications of this selection for the overall budget.

In terms of the stadium briefing guide by John and Sheard (John et al., 2013) the tool can contribute to an understanding the scale of the project, the associated timescale for delivery, and revenue potential. It can inform the potential and risks associated with the circulation, access, and safety aspects of the masterplan in the vicinity of the stadium and its effect on the existing urban fabric. Subsequently, the workflows inform decisions about the functions of the venue and the potential for hosting different events in relation to existing site conditions. The tool can also be used to explore different options for the programmatic distribution, both inside and outside the venue.

Analysis based on limited site information such as site surveys provides a simple but potentially very useful foundation for developing feasibility studies for capacity, masterplan safety zone and access distances, and for evaluating different programmatic concepts. The ability to bring benchmarks from previous projects sets the foundation for the development of the project programme and execution plan as these are developed based on the same design characteristics. Subsequently, in the hands of experienced designers and quantity surveyors, these workflows can directly contribute to the development of the project budget and streamline the costing exercise towards best fit between construction strategy, site, and client expectations. The capacity and access analysis will be useful for the work of sports and government organisations as they directly inform the provision of the sports-related facilities and their relationship to the rest of the venue. In terms of safety, stakeholders such as police and fire departments can contribute to the project even before the start of the design process, by estimating risk factors.

The workflows described allow for informed morphological feasibility analysis aimed at fabrication. Developing a design space for repeating prefabricated elements is the core of the model and enables a direct estimate to be made of the number of elements that repeat and elements that are of the same type but with specific customisation. This process also offers clarity on the setup of the project team, Responsibility Matrix, and other professional services. In turn, these aspects result in the setting up of information exchanges which directly influence the contract and the overall procurement strategy.

#### 5.3.4.1 RIBA Stage 1 Defining the brief - Data creation

The involvement of an architect or specialist designer brings an additional set of information to the model that cannot be easily interpreted by people with no background knowledge of stadium design. This research works on the assumption that specialist stadium designers can estimate the capacities that fit within a given site and those individuals require much more detailed information about the range of solutions that can be built. The input to the parametric model for this stage again requires a definition of the Zone 4 entry points, the centre of the playing field, and the site outline. In addition to these parameters, for this level of design development the model requires a range of potential capacities that best reflect the site potential and basic seating bowl configuration.

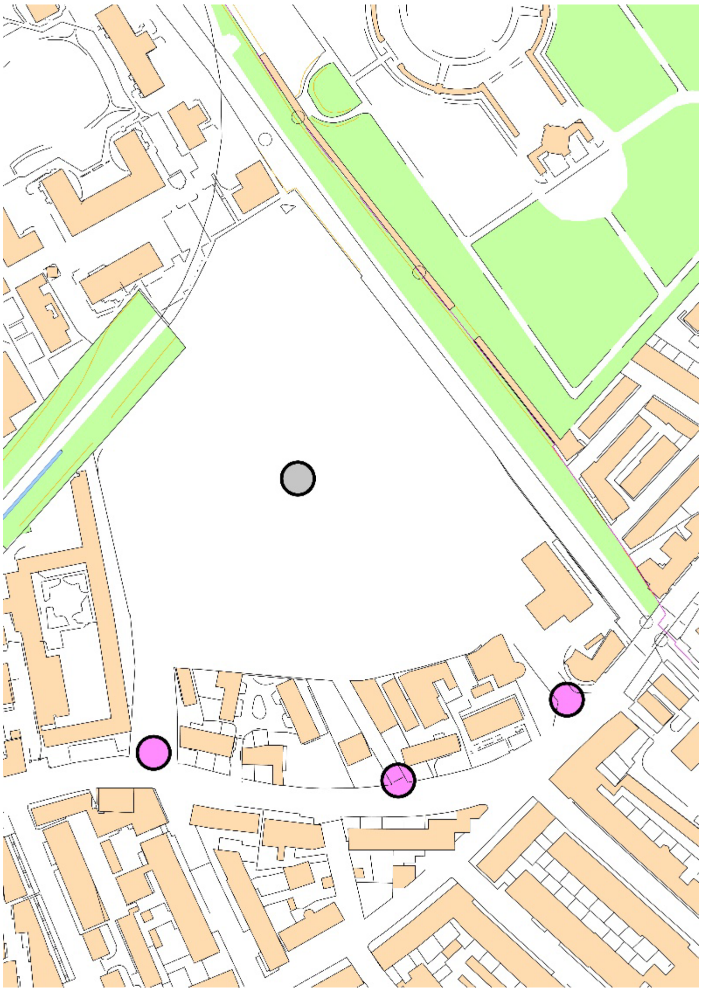


*Figure 5.19. Site of Stamford Bridge Stadium with centre of playing field and Zone 4 entry points indicated in magenta (Milev, 2022)*

The model can further incorporate client aspirations and other external factors from the site's external ecosystem such as right to light, physical obstacles, or presence of other design restrictions. The size limit allows detailed investigation of the multi-tier configurations within the capacity range and a more detailed overview of the ingress and egress circulation within the stadium itself and to the masterplan exit points. As this stage does not involve the actual design, this information is critical to defining the brief and the creation of a stepping-stone towards the data-driven development of options in the next procurement stage.

An example of the data creation and analysis for this level of design development is the theoretical redevelopment of the Stamford Bridge stadium in west London. As described in Chapter 3, the site is located in a dense urban area and there are a number of additional design restrictions, such as right to light for the buildings on the south side. The model simulates a set of potential design solutions based on shifting the centre of the playing field to the west and lowering the field of play below ground level to satisfy existing planning conditions. The design space reduction is based on the design objectives described above. This workflow has significant potential for practical application because it goes systematically through many design solutions and can potentially identify solutions that would have been omitted in a traditional site analysis.

*Table 5.9. RIBA Stage 1 inputs*

| Features | Data | Input |
|---|---|---|
| Centre of playing field | longitude, latitude | 525712.973366,177411.095059 |
| Entry point locations | longitude, latitude | 525860.75,177280.55<br>525765.84,177236.66<br>525626.05,177249.12 |
| Capacities | Range | 35 000 – 45 000 |
| Number of tiers | Range | 1 – 3 |

### 5.3.4.2 RIBA Stage 1 Defining the brief - Data processing

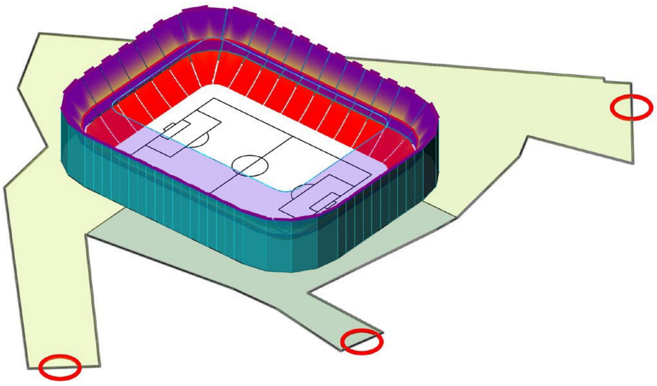


Figure 5.20. RIBA Stage 1 analytical model in the context of theoretical Stamford Bridge redevelopment with offset of centre of playing field to the west

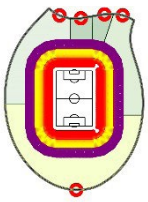
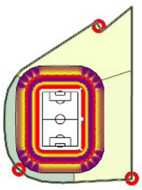
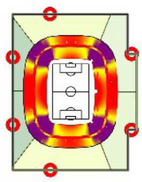
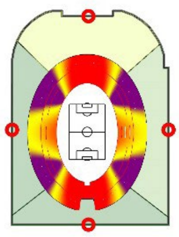
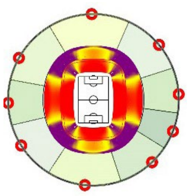
Following the input of the parameters that define the design space, the parametric model generates a series of simulations of design solutions with all possible orientations, tier configurations, and capacities within the specific ranges. The resulting circulation distances are measured and added up as a direct distance from the masterplan entry points to stadium entry, the vertical distance from the ground level to the exit point on top of each tier, and from the seat to gangway to the exit above. It is important to note that the model at this stage does not include vomitories, as these add additional complexity that will be required later on in the design process. On the other hand, the model includes the simulation of the viewing quality as 'C' value, which enables a specialist designer to select the morphologies that fit the site based on this metric. Further on, the model again includes area calculations for the circulation areas in Zone 5; the aim is again to ensure that the distribution of crowd flow is as even as possible towards the stadium entry points.

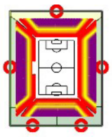
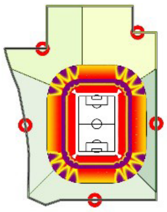
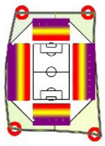
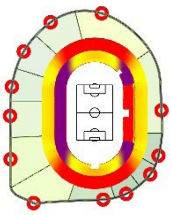
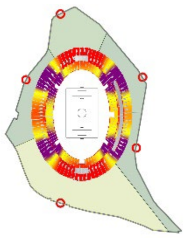
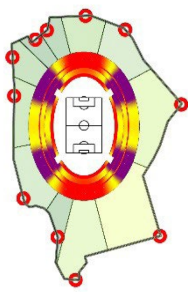
Table 5.10. RIBA Stage 1 NN training data entry example

| Analysis feature | Data type | Example |
|---|---|---|
| Distance seat to masterplan entry | Average | 216.45m |
| High quality seats | Percentage of seats with 'C' value above 120 | 18.46% |
| Masterplan areas | Difference between largest and smallest external areas | 12335.35 sqm |
| Building footprint | Building area | 13238.87sqm |
| Capacity | Total number of seats minus gangways | 30756 seats |
| Number of element types | Number seating bowl horizontal element groups by area | 6 |
| Total number of elements | Total number of seats minus gangways | 540 |
| Morphology type | Shape grammar identifier | Type 6 |

### 5.3.4.3 RIBA Stage 1 Defining the brief - Benchmarks

*Table 5.11. RIBA Stage 1 case study performance benchmarks*

| Case Study | Visualisation | Distance seat to masterplan entry | High quality seats | Masterplan areas m2 | Footprint m2 | Element types | Elements total | Capacity | Morph type |
|---|---|---|---|---|---|---|---|---|---|
| Allianz Arena, Munich |  | 283.70m | 4.30% | 10435.99 | 52936.04 | 16 | 10387 | 75024 | 2 |
| Allianz Riviera, Nice |  | 210.00m | 10.74% | 13953.24 | 37887.41 | 21 | 4336 | 36178 | 2 |
| Arena da Amazônia, Manaus |  | 272.19m | 9.92% | 4396.69 | 33255.44 | 22 | 4892 | 44300 | 7 |
| Olympiastadion, Berlin |  | 214.88m | 19.32% | 8248.37 | 34087.42 | 22 | 4892 | 74667 | 6 |
| Mane Garrincha, Brasilia |  | 288.83m | 4.98% | 5568.02 | 52936.04 | 16 | 10387 | 72788 | 7 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| RheinEnergie Stadio, Cologne |  | 120.56m | 3.51% | 1051.02 | 38047.78 | 33 | 5848 | 50000 | 1 |
| Merkur Spiel-Arena, Dusseldorf |  | 257.56m | 6.62% | 9682.93 | 38898.00 | 16 | 3164 | 54600 | 2 |
| Craven Cottage, London |  | 137.61m | 23.09% | 3052.64 | 28186.29 | 4 | 3984 | 22384 | 1 |
| Kyiv Olympic Stadium |  | 193.75m | 24.96% | 4746.08 | 48312.24 | 21 | 2800 | 70050 | 4 |
| London Stadium |  | 288.19m | 24.84% | 12094.36 | 52217.88 | 23 | 5388 | 80000 | 6 |
| Tokyo Olympic Stadium |  | 284.63m | 25.09% | 10435.99 | 47294.94 | 14 | 4844 | 68089 | 6 |

### *5.3.4.4 RIBA Stage 1 Defining the brief - Data analysis and output*

As with the analysis at Stage 0, identifying the best-performing solutions is essential for this design phase. Again, the problem can be defined as a classification task of grouping the members of the design space based on their performance within the analytical metrics. The data analysis is done through a NN model trained on an extraction from the dataset labelled through voting (Burka et al., 2022). The multi-objective optimisation focuses on identifying the best-performing solutions in terms of total circulation distance distribution for each seat as a point cloud, the best-performing solutions for sightlines as a point cloud, and lowest overall building footprint. The output of the analysis is a set of ranges for the best-performing capacities, tier configuration, Zone 5 distributions, and morphologies. After this, the model outputs areas, volumes, and number of structural elements as a broad indication for the definition of the project budget. Once these are identified, the architect selects the most promising options and takes them forward as a reference in the development of the concept design in the next phase. As with the previous applications, the pretrained NN model can be used for the analysis of other cases with the same analytical categories.

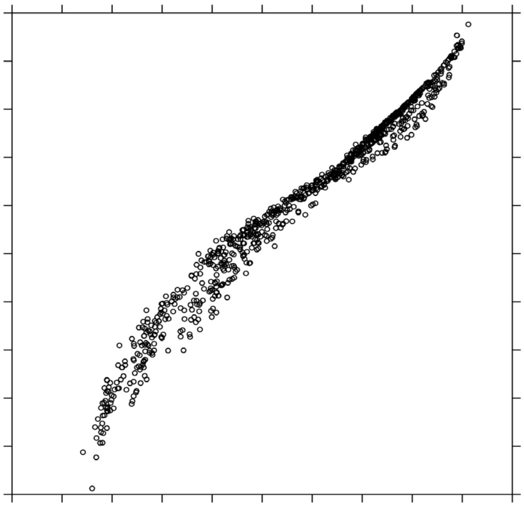


*Figure 5.21. Neural Network validation plot based on 380 training inputs*

*Table 5.12. Neural Network hyperparameters and prediction rate*

| | |
|---|---|
| Learning rate | 0.1 |
| Network topology | Feedforward network |
| Type of hidden layers | Fully connected |
| Number of epochs | 1000 |
| Sigmoid's Alpha | 1.0 |
| Number input neurons | 8 |
| Number of hidden neurons | 2 |
| Activation function | BipolarSigmoidFunction |
| Optimizer | ResilientBackpropagation |
| Momentum | 0.0 |
| Chromosomes | 100 |
| Regularization | False |
| Adjustment | 10 |
| Bayesian alpha | 0.1 |
| Bayesian beta | 1.0 |
| Accuracy of prediction | 92.75% |

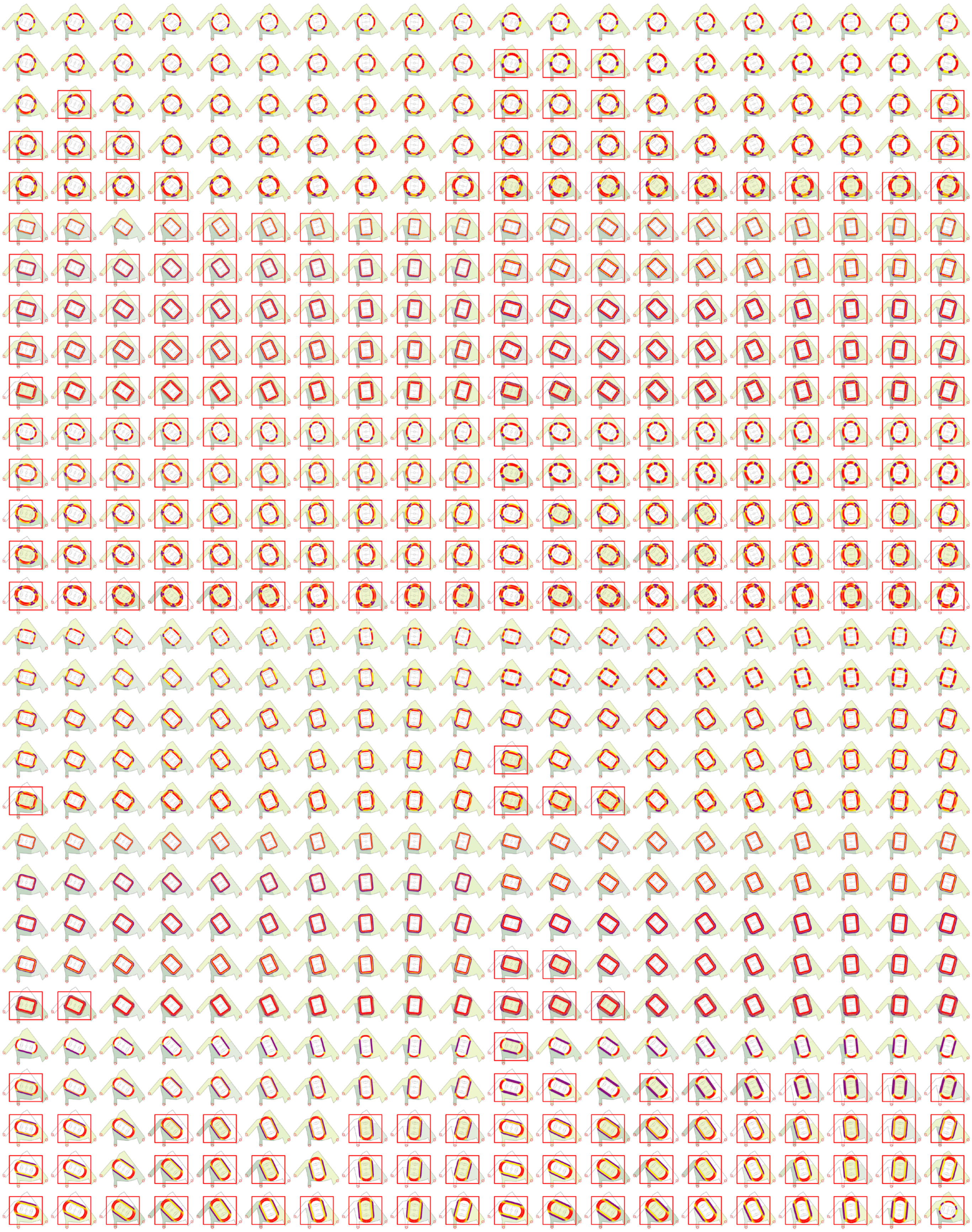


*Figure 5.23. RIBA Stage 1 identification of unfeasible solutions*

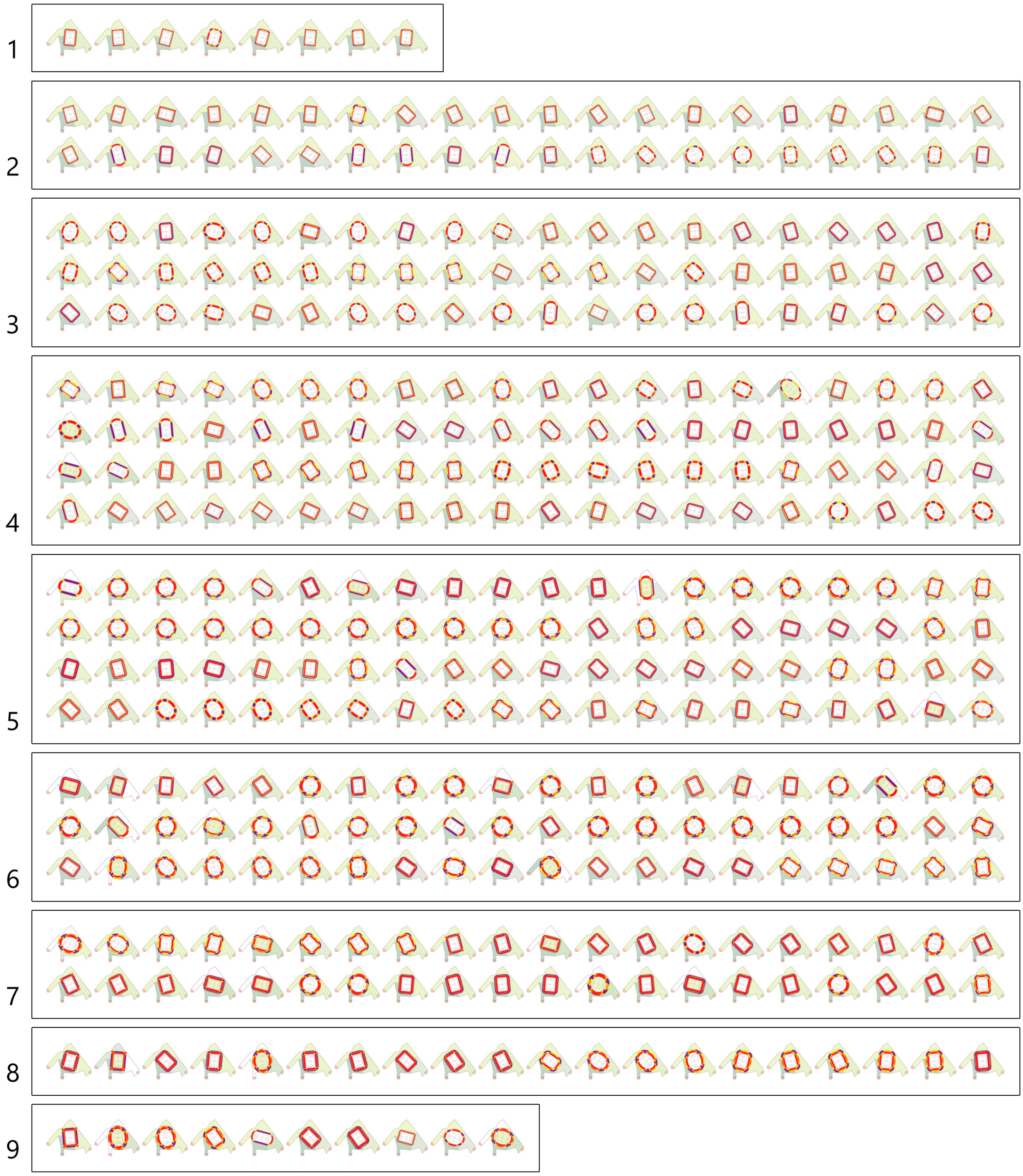



*Figure 5.24. RIBA Stage 1 potential solutions classification*

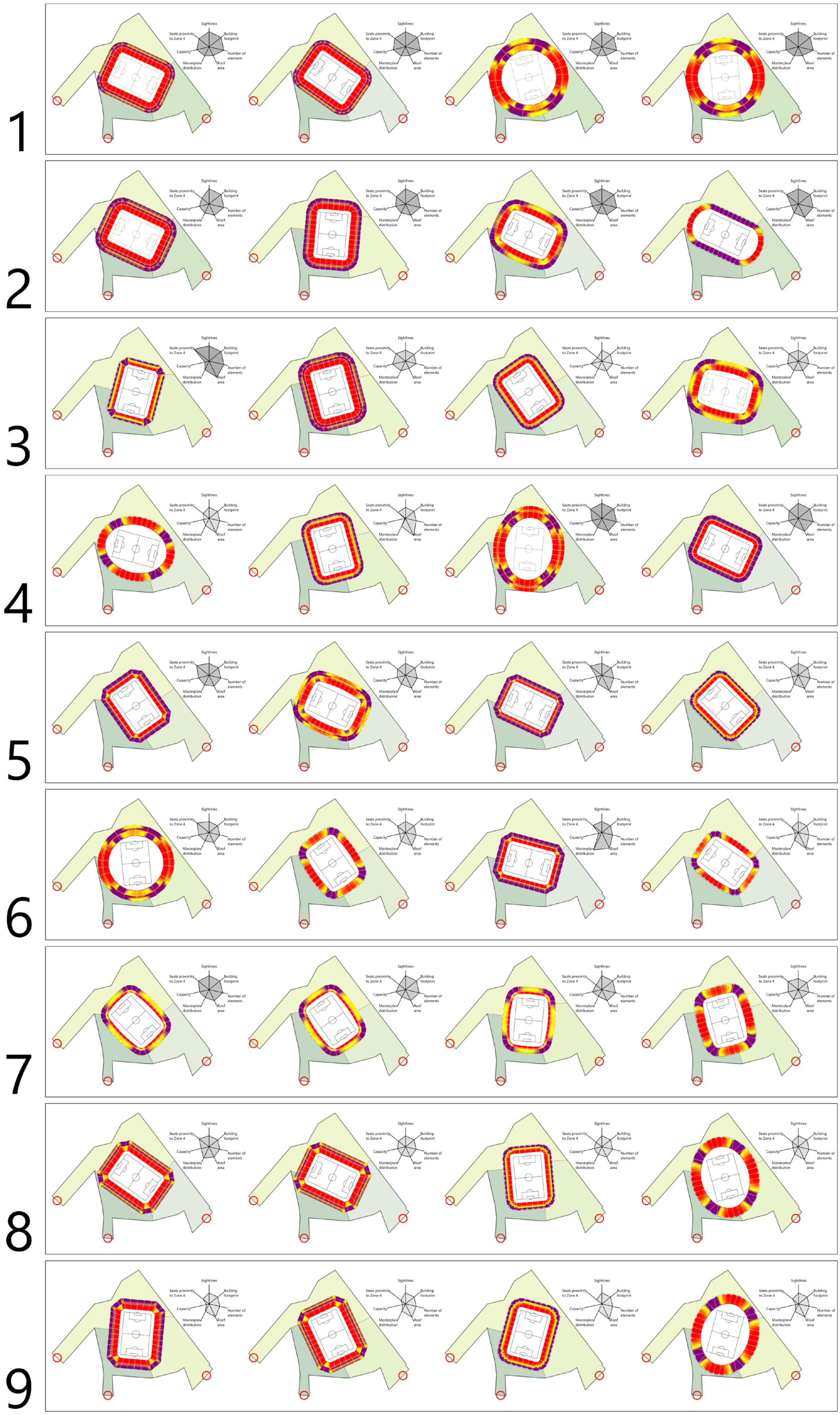



*Figure 5.25. RIBA Stage 1 potential solutions sample*

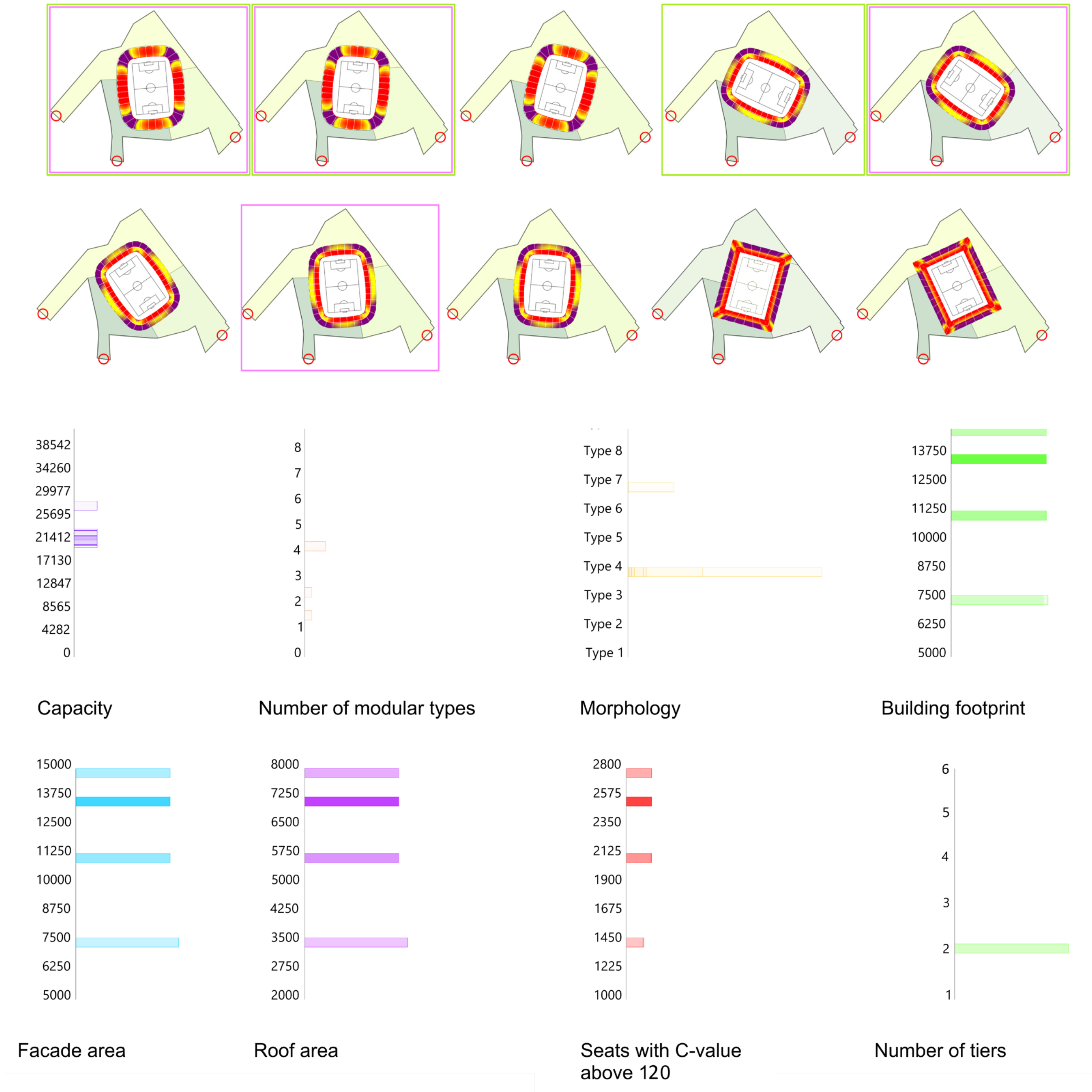



*Figure 5.26. RIBA Stage 1 best performing cases and statistical analysis of performance distribution*

### 5.3.5 Concept design RIBA Stage 2

The concept design stage is the first design phase, and it is aimed at defining the basic architectural and structural properties of the stadium and identifying whether the spatial requirements from the client's brief can fit into the proposed strategy. The primary aim of this phase in the traditional procurement strategy is to demonstrate that the design concept can work with all the spatial adjacencies considered. The focus is the integration of architecture and structure, but this phase also introduces the rest of the design disciplines into the project and explores the basic strategies deployed for resolving the architectural task. Since the introduction of BIM workflows in stadium design this stage is most likely to conclude with a basic 3D digital model and a brief report with various options for the client to choose from. The option selected is then taken into Stage 3, where it is detailed further. Apart from a two-stage design and build contract, the rest of the procurement routes will go to tender in Stage 4.

The workflows described by the practice side of this research create a substantial opportunity to rebalance the workload in the overall delivery process by reducing the work required for this design stage. The two primary directions that this process can take are a reduction of the design process and validation of concepts. In terms of the stage-specific tasks, the primary element is the creation of a number of options that fit the client's brief, the site conditions, and other external pressures from the project's ecosystem. The utilisation of a semi-supervised machine learning pipeline is essential for this aim because the designer needs to refer to existing standards and regulations while at the same time exploring the design space and identifying solutions that may have potentially been omitted. The output of this stage is a digital model that is then transferred to

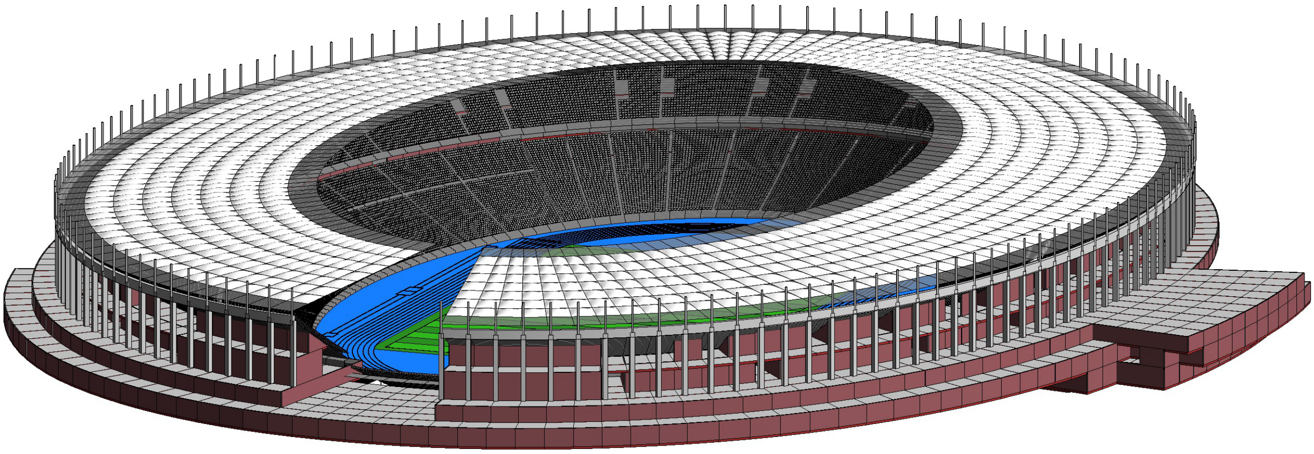


*Figure 5.27. Stage 2 model export to BIM platform (Revit 2023)*

Revit or any other BIM platform for further detailing. The result of this process is a simplification of the design delivery and coordination across the entire design team.

#### 5.3.5.1 RIBA Stage 2 Concept development - Data creation

The identification of the core aims of the design project in the client brief at Stage 1 serves as the basis for the definition of the design space to be explored in this design stage. The overall aim is to develop an architecturally and structurally coordinated concept which performs well across the optimisation objectives. Those aims are further defined by the selection of a design solution with optimal sightlines, shortest exit distances, and functional division of the interior and results in a task that fully utilises the computational capabilities of machine learning. The final output from this process is a set of design options that are presented to the client for selection, and these solutions must be assessed by both professionals and non-professionals.

The development of the design space is based on a narrowed-down selection of capacity range, orientation, location of the centre of the playing field, ranges for the height of the different levels, guidelines for spatial programmatic requirements, morphology and structural grid division. As with the previous phases, the locations of the Zone 4 entry points are critical, but by this phase there should be a general understanding of how the stadium would sit in its urban environment. In terms of circulation, the parametric model includes advanced circulation elements such as vomitories and stairs to concourse levels, internal vertical circulation, stadium gates, podium, and stairs to the podium. The sightlines are defined as the minimum 'C' value for the section of the grandstand. The model, however, is still accessible to both professionals and non-professionals: the architect, engineer, contractor, other design discipline professional, client or any other stakeholders input the basic project characteristics and receive a data-driven representation of the range of potential solutions.

An example of this workflow is the theoretical redevelopment of St Mary's stadium in Southampton, currently a 32,384-seat stadium designed by Miller Partnership in the early 2000s. The site is accessible from the north and the study explores a new design that opens up access routes at two points through the industrial zone on the south.

| Table 5.13. RIBA Stage 1 inputs | | |
|---|---|---|
| **Features** | **Data** | **Input** |
| Centre of playing field | Longitude, Latitude | 403712.868313601043.343081 |
| Entry point locations | Longitude, Latitude | 472925.505404499999.140885<br>331470.982652504764.863425<br>494166.388303691222.969444<br>323762.48649804259.1598 |
| Morphology | Type | 0-9 |
| Capacity | Range | 30,000 – 40,000 |
| Layout | Percentage of overall area range per function | Concourse 25,000sqm – 45,000sqm<br>Commercial 5,000sqm - 15,000sqm<br>Hospitality 5,000sqm -10,000sqm |
| Level height | Range per level | Ground floor 1.5m – 2.5m Level 01 4.5m -6.5m Level 02 8.5m -10.5m |
| Structural grid division | X and Y ranges | X 7.5m – 8.5m Y 8.0m – 9.0m |

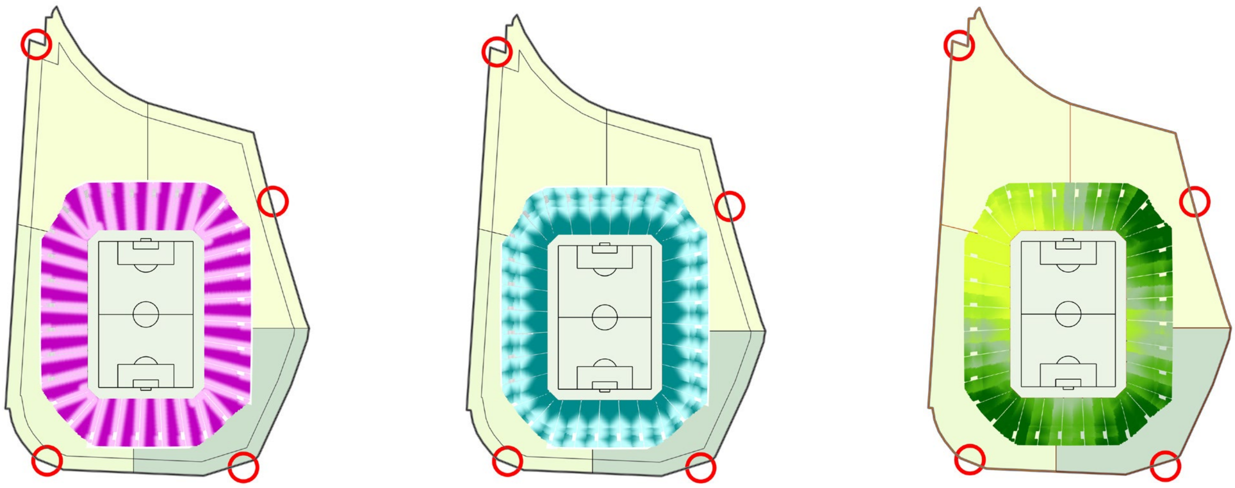


*Figure 5.30. St. Mary's Southampton potential design solution distance seat to gangway, seat to bowl exit, seat to masterplan exit*

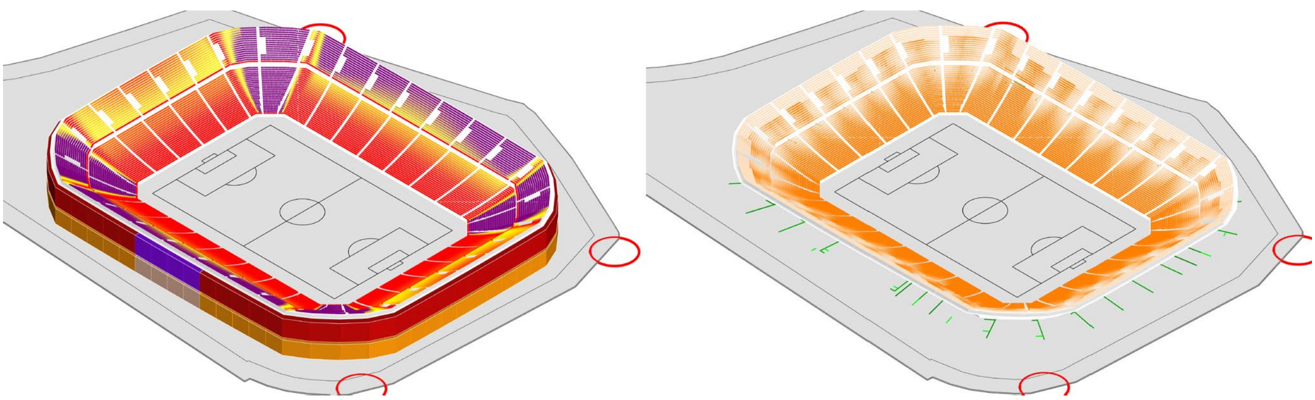


*Figure 5.28. St. Mary's Southampton potential design solution sightline quality and layout (left), distance seat to stadium exit and concourse paths from bowl to stadium exit (right)*

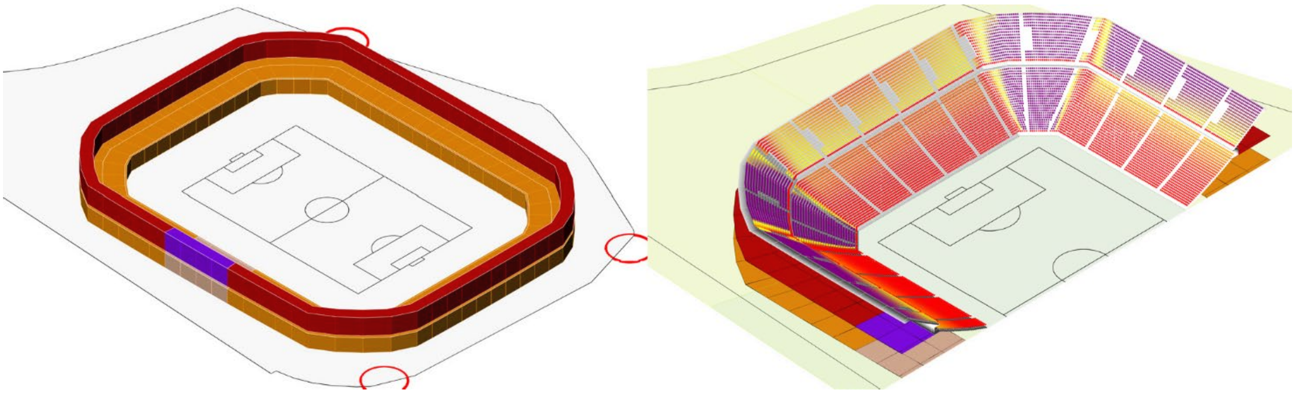


*Figure 5.31. St. Mary's Southampton potential design solution layout (left) distance seat to stadium exit and sightline quality and layout - section (right)*

### 5.3.5.2 RIBA Stage 2 Concept development - Data processing

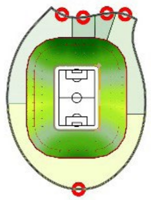
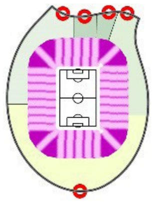
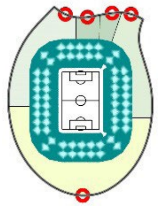
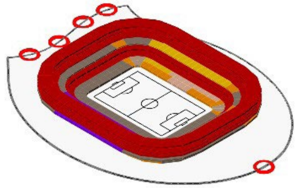
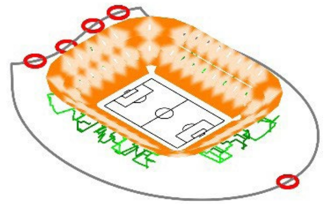
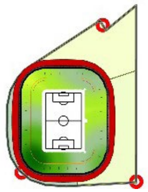
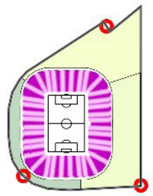
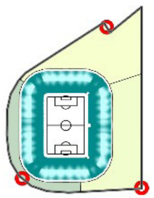
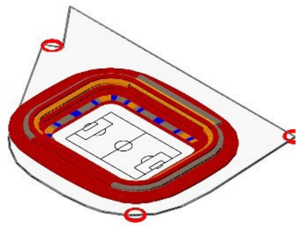
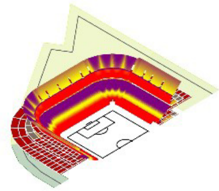
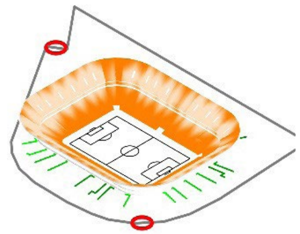
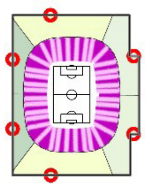
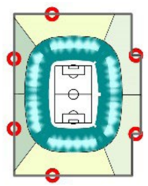
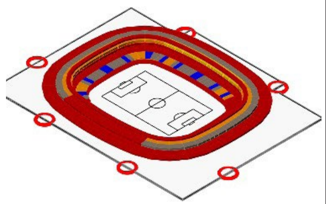
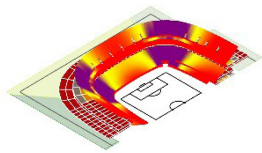
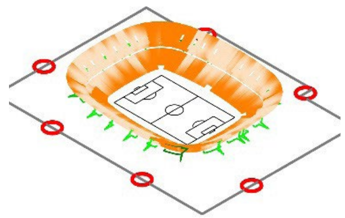
As with the previous workflow examples, the parametric model generates options within the ranges defined by the client. Each option is simulated, and the legally non-compliant solutions are filtered out. The primary difference between this phase and the previous analysis is the level of detail and the range of solutions, as the changes between inputs are much finer and the morphological studies allow asymmetrical seating distribution to be explored, with the aim of maximising the utilisation of the site and the programmatic requirements in the client brief. The performance of the design for each category and metric is then recorded and structured into a dataset.

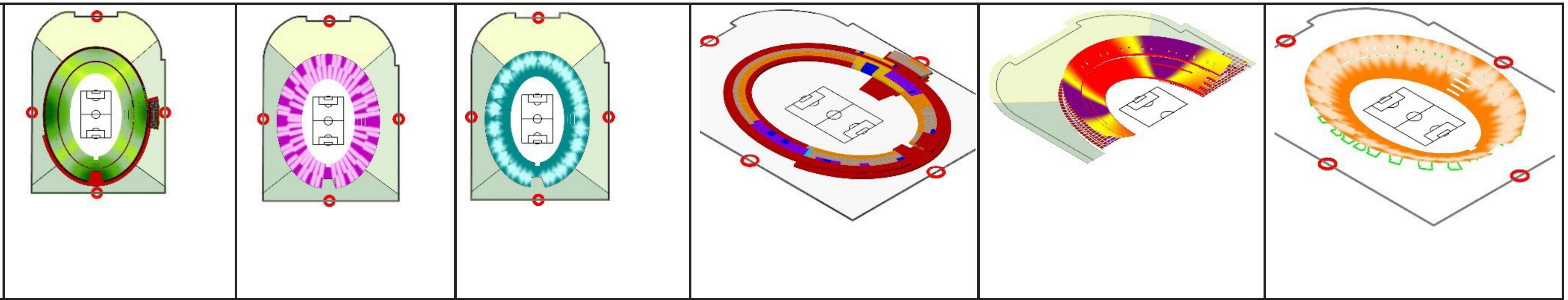
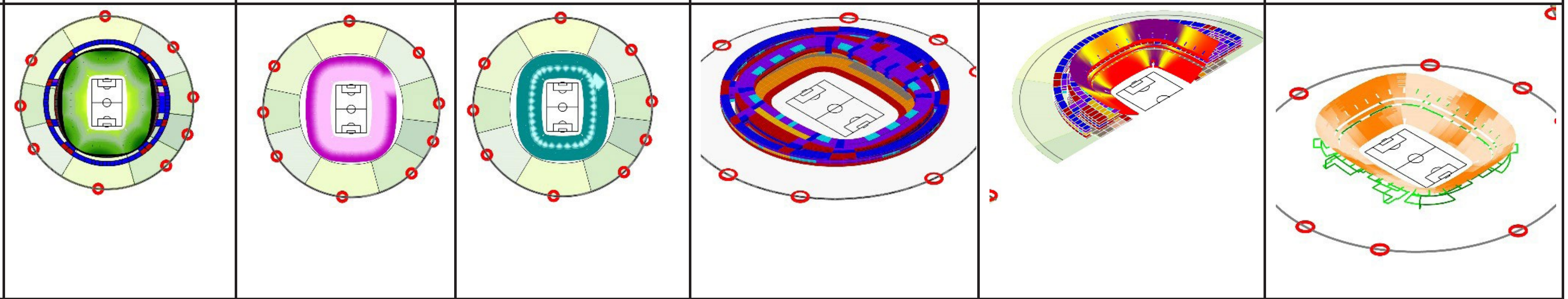
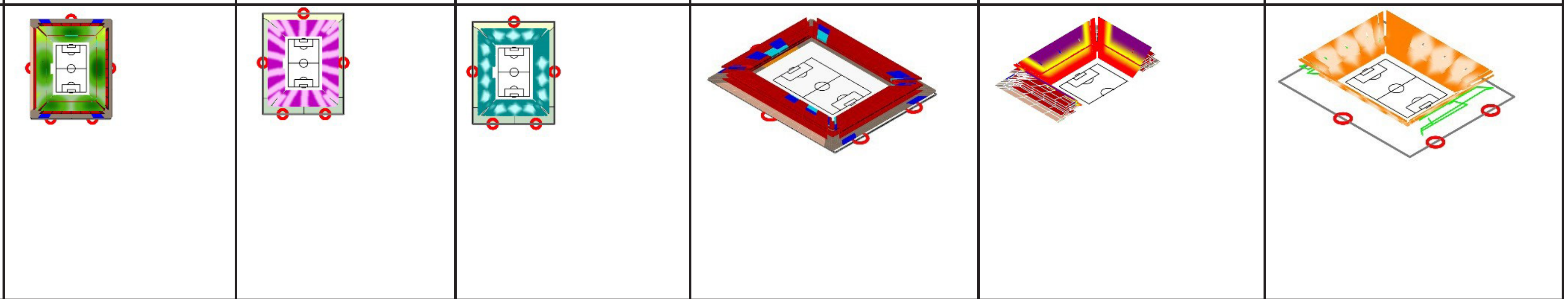
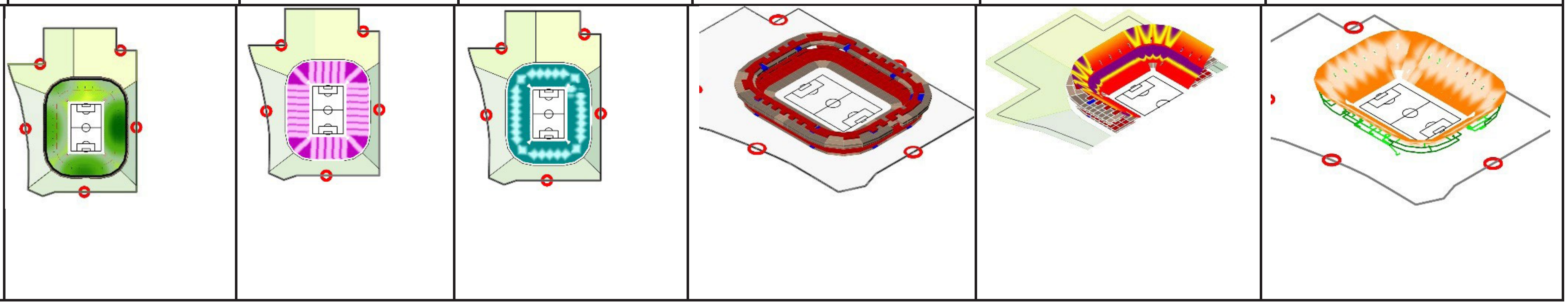
*Table 5.14. RIBA Stage 2 data entry example*

| Analysis category | Analysis feature | Data type | Example |
|---|---|---|---|
| Circulation | Distance seat to gangway | Average | 5.12m |
| | Distance seat to seating bowl exit | Average | 15.34m |
| | Distance seat to stadium exit | Average | 54.23m |
| | Distance seat to masterplan entry | Average | 216.45m |
| Layout | Masterplan areas | Difference between largest and smallest external area | 12335.35 sqm |
| | Layout | Area ratios | Concourse – 40%<br>Commercial – 15%<br>Service – 10%<br>Players – 10% |
| Capacity | Capacity | Total number of seats | 21,372 seats |
| Sightlines | Number of seats with 'C' value above 120 | Number | 4,314 |

## 5.3.5.3 RIBA Stage 2 Concept development – Benchmarks visualisation

*Table 5.15. RIBA Stage 2 case study performance benchmarks visualisations*

| Case Study | Distance seat to Zone 5 | Distance seat to gangway | Distance seat to bowl exit | Layout | Sightlines and Layout | Distance seat to stadium exit |
|---|---|---|---|---|---|---|
| Allianz Arena, Munich |  |  |  |  |  |  |
| Allianz Riviera, Nice |  |  |  |  |  |  |
| Arena da Amazônia, Manaus |  |  |  |  |  |  |

| | |
|---|---|
| Olympiastadion, Berlin |  |
| Mane Garrincha, Brasilia |  |
| RheinEnergieStadio, Cologne |  |
| Merkur Spiel-Arena, Dusseldorf |  |


Craven Cottage, London
Kyiv Olympic Stadium
London Stadium
Tokyo Olympic Stadium

#### 5.3.5.4 RIBA Stage 2 Concept development – Benchmarks numerical

*Table 5.16. RIBA Stage 2 case study performance benchmarks*

| Case Study | Distance seat to gangway | Distance seat to seating bowl exit | Distance seat to stadium exit | Distance seat to masterplan entry | Masterplan areas | Programmatic distribution | Capacity | High quality seats |
|---|---|---|---|---|---|---|---|---|
| Allianz Arena, Munich | 5.53m | 13.51m | 52.19m | 283.70m | 13953.12 | 12.45% 13.66% 2.48% 18.56% | 75024 | 4.30% |
| Allianz Riviera, Nice | 4.05m | 10.17m | 51.94m | 210.00m | 8476.23 | 1.4% 14.1% 2.63% 14.36% | 36178 | 10.74% |
| Arena da Amazônia, Manaus | 4.29m | 9.64m | 65.87m | 272.19m | 4396.69 | 1.31% 16.01% 2.55% 14.67% | 44300 | 9.92% |
| Olympia stadion, Berlin | 4.58m | 15.12m | 94.25m | 214.88m | 8237.57 | 4.11% 11.65% 5.65%9.3% | 74667 | 19.32% |
| Mane Garrincha, Brasilia | 9.31m | 9.64m | 76.59m | 288.83m | 5568.02 | 3.42% 6.76% 2.04% 9.74% | 72788 | 4.98% |
| Rhein Energie, Cologne | 7.21m | 17.05m | 55.87m | 120.56m | 1073.71 | 2.67% 1.99% 7% 19.18% | 50000 | 3.51% |
| Merkur Spiel-Arena, Dusseldorf | 4.86m | 18.15m | 59.40m | 257.56m | 9682.93 | 1.88% 0.85% 1.43% 34.49% | 54600 | 6.62% |
| Craven Cottage, London | 5.10m | 24.10m | 35.91m | 137.61m | 3214.78 | 18.42% 7.56% 2.34% 6.45% | 22384 | 23.09% |
| Kyiv Olympic Stadium | 3.43m | 14.88m | 62.96m | 193.75m | 4746.08 | 5.58% 3.8% 5.45% 9% | 70050 | 24.96% |
| London Stadium | 2.25m | 13.36m | 45.82m | 288.19m | 12094.36 | 3.02% 22.82% 8.95% 6.36% | 80000 | 24.84% |
| Tokyo Olympic Stadium | 4.32m | 8.69m | 52.42m | 284.63m | 10435.99 | 2.63% 10.52% 0.86% 31.86% | 68089 | 25.09% |

### 5.3.5.5 RIBA Stage 2 Concept development - Data analysis and output

The approach to resolving the design problems at this stage is different from that of the previous two phases as the requirement is not only to test for feasibility and provide guidance for design characteristics, but also to explore new solutions. The approach taken here is classification: the model groups the solutions based on shared characteristics, but the aim of selecting the best-performing solution is not fundamental. As a result, the approach is more interactive: the designer works with the model and trains it through their design decisions. This approach is based on the semi-supervised machine learning pipeline based on clustering with the *k*-means algorithm, where the groups are created based on the relationship between the performance values without labels but at the same time the best-performing solutions are identified visually within the output. The designer then selects one of the groups, the selection is labelled, and the design space is narrowed based on the properties of that particular group. A new set of solutions is then generated by the parametric model and the process is repeated until a set of solutions is identified that fits the designer's and client's expectations. The output is a 3D model that can be sent for additional façade design, visualisation, or to a BIM platform such as Revit.

*Table 5.17. Neural Network hyperparameters and prediction rate*

| | |
|---|---|
| Learning rate | 0.1 |
| Network topology | Feedforward network |
| Type of hidden layers | Fully connected |
| Number of epochs | 1000 |
| Sigmoid's Alpha | 1.0 |
| Number input neurons | 8 |
| Number of hidden neurons | 2 |
| Activation function | BipolarSigmoidFunction |
| Optimizer | ResilientBackpropagation |
| Momentum | 0.0 |
| Chromosomes | 100 |
| Regularization | False |
| Adjustment | 10 |
| Bayesian alpha | 0.1 |
| Bayesian beta | 1.0 |
| | |
| Accuracy of prediction | 90.86% |


*Figure 5.32. K-means clusters based on sightline performance and manual labels by designer*

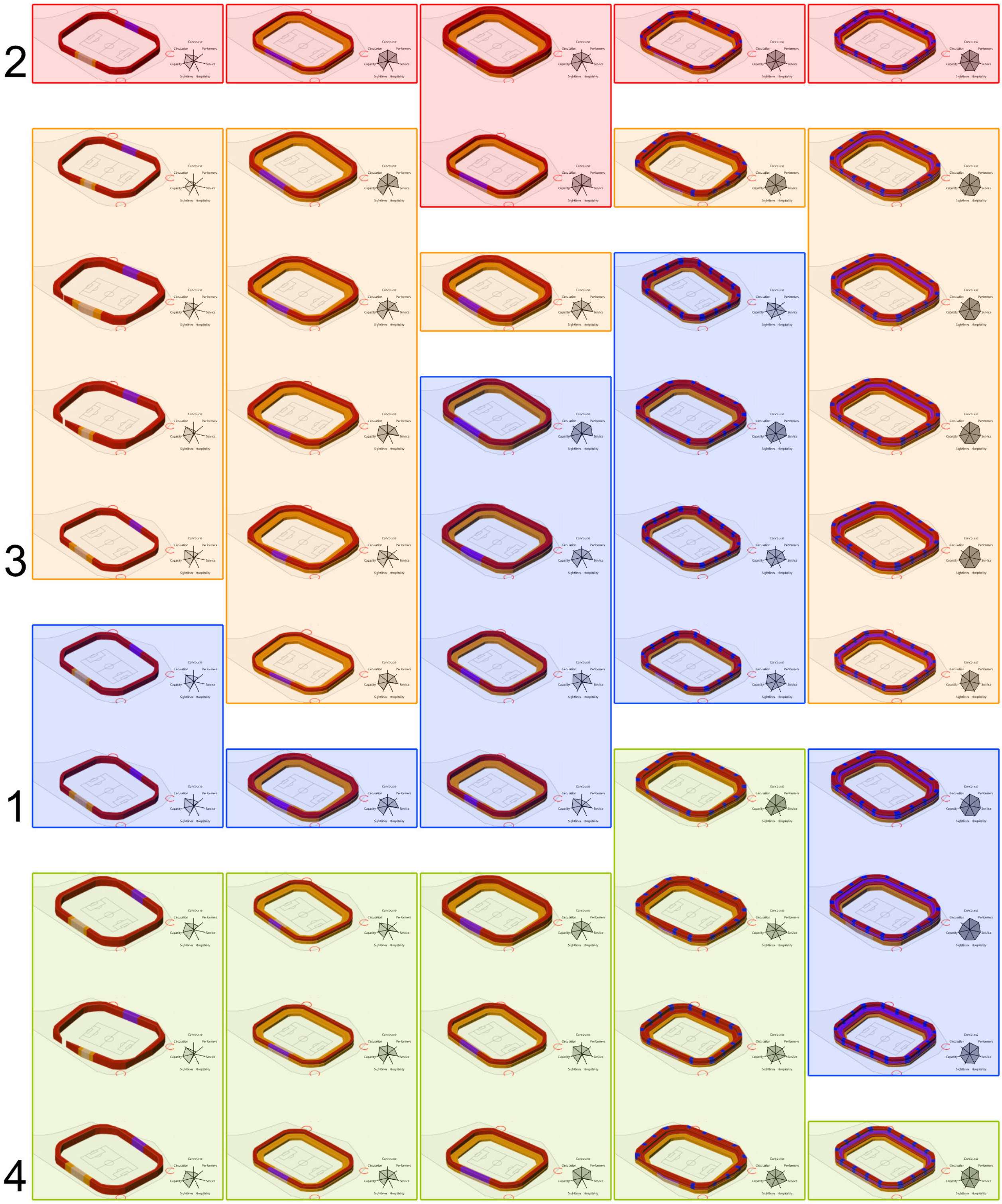



*Figure 5.33. K-means clusters based on layout distribution and manual labels by designer*

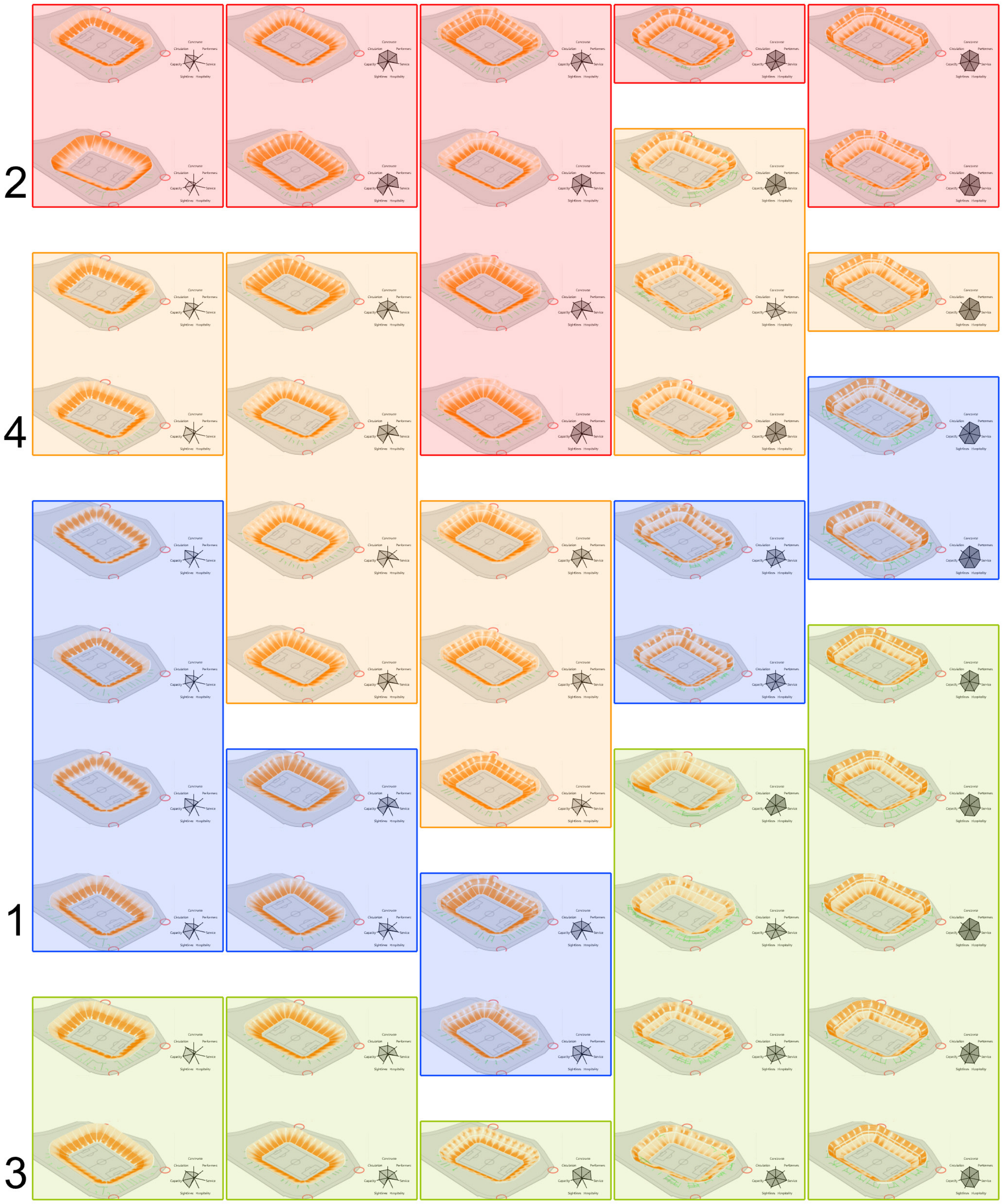



*Figure 5.34. K-means clusters based on circulation distance to stadium exit and manual labels by designer*

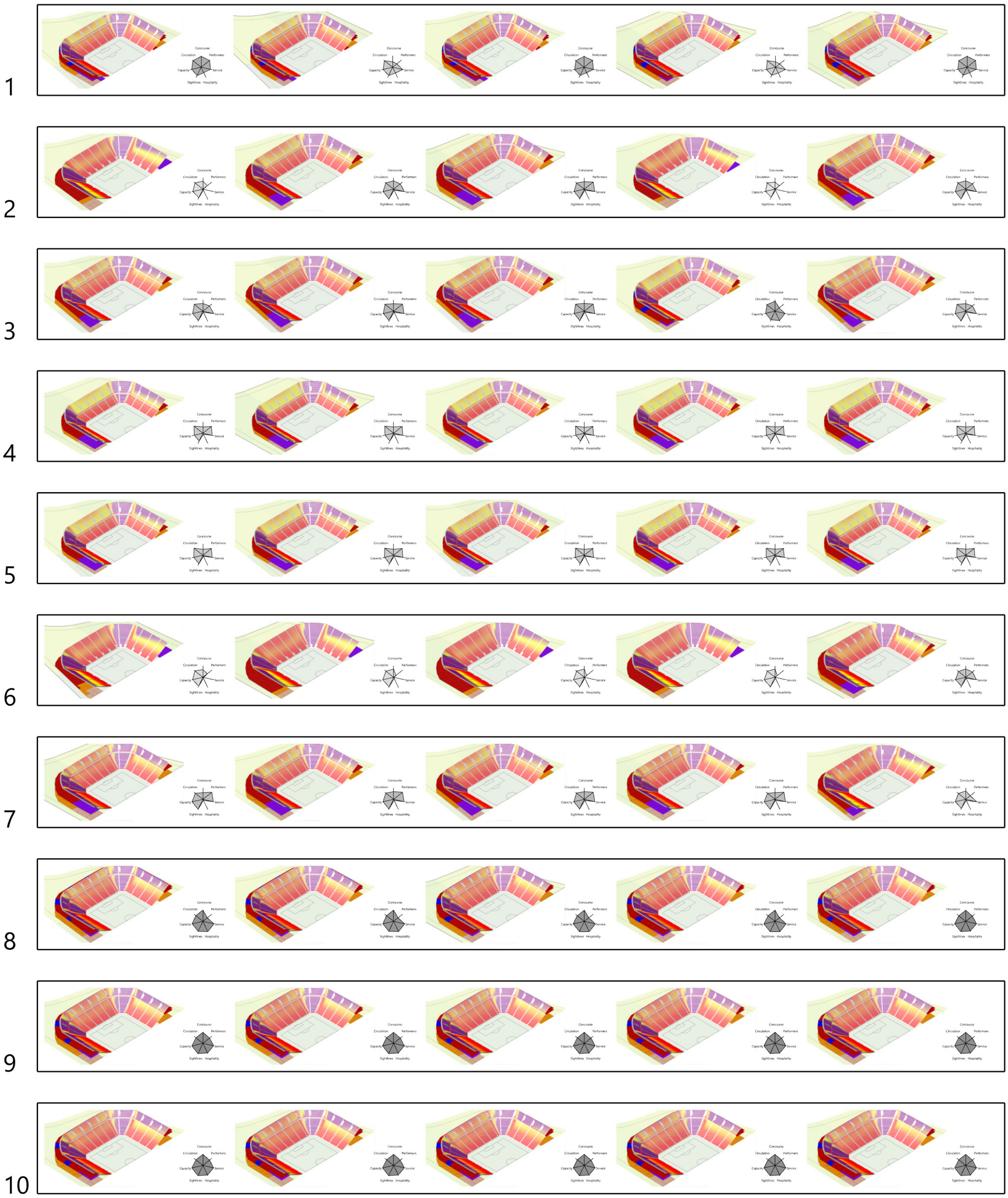
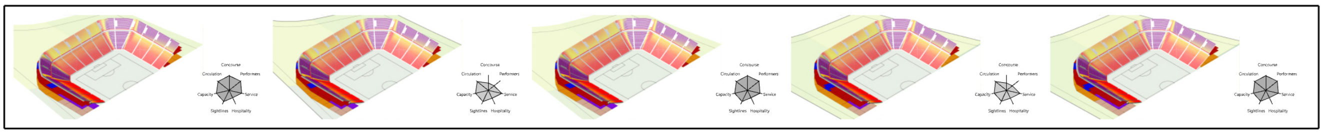



*Figure 5.35. NN classification based on labels created by designer*



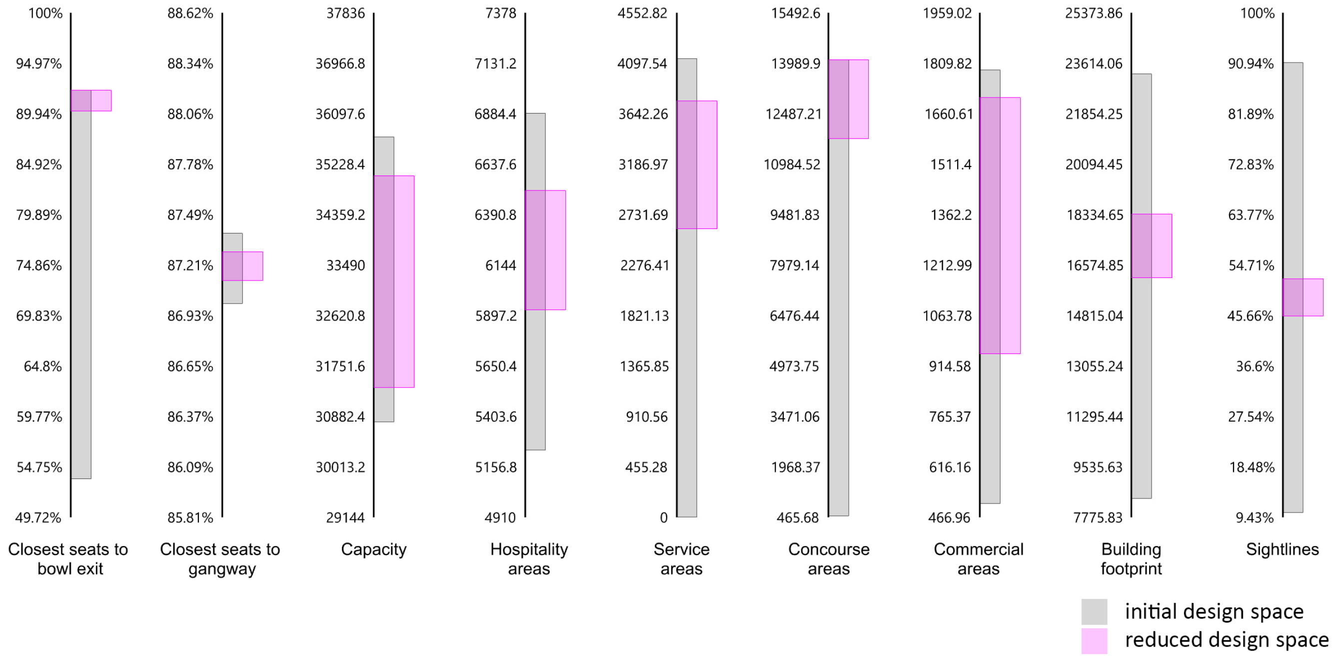



*Figure 5.36. Redefinition of design space based on best performing group identified through designer labelling*

### 5.3.6 Spatial Coordination - RIBA Stage 3

This phase of the project development is aimed at testing and validating the architectural and engineering concept established in the previous stage for its compatibility with the design solutions proposed by the other design disciplines identified in the RIBA (2020) PoW. The concept is also tested against the building regulations and other legislation. The process results in a design that is spatially coordinated, with all the members of the team confident that they can continue detailing their designs, and the whole project meets the client expectations and cost limits. At the end of the phase, the design team submits the planning application.

The BIM overlay on the PoW merges this stage with the next one, Technical design, into one main process of data sharing and integration for the design coordination and detailed analysis (Sinclair, 2013). This is a very important step, as it challenges the boundary between spatial coordination and detailing and offers the possibility of revising the design process in the light of the development of the digital and automated design. From a BIM perspective, this phase is aimed at creating a fully coordinated digital model across all disciplines and testing the performance of the design.

The concept of modularity is key to this. Multi-objective optimisation at different scales provides the foundation of a coordinated approach to the quantification and benchmarking of sections of the design. An automated design analysis and optimisation framework can test the strategies deployed and sub-optioneering within the scales themselves can automatically resolve design issues and improve the design with a fraction of the work associated with the current process.

Multi-objective optimisation workflows also benefit the design process through analysis, comparison, the development of variations, and the enhancement of the design for circulation, sightline quality, spatial arrangement optioneering, and optimisation for modularity. The quantification of the spectator circulation allows a number of detailed studies to be performed in order to improve the design. The test for legal compliance in terms of exit distances can be performed either as part of the design process involving other elements or solely to verify the solution. Further on, this analysis is performed across the modular scales and across the masterplanning zones defined in the FIFA, UEFA, and *Green Guide's* recommendations (Department for Culture, Media and Sport, 2008; Fédération Internationale de Football Association, 2011d, 2011a; Union of European Football Associations, 2014) . Fragmenting the analysis into smaller sections enables a targeted approach and facilitates cross-disciplinary communication. In addition, this process incorporates the spatial analysis of proximities between layout elements and circulation paths. This analysis is detailed further in terms of the bowl design: the study is based on the distance of individual sets to functional elements and produces an overview of the distributions in the stadium seating areas. The process produces a visual output of a seating point cloud with colour indicators for the performance of each seat. The machine learning model in turn analyses the distributions based on the point cloud data and produces optimisation solutions that are based on a large set of distances which create a series of quantified relationships of seating to circulation, programme, and masterplan.

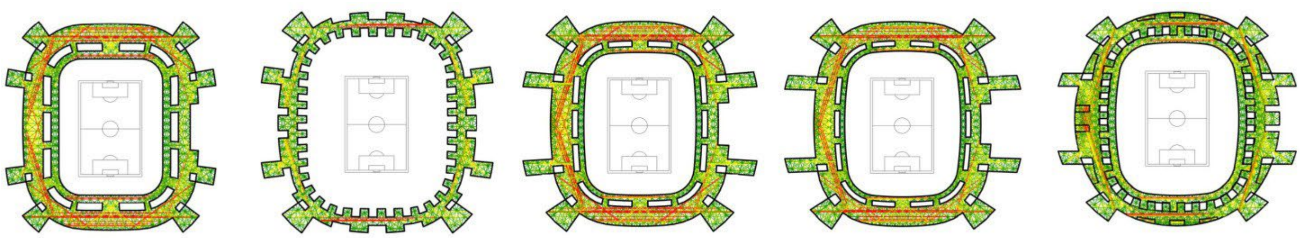


*Figure 5.37. Generation of concourse variations based on isovist analysis within parametric model*

The multi-objective optimisation of the internal layout is based on areas, frontage to circulation areas, distances between layout elements, isovist, and the circulation analysis described above. Traditionally, the programmatic areas in the stadium are analysed as percentages of the total area (Castro, 2020; John et al., 2013). In terms of the concourse, the recommended utilisation density is two people per square metre: the highest acceptable density for commercial and circulation features is four people per square metre. The contribution of this research is  the identification of additional metrics for this analysis through the typological study and the quantified relationship between circulation, internal layout, and bowl design. The quantification and analysis of retail frontage has the potential to bring machine learning to performance-based layout development. This particular approach is significant because it enables an analysis of the potential for commercial exchange points, which is directly related to the number of items sold per time period. This is an important feature of stadium design, due to the limited period at half-time in a match for spectators to make purchases. In addition, this feature has a significant impact on the safety and exit distances, because queues affect the crowd flow in the concourses (Brocklehurst et al., 2005; Luque Sánchez et al., 2020; Minegishi and Takeichi, 2018). The multi-objective optimisation techniques can also benefit the layout planning through distance and distribution analysis. This can be done though the development of a design space for potential solutions and benchmark comparison with previous cases and with the client's expectations. The parametric model currently uses the structural grid cells for this analysis: the cells are subdivided into smaller sections and assigned functions. The process of grid subdivision is infinite and can be brought to a very granular level, but to reduce the necessary computation, the model currently splits each cell into 256 smaller units. Those functions are input in the model as numerical values, and each cell has a floor and location identifier. The machine learning models are

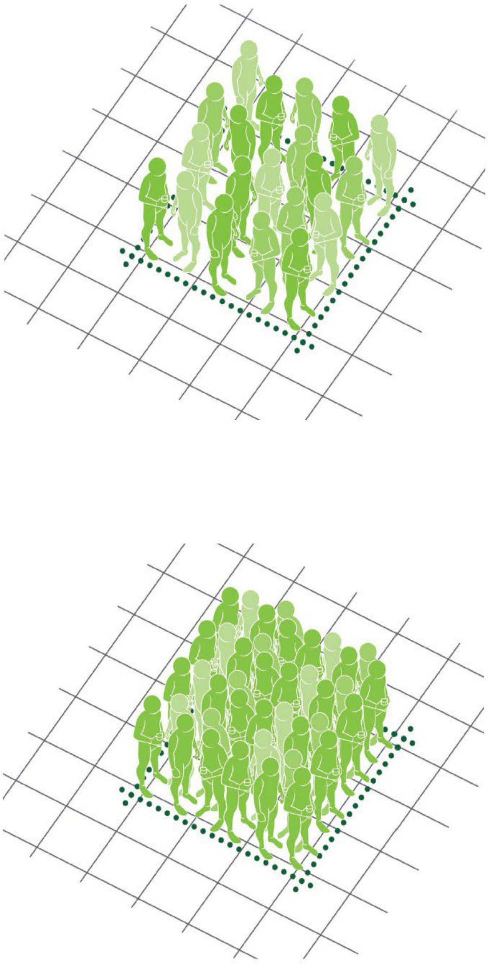


*Figure 5.38. Green Guide visualisation of two people per m2 of concourse recommendation (top) and highest acceptable density of four sectators per m2 (bottom) (Department for Culture, Media and Sport, 2018)*

trained on the numerical input values and define the design space through these parameters.

The inclusion of the of the sightline optimisation follows the overall push of the PoW towards the detailing of the Stage 1 architectural concept. Sightlines have a significant influence on the overall building morphology, but once this is resolved in Stage 1, the impact of the sightlines focuses primarily on the detailing of specific features in the stadium bowl. Building on the concepts

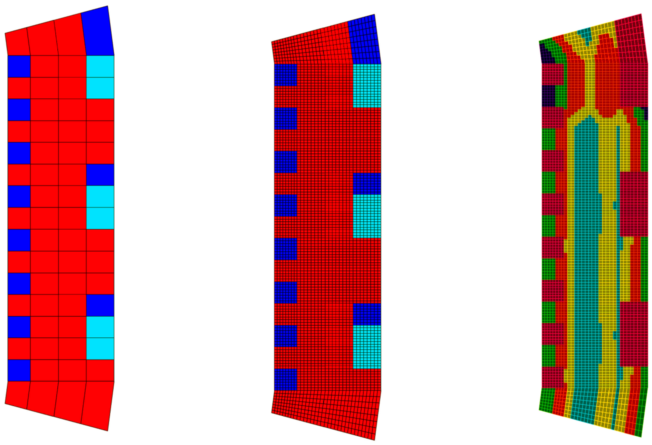


*Figure 5.42. Allianz Arena ground floor concourse East stand plan, parametric representation, grid subdivision, internal layout performance distribution zones*

developed by Joseph and Kim (2015) the optimisation at this scale focuses on reducing views that are restricted by any form of obstruction. The primary analytical elements in this process are the arrangement of bays at the sector scale and the introduction of obstructions such as safety features like barriers near the bowl exits. These are analysed as individual units and the overall goal is to reduce the degree to which they interfere with the viewing of events. The sightline analysis also focuses on the row depths and the provision of different types of spectator experience. This process is based on identifying hospitality zones and linking them to the corresponding areas in the seating bowl. Working reversely from the sector scale towards the bay and section, this process develops a design space and seeks the optimal distribution of different seating types.

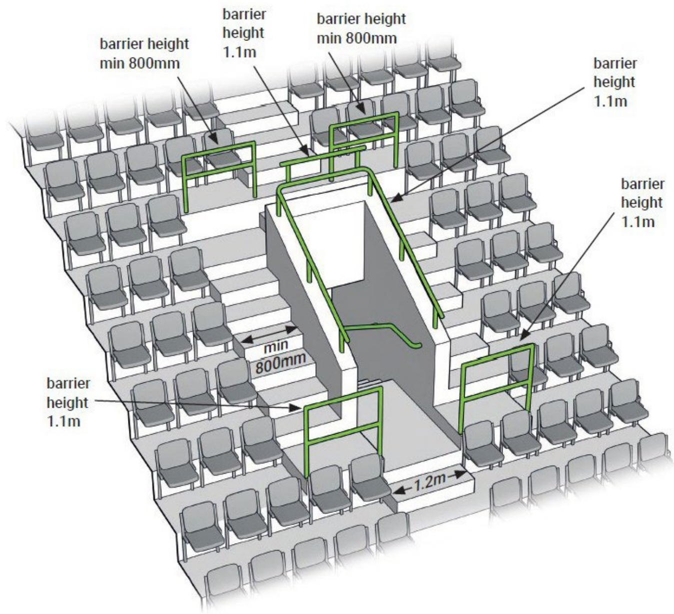



*Figure 5.40. Green Guide safety barriers near vomitories (Department for Culture, Media and Sport, 2018)*

## 5.3.7 RIBA Stage 3 Bay scale optimisation

### *5.3.7.1 RIBA Stage 3 Bay scale optimisation - Data creation*

The overall morphology, orientation, and location of the centre of the playing field are resolved and the inputs controlling those features are then kept constant within the parametric model. Further on, the modular division, grid size, and slab levels are also resolved, and the design moves towards defining the bay and sector scales in greater detail. A modular stadium is traditionally understood as an assembly of bays arranged around a playing field. Developing and optimising the bays is strongly linked to the programme provision in the interior and the locations of the facilities associated with the varying range of catering options based on ticket price. Addressing those factors is a task that, in contrast to the previous stages, is no longer explorative but instead is aimed at the direct optimisation of a set of solutions based on a specific set of goals.

An example of this process is the theoretical revision of the design of the relationship between the existing two-tier solution of the Kyiv Olympic stadium with the 2011 refurbishment of the West stand by gmp. The design of the main stand includes a hospitality tier, which interrupts the view of about 200 seats on each side. The objective of the optimisation is to reduce the number of seats with a restricted view, and to maximise the number of hospitality rows and the proximity of the hospitality facilities to the playing field. Those objectives conflict because the closer and larger the hospitality tier is, the more it restricts the views there.

The inputs for this process are related only to the features specific to defining a bay configuration that can later be adapted to the overall sector arrangement – the designer defines the design space with ranges for the desired 'C' value, distance from touch line, number of rows, row depth, tier offset. The rest of the input parameters are defined as fixed values.

*Figure 5.43. Kyiv Olympic stadium by gmp restricted views areas highlighted in magenta (base plan Architectural Record, 2012)*

Figure 5.46. Kyiv Olympic stadium west stand(“Google Earth,” 2023)

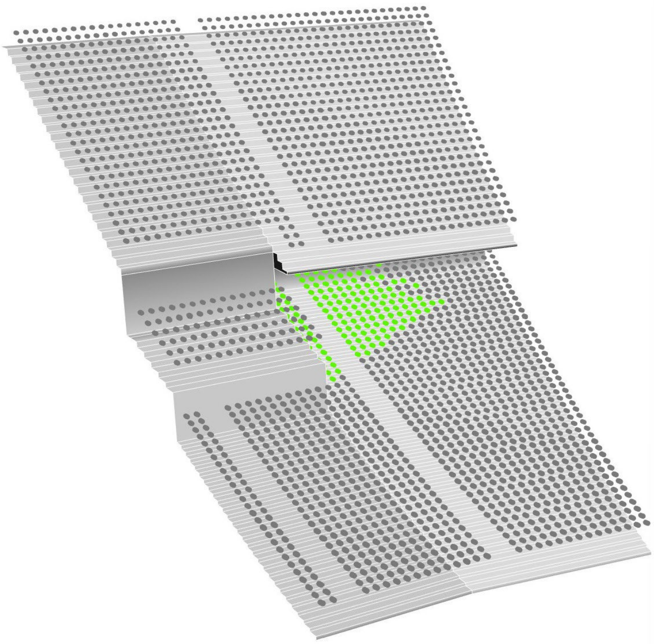


Figure 5.40. Kyiv Olympic stadium restricted view seats

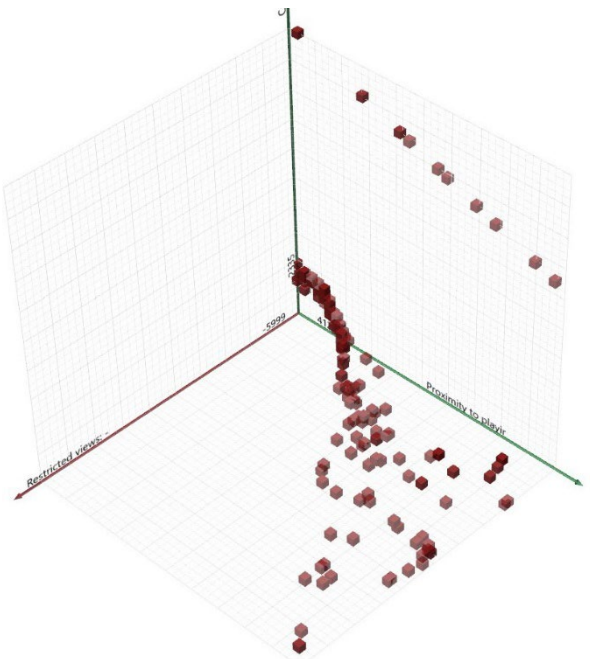



Figure 5.41. Set of solutions after 3 generations

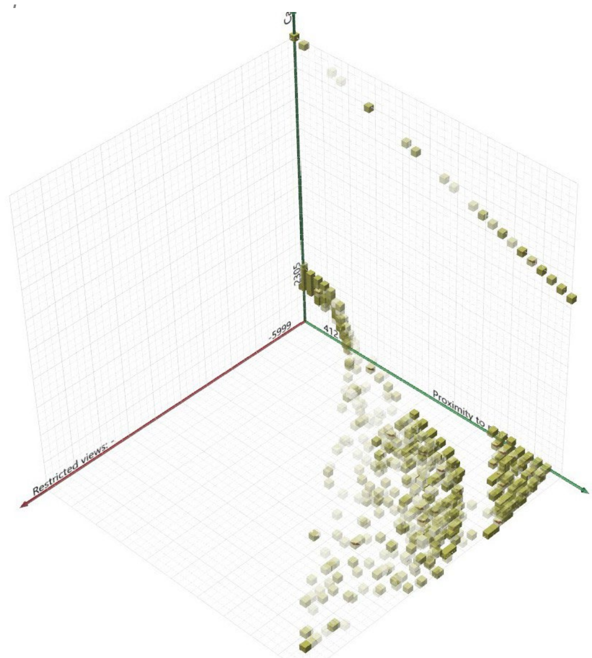



Figure 5.49. Set of solutions after 242 generations

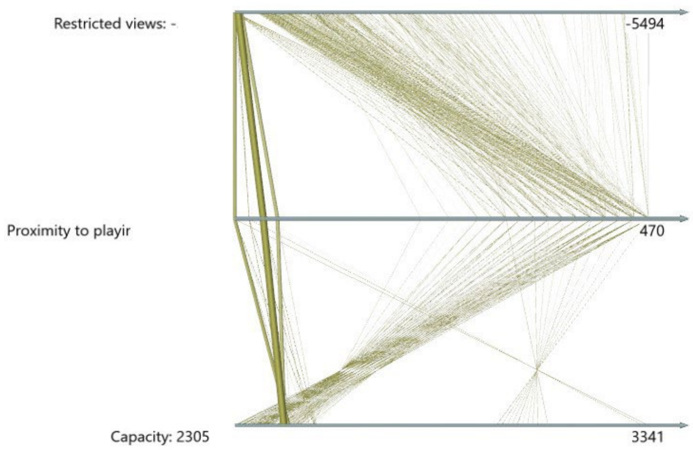



Figure 5.51. Set of solutions after 2492 generations

| Table 5.18. RIBA Stage 3 bay scale optimisation inputs | | |
|---|---|---|
| **Features** | **Data** | **Input** |
| Hospitality tier start | Row number range | 5 - 45 |
| Hospitality tier end | Row number range | 6 - 46 |
| Row depth | Length range | 800 mm – 1100mm |
| Bay number | Bay range | 18-19 |
| Hospitality tier height | Height range | 2.5m – 5m |

#### 5.3.7.2 RIBA Stage 3 Bay scale optimisation - Data processing

In contrast to the previous stages, the multi-objective optimisation is based on an evolutionary approach and the parametric model does not generate a full set of solutions. The optimiser produces a set of input values within the ranges defined by the designer and the parametric model outputs performance metrics for each case – the number of repeating elements and the overall 'C' value for the sections where the bays will be positioned. Based on evolutionary principles, the process iteratively attempts to identify well-performing solutions deriving from the performance of the previous generations of solutions.

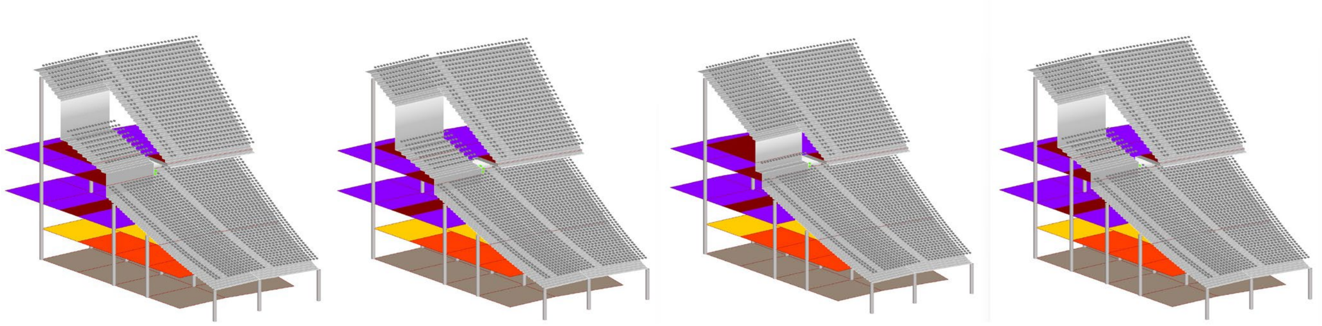


*Figure 5.53. Set of well performing solutions with restricted view seats highlighted in green. On average the optimisation reduced the number of affected seats with 90% to 95%*

#### 5.3.7.3 RIBA Stage 3 Bay scale optimisation - Data analysis and output

The optimisation process is fully automated, using the Octopus tool in Grasshopper, a multi-objective optimiser available for Rhino 7. Its important advantage is that it explores Pareto fronts. The output of the analysis is a set of solutions and the identification of ranges for inputs for the parametric model. If this section of the design is led by the architect, the findings from these studies are then sent to the engineers for structural analysis. The workflow can be independently utilised by the engineers for the modular optimisation of the design.

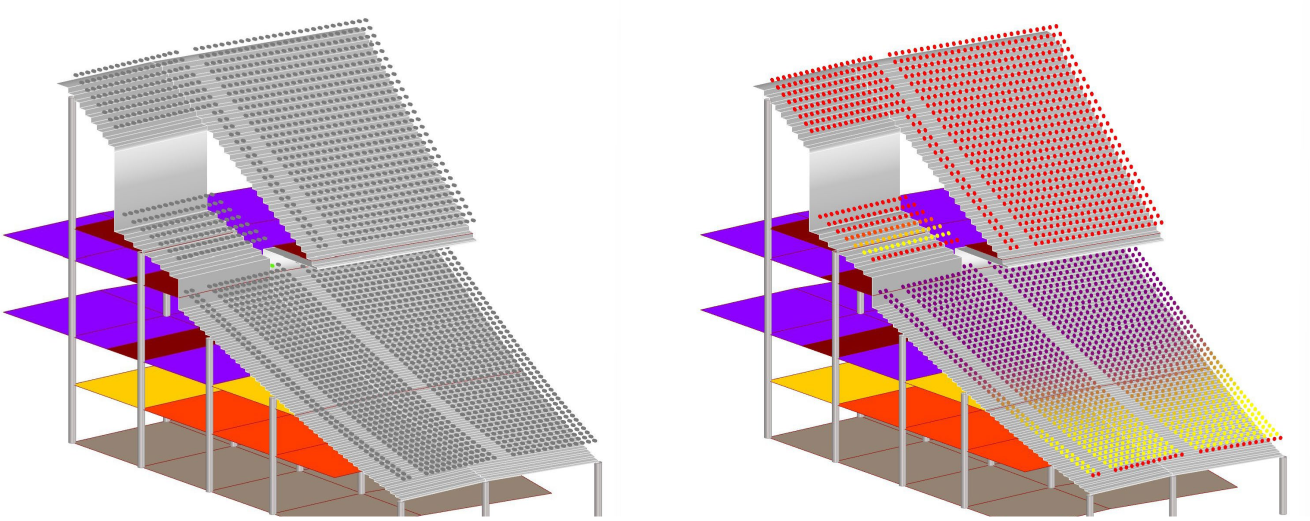


Figure 5.54. Kyiv Olympic stadium optimised solution with restricted views highlighted in green (left) and 'C' value sightline analysis (right)

## 5.3.8 RIBA Stage 3 Stand scale performance assessment

### *5.3.8.1 RIBA Stage 3 Stand scale performance assessment - Data creation*

The relationship between the internal layout and the seat distribution in the stadium bowl is a network of design problems that has the potential to be quantified and optimised computationally, in contrast to current design practice. The scale of simulation and analysis is the stadium stand, and the parametric model builds up the information required for the machine learning models based on the assembly of the structural bays. For this process to be initiated, the designer must have defined the seating bowl properties and the height of the internal slabs and have a general understanding of how the layout features will be distributed in plan. The designer then inputs the ranges of the locations of structural bays, the end of gangway or vomitory bowl exits, and the pattern of layout features on the specific slabs.

The example analysed in this study is the main concourse in the East stand of the Allianz Arena Munich. This stadium is one of the best examples of early twenty-first-century modular designs, but even in this case it is possible to identify zones which could benefit from a redesign with machine learning. The analysis starts with the current layout and a set of potential design variations by moving the commercial unit distribution pattern across the concourse. For the performance assessment and optimisation process to start, the designer inputs the location of the concourse, a numerical representation of the internal layout, and ranges for the locations of the vomitories/seating bowl exits.

| Table 5.19. RIBA Stage 3 bay scale performance assessment inputs | | |
|---|---|---|
| **Features** | **Data** | **Input** |
| Programme | Functional pattern | 11, 11, 11, 11, 1, 11, 11, 5... |
| Level | Number | 3 |
| Vomitory start | Range | 0-20 |
| Bays | Bay range | 45 - 61 |

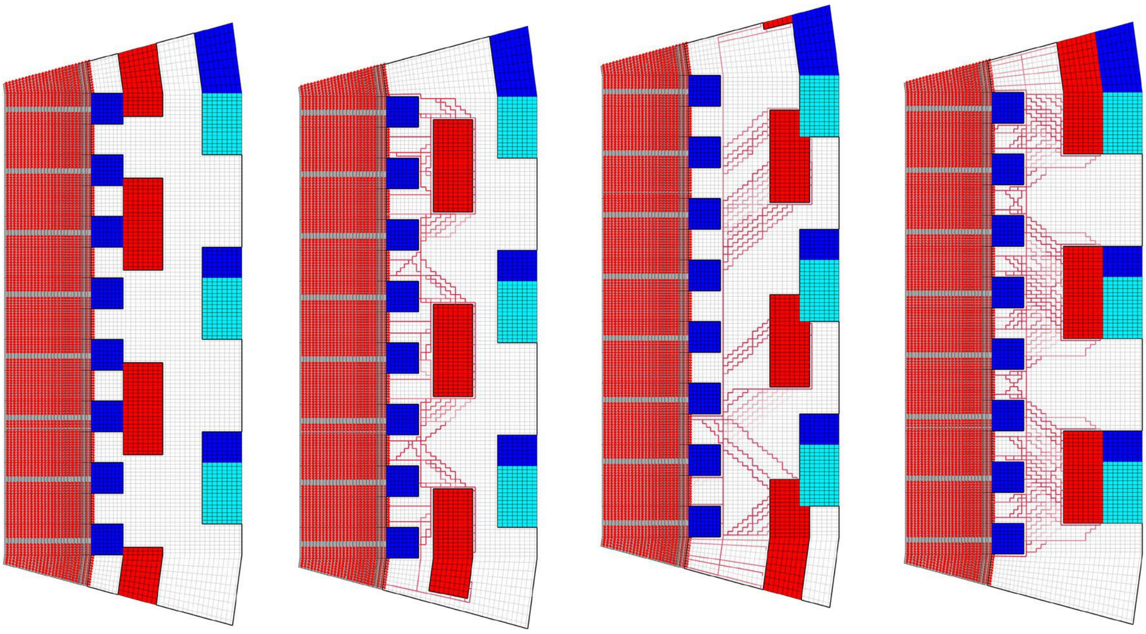


*Figure 5.56. Allianz Arena east stand parametric variations of locations of commercial units and paths to concourse entry points*

#### 5.3.8.2 RIBA Stage 3 Stand scale performance assessment - Data processing

The performance metrics in this workflow are average distance seat to commercial unit, the commercial and concourse areas per seat, and an isovist concourse analysis aimed at solutions with the longest rays. The circulation distance is measured from the seat to the centre line of the gangway, then as the direct distance to seating bowl exit, the vertical distance to the concourse, and finally the combined travel distance on the concourse circulation grid.

The functional areas are added together and divided by the number of seats that can access the concourse. The areas are measured from the model and reflect any overlaps with other functions that the generation of variations may produce.

The internal sightline isovist analysis is based on the locations of the centre points of the grid lines, and the designer can specify how many rays are projected from each viewing position in the interior. The study is limited to a single concourse, but individual optimisations can be linked to form a full representation of the stand.

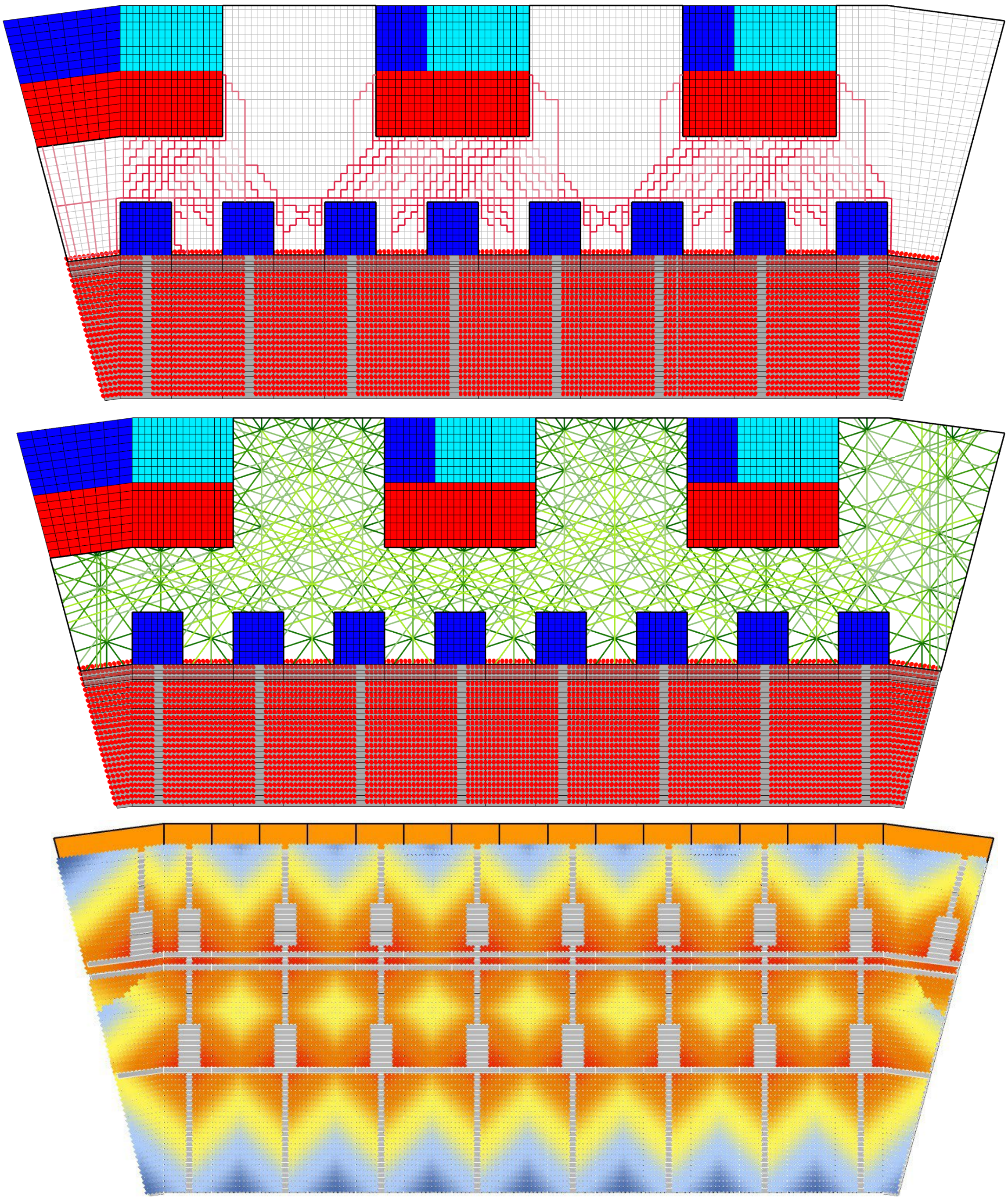


*Figure 5.57. Allianz Arena east stand concourse paths(top), isovist (middle), distance seat to commercial (bottom)*

| *Table 5.20. RIBA Stage 3 data entry example* | | |
|---|---|---|
| **Analysis feature** | **Data type** | **Example** |
| Concourse level | Identifier | 2 |
| Distance seat to commercial | Average | 17.7m |
| Number of concourse isovist paths above 50m | Number | 235 |
| Commercial area per seat | Area | 1054 sqm |
| Concourse area per seat | Area | 10246 sqm |

### *5.3.8.3 RIBA Stage 3 Stand scale performance assessment - Data analysis and output*

As layout planning is a process that has the potential to develop a vast design space, the approach taken is to limit variation through human input by reducing the departing design space. The most applicable workflow in this case is a revision of the supervised method, in which the performances of the case studies are labelled based on the optimisation criteria. Instead of using them directly to train an NN, the dataset is transposed so that each grid cell is defined by the performances of all the case studies. Using voting, the labels are consolidated into an individual label for each cell, which reflects the performance of the cell across all the cases. An extract of these labels is used to train a NN model. The NN model then groups the layout grid cells based on their performance. The model then outputs heatmaps graphically, indicating the performance of each cell, which assists the development of the actual plans. The heat maps can also be used to define the locations of the walls of different layout functions.

*Table 5.21. Neural Network hyperparameters and prediction rate*

| | |
|---|---|
| Learning rate | 0.1 |
| Network topology | Feedforward network |
| Type of hidden layers | Fully connected |
| Number of epochs | 500 |
| Sigmoid's Alpha | 1.0 |
| Number input neurons | 5 |
| Number of hidden neurons | 2 |
| Activation function | BipolarSigmoidFunction |
| Optimizer | ResilientBackpropagation |
| Momentum | 0.0 |
| Chromosomes | 100 |
| Regularization | False |
| Adjustment | 10 |
| Bayesian alpha | 0.1 |
| Bayesian beta | 1.0 |
| | |
| Accuracy of prediction | 77.29% |

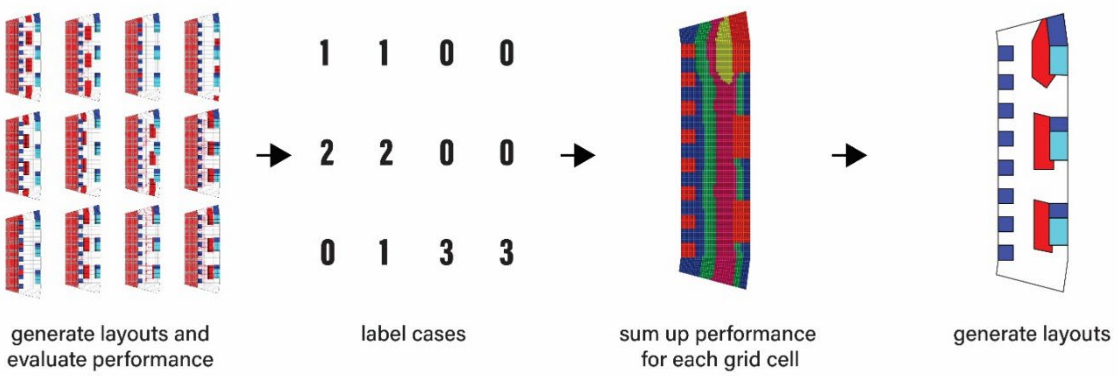





*Figure 5.59. Machine learning support for performance based layout development*

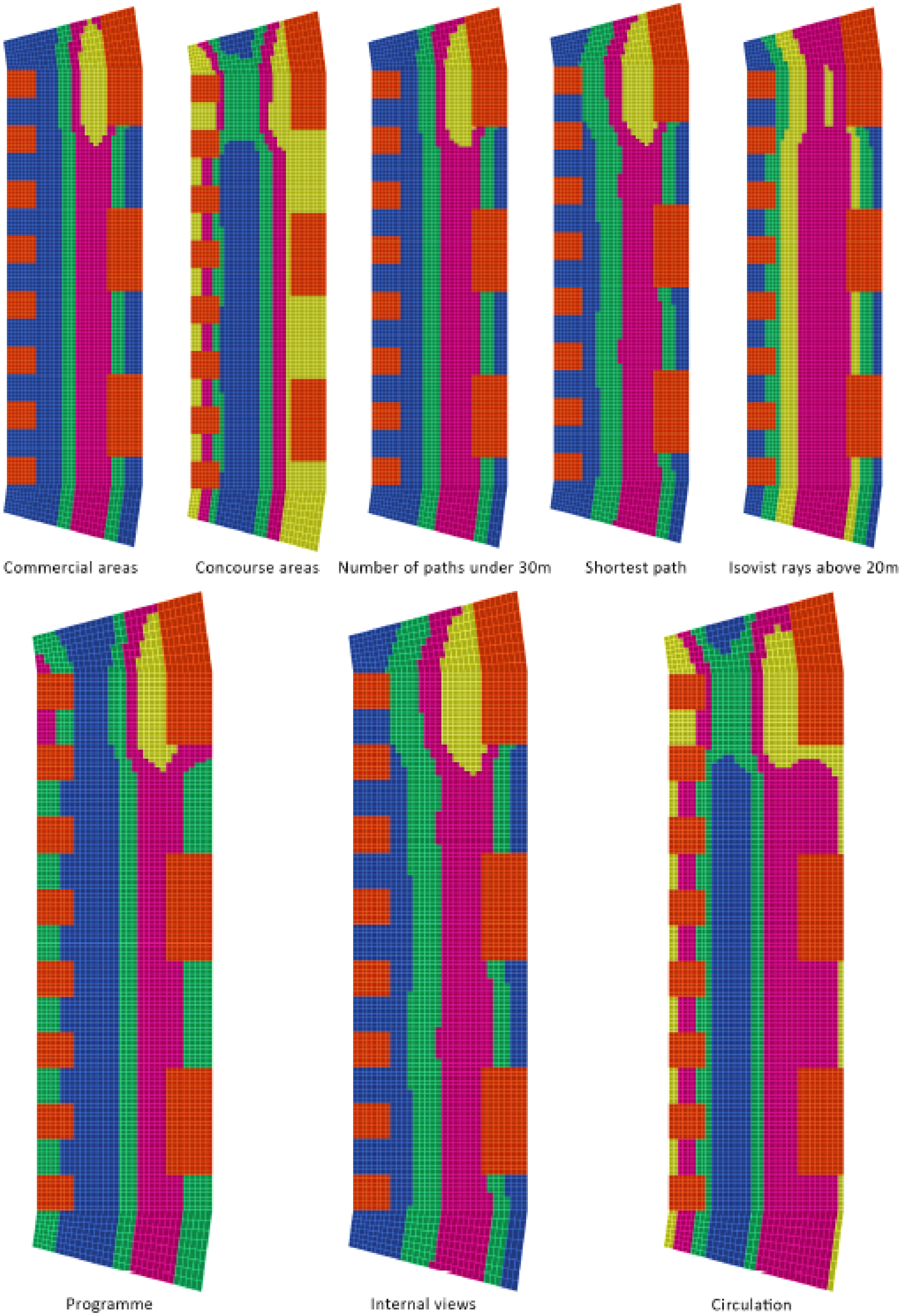



*Figure 5.60. Layout performance heatmaps*

## 5.4 Relevance of the research to the construction industry

### 5.4.1 Design for Manufacture and Assembly Overlay

#### *5.4.1.1 RIBA Plan of Work 2020*

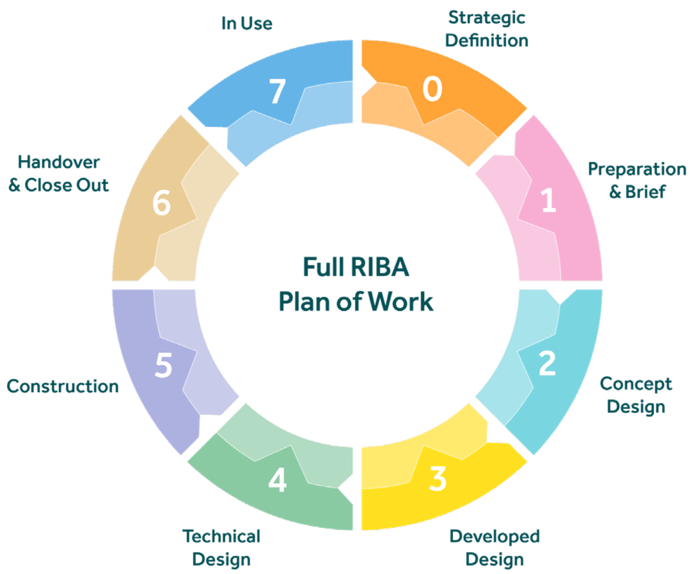



*Figure 5.62. RIBA (2020) Plan of Work 2020*

The publishing of the Farmer Review on the UK Construction Labour Model (2016) was a milestone in the transformation of the construction industry that resulted in a significant change in the relationship between the client, the design, and construction teams (RIBA, 2020). Digitalisation and increased integration diminished some of the existing boundaries and brought new roles that had previously been allocated to different teams in vastly revised procurement strategies (Association for Consultancy and Engineering, 2019). The UK government responded through the creation of The Construction Playbook (Cabinet Office, 2022) aimed at better, greener, faster delivery with a further focus on the adoption of new technology and greater integration at industry level through legislative means. Subsequently, there was a commitment to net zero carbon in 2019 with the construction industry at the forefront of its sustainability targets (HM Government, 2021). All those aspects forced the RIBA to re-evaluate its plan of work yet again, to facilitate the anticipated changes. The focus on modern methods of construction [MMC] and an approach to define value were clear. This new framework subsequently introduced strategies as decision-making processes for conservation, cost plans, fire safety, health and safety, inclusive design, planning, plan for use, and sustainability. All these aspects were gathered under the overarching umbrella of the digital delivery process and could be quantified and benchmarked.

The most important aspect of the RIBA PoW 2020, however, was not the document itself but the Design for Manufacture and Assembly [DfMA] Overlay (Thompson, 2021) on the frame work. This document represented the admission by the RIBA that business as usual in the design and build industry cannot respond to global challenges such as climate change and an increasing population, nor the aspects identified in the Farmer Review (Thompson, 2021). The four pillars that could support a change in the industry were all found in the rapidly developing technological sector – computer processing, materials science, manufacturing and data analysis (Thompson, 2021). The aim of the digitalisation of the entire process was openness and clarity, in contrast to the economically opaque process in traditional construction. This was to be achieved through the inherent facility of the digital domain for the documentation, simulation, and verification of every aspect of the design, manufacture, and assembly route. The ultimate goal, however, remains the development of the digital twin concept for every building in the UK (Walters, 2019). This database will contain complete simulations of the performance and design of every building in the UK that at later stages can be used to predict and optimise design and performance. The core of the concept remains the utilisation of MMC in the context of pre-manufactured value [PVM] as tool to quantify and evaluate the value of every building element in the UK. The DfMA Overlay on RIBA PoW 2020 challenges the existing framework through its emphasis on the initial stages of the design development process in order to introduce the MMC approach as early as possible, so that associated cost can be reduced.

#### *5.4.1.2 Modern Methods of Construction*

MMC is a broad term that includes all the processes and building methods in housing construction that increase production, reduce labour, and lead to an overall optimisation of the building delivery process (Thompson, 2021). The term 'modern' is slightly misleading, as most of the approaches already exist in the manufacturing context but are yet to be fully adopted in construction. The fundamental difference from traditional construction is the focus on the design of the element – how it is manufactured and assembled in order to reduce the production cost. Originally defined as Design for Manufacture and Assembly [DfMA], this way of conceptualising a design relies on the off-site manufacture of elements that are assembled in a factory and then transported to the end user. With the development of production technology, a second aspect has recently started to emerge – the idea of mass customisation and the production of similar families of items that are customised to serve a unique purpose (Thompson, 2021). The primary drivers for this development are the digitalisation of design, the ability to mass produce large-scale structural


*Figure 5.63. DfMA overlay on RIBA Plan of Work 2020 (Thompson, 2021)*

elements in a factory, and the ability to assemble the elements interchangeably in order to achieve different results. This process has proven to increase efficiency, quality, compliance and control, and safety in production, reduce labour, and provide additional social and sustainability benefits (Thompson, 2021). When translated to the building design and construction process this concept enables the optimisation of the entire delivery pipeline through a redefinition of how we think about buildings. At this point the role of the architect and designer becomes pivotal – a drastic shift from the traditional approach of designing buildings is required, towards an educated ambition to understand the manufacturing process and the assembly of pre-manufactured elements.

The reasons for moving to the DfMA model in construction are practical – the cost of labour on site is twice as high as it is in a factory, while the production cost is almost halved in relation to that associated with traditional models (Fraser, 2015). In addition, off-site manufacture increases the speed of production and quality control while reducing administrative work. In terms of sustainability, there is less material use and waste, lower transportation costs, less pollution, less energy and water use on site, and better energy performance in use, and the process encourages the circular economy (Thompson, 2021). The primary aspect, from a design point of view, is the development of a different way of thinking that links the design with the opportunities created by mass-production. MMC focus on interchangeability – elements are designed so that they can be substituted. This opens up the design process to open market competition, which results in lower costs and product optimisation. The UK government strategy is currently aimed at the creation of platform thinking, in which competitive products can be compared and selected within the project design. An example of this type of concept is the use of families in the BIM Autodesk software Revit which enables the designer to select from a number of products from repositories such as the NBS National BIM Library (NBS, 2023). This innovative process brings the tender process within the design process itself and enables the price and performance attributes of every building element to be competitively evaluated.

The abundance of product information in a platform tender environment, however, creates a different set of challenges for the designer. MMC has specific requirements that have to be taken into account early in the design process in order to reduce cost (Thompson, 2021). Further, it is extremely time consuming to review and evaluate the qualities of every product and their compatibility with the rest of the elements in the assembly system. Because of this, a different way of selecting those elements is needed. The data-rich environment of the fully digital design process provides the key to the selection process. The circular nature of the RIBA PoW means that performance data can be included in a dataset and that machine learning can be utilised to narrow down of a list of options or ultimately to select a final solution based on interoperability and performance (Mosca et al., 2020). The benefits of using the methods described in this research can be seen most clearly from the perspective of establishing a starting point for automating the design and tender process, which creates the opportunity for the development of what the RIBA DfMA Overlay speculatively defines as 'one-stop shops' (Thompson, 2021), where the client arrives with an idea and leaves with fully-tendered construction package. This potential progression will challenge the profession dramatically – the architect will no longer design, but merely approve, the fully detailed and tendered AI design solution. Another interesting aspect that is yet to be defined is whether this one-stop AI model is centralised, based on the National Digital Twin Programme(IBM, 2020; Walters, 2019), and whether there are a set of proprietary private AI models that control all construction, or a hybrid system of a government-centralised model which controls the output of private AI models.

### 5.4.2 Pre-Manufactured value, Standardisation, Value toolkit

With the conceptual proposal for the extension of the pre-tender phase of the building procurement pipeline, the UK Government had to develop a metric that quantifies the value of the projects delivered in this way. The pre-manufactured value, or the amount of construction that happens off site, was the concept that was adopted. This was further developed by the Construction Industry Research and Information Association into an analytical methodology focusing on direct project impact factors such as cost and labour, indirect factors (environmental and life-cycle concerns), and wider social implications (Jansen Van Vuuren and Middleton, 2020). Another important aspect that emerged from this inquiry was the idea of standardisation – again originating in the manufacturing world, the idea was taken into the domains of both product and process.

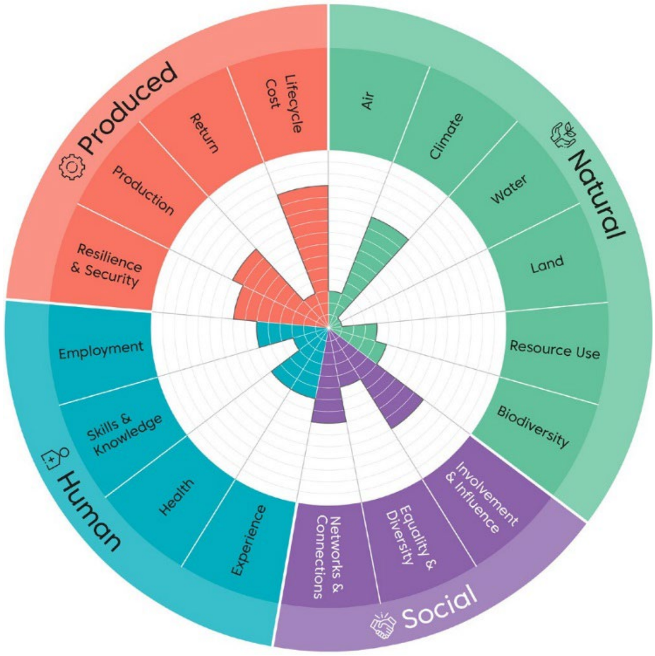


*Figure 5.65. Construction Innovation Hub (2022) Value toolkit evaluation categories*

In terms of the product itself there is little change from its original meaning – designs that are known to work are mass produced and their properties are enshrined in standards and codes. The new delivery method, DfMA, also benefits from the standardisation of the design and optimisation processes –not only products, but also processes, are interchangeable – which will open up the market for further competition, thus reducing cost (Thompson, 2021).

In 2020 the Construction Innovation Hub produced a toolkit that attempts to define and quantify the value of building projects through the entire lifecycle of the project. This document focuses on five key aspects – natural, social, human, manufactured, and financial (Construction Innovation Hub, 2022, 2020). Intended as a driver for the adoption of DfMA, the *Value Toolkit* aims to support the decision-making process throughout the whole design, construction, and operation of a building by reinforcing the government's key objectives – MMC adoption, social impact, and sustainability.

### 5.4.3 Interdisciplinary data management in contemporary project procurement

The nature of off-site prefabrication creates a set of challenges and opportunities that do not exist in traditional professional practice. As the bulk of the production and assembly is carried out in a factory, there is strong emphasis on the early identification of the MMC deployed and a shift in the design freeze as soon as manufacturing begins. The rationale for this is because the cost of changing elements on site is significantly higher than in traditional construction. Further, this factor stipulates a fully coordinated design across all disciplines with no conflicts. The platform approach favoured by the UK Construction Sector Deal (HM Government, 2018) is a significant step towards the horizontal distribution of design liability, but it also needs to be reflected in the overall procurement strategy. This multifaceted issue can be overcome, and the process further optimised, through the utilisation of a machine learning model for the coordination and early identification of critical issues and conflicts.

The second aspect of the procurement process that can be facilitated by data management with the machine learning tools identified in this research is the automation of the design itself. The two critical issues from this perspective are the ability to learn from previous projects about relationships between systems that work and the ability to identify construction elements that work together and provide best value. Training a machine learning model to optimise a design based on design performance is directly linked to the next stages of technical delivery and the selection of various building elements. The RIBA DfMA Overlay stipulates the utilisation of automated configuration, optimisation, and customisation tools, as well as the reuse of digital models that are known to work (Thompson, 2021). The practice side of this research is focused entirely on the development of a framework of a set of machine learning tools to facilitate this process. Subsequently the output of the parametric model links the design produced directly with one of the platform programmes identified by the RIBA, Revit, and utilises machine learning in the panelisation of building elements and the allocation of families for specific functions. Further on, the interface enables interchangeability – as families are modular, they are specified in the parametric model only as identifiers, and once the model is translated to Revit, the families are automatically populated in the BIM model. In contrast to the traditional design development of large-scale infrastructure projects, in which at RIBA Stages 3 and 4 the design team expands dramatically in order to translate the model manually (Sinclair, 2011), this approach enables a much more efficient workflow at a fraction of the labour and financial cost.

The machine learning-supplemented approach defined in this project also contributes to the verification of the final design and has the potential to significantly reduce the workload of the BIM manager. In addition, this workflow will greatly reduce the overall design and construction phases of the typical lifecycle of a BIM-based project. A key aspect of this factor is the interoperability of the BIM software and the output of the parametric model – the building information data generated and analysed is in the same format across all the software solutions and there are no obstacles in its translation and manipulation. Further on, this advanced workflow allows for incorporation of the actual manufacturing and assembly workflow in the parametric model, which enables the optimisation of the entire procurement process.

The limitations to this approach are found in the critical design issues highlighted in the RIBA DfMA Overlay. The first is the interoperability of the different MMC and building systems deployed, and the tolerance between them. The way this research addresses these is based on the platform thinking described above – each building element and system are distributed in the parametric model through their association with a building element or zone like primary structure, envelope, basement, roof, etc. In this way the coordination is hierarchical, as in traditional procurement which enables the existing knowledge about the system requirements to be deployed in an automated workflow. The approach of reducing the design space from a modular perspective addresses another of the considerations expressed by the RIBA – the reduction in variation in order to facilitate manufacture and assembly, thus reducing cost. The utilisation of shape grammars for the definition of the structural grid of the stadium enables the detailed representation of several case studies and the generation of alternative designs constrained within the geometrical and morphological properties of the design. Depending on the overall layout, the script can generate vastly divergent solutions. However, the subsequent design space reduction allows for optimisation based on the number of repeating elements – for example, the premanufactured bowl, floor, or façade components. This approach will also improve the actual assembly on site as, through optimisation, there will be fewer element types, which will result in shorter construction times. In the long run, the modular approach to the construction of the parametric model and the resulting modularity of the designs generated will facilitate the operation, maintenance, and decommissioning of the building. In terms of sustainability, this approach also enables the reuse of building elements in other buildings in a way similar to the 974 Stadium in Qatar, by Fenwick Iribarren Architects, in which the whole design was focused on dismantlable objectives(Quirke, 2021).

Another important aspect of constructing a modular parametric model aimed at optimisation with machine learning is the relationship between MMC and the spatial coordination of the design. In a traditional design workflow this stage is entirely dependent on the architects' accumulated knowledge and the input from other disciplines. From the perspective of DfMA this means that the design must be fully reliant on the MMC selected at the early design stages. An example of such an approach would be the location of the commercial units in the concourse and the type of structural system deployed to maximise the shop frontage which, in turn, would offer more tills to serve more spectators without structural elements impeding the process. Another application is to stack up toilet facilities across floors in order to minimise pipe lengths.

### 5.4.4 Missing skills in contemporary practice and pedagogy

*Figure 5.66. Fenwick Iribarren Architects 974 Stadium prefabricated modular element sequence of construction for a structural bay (Elengical, 2022)*

The Construction Leadership Council (CLC) estimated that in 2018 more than 3.5 million people in the UK worked in the construction sector, contributing £366 billion in economic output (Construction Leadership Council, 2019). The introduction of a DfMA approach creates a major rift between the existing skills of the labour force and the requirements for MMC, in terms of both construction and project management (Thompson, 2021). To address these, the CLC proposed a major transformation of the sector and its relationship with the educational sector, with more emphasis on practice-based knowledge exchange in the form of the apprenticeship schemes. The CLC subsequently identified the areas of smart construction, carbon net zero, digital transformation, skills for repair, maintenance and improvement, and collaborative skills as the primary focus for future skills development (Construction Leadership Council, 2019). Based on the CLC research and the UK BIM Framework Learning Outcomes (Centre for Digital Built Britain, 2020) the RIBA DfMA Overlay groups the skills required for the construction sector in the future as productising skills, computer coding and data science skills, information management skills, MMC optioneering skills, manufacturing knowledge, collaboration behaviours, and integrator roles for systems engineering. All these roles are based on data-driven design, manufacturing, and project management tasks, which are already in the process of being fully automated through machine learning and AI. The contribution to the skills shortage discourse that this research makes is the empirical reinterpretation of the roles of the architect and the structural engineer in this process: these are rapidly shifting from being data-producing agents to data-management and verification roles. From the perspective of stadium design this means that in the near future there will less and less demand for draftspeople, 3D modellers, Stage 4 technical design specialists, and visualisers. On the other hand, there will be increasing interest in data managers such as BIM coordination managers and people with coding skills who can optimise aspects of design. Another important feature that emerges from this research is the understanding of the practice of the data-driven design – inevitably the architect's office of the future will employ people, but the defining characteristic of those future organisations will be the data they own – past projects and performance data which can be used to train AI models.

| Outcomes and Benefits | | | |
|---|---|---|---|
| | Has potential to contribute to achieving outcome | | |
| | Productivity | Quality | Net Zero |
| Skills for Smart Construction | ✓ | ✓ | ✓ |
| Digital Transformation | ✓ | ✓ | ✓ |
| Skills for RMI | ✓ | ✓ | ✓ |
| Collaborative Skills | ✓ | ✓ | ✓ |
| Next-generation Learning | ✓ | ✓ | ✓ |

*Figure 5.67. Construction Leadership Council (2019) anticipated benefits of change of education mode by skills group towards objectives*

The shift to identifying manufacturers in the DfMA overlay at the beginning of Stage 2 (Thompson, 2021), with the review of possible contractors even before the appointment of the project team, makes existing design workflows incompatible with the off-site manufacturing strategies in the overlay. Traditionally, other disciplines have little or no input at this design phase, but the DfMA stipulates the identification of MMC that is already incorporated in the building systems. This misalignment of programmes creates a rift in the design process that can only be addressed through a holistic approach to the design. The 2013 BIM overlay on the PoW identifies this problem and proposes an earlier start for the collaborative process through a pre-start BIM meeting aimed at agreeing on strategies and starting to develop a library of BIM objects for the all the systems in the project (Sinclair, 2013). The DfMA is even more specific, and requires a BIM library with Stage 4-ready objects and certainty over strategic parameters like floor-to-floor heights, spans, space requirements and foundation design, planning advice, and transport to be incorporated in the design as early as possible (Thompson, 2021). Given the advances in BIM technology, this process is feasible, but creates significant constraints on the design which in a traditional procurement context would have been resolved at later stages. Working with both the design teams, the client, the other stakeholders, and contractors as early as the Concept Design stage shifts the majority of the design development into this phase and transfers major sections of the subsequent design phases towards the client's team and the contractors.

The resulting shift of design deliverables towards the beginning of the DfMA process creates significant stress for the design team and requires the coordination of the design across disciplines at the late Stage 4 level. Further, the commonly accepted and predominantly anticipated process of value engineering also has to start at approximately the same time as the design itself. One of the potential solutions for such a dramatic shift in responsibility is the automation of the process itself and platform thinking, as described by the DfMA (Thompson, 2021) and the Industrial Strategy reports (Jones et al., 2019; Mosca et al., 2020). Further, the modularity of the analytical scales of this research, as described in the previous chapters, corresponds with the scales of design representation of various BIM libraries and platforms currently being promoted by the Construction Sector Deal (HM Government, 2018). In terms of stadium design, the implications of this way of thinking have a dramatic effect on the delivery process and the structure of the design team – traditionally the number of designers increases the further into the RIBA stages the project proceeds (Sinclair, 2011). In contrast to this approach DfMA presupposes a much a larger pool of skills and knowledge at this phase, while the other stages can benefit from a smaller design team aimed at coordinating the output from the manufacturing process.

# Conclusion

## 6.1 Resolution of research questions

This cross-disciplinary research aims to develop workflows for the analysis and performance-based optimisation of stadium design using machine learning within the project delivery framework of the RIBA PoW (2020). The research built on existing spatial representation and analysis methods from the fields of architecture and structural engineering. The proposed analysis and design methodology uses shared relationships and design drivers that serve as a basis for the development of a parametric model. Through a typological study, the research has also identified analytical dimensions to  improve the spectator experience, layout, and sightline quality. The output were workflows enhancing the analysis and design tasks within the RIBA PoW Stages 0 to 3 (2020) utilising evolutionary, supervised, and semi-supervised machine learning algorithms.

At the onset, the research aimed to reevaluate stadium design from the perspective of new approaches to its design analysis and optimisation with the use of computational technology in reference to modularity and data-driven design. This objective was met through the construction of the parametric model and the subsequent development of machine learning-supplemented analysis and optimisation workflows. The research objective of re-evaluation of stadium design in the context of performance-based architecture in terms of sightlines, circulation, and layout was met through the findings of the typological study and development of a set performance benchmarks based on existing case studies and a set of parametric variations. The objective to develop and validate a set of machine learning workflows that fully utilise new developments in computational technology and modern procurement strategies was met through the development of the machine-learning supplemented workflows and validated through their deployment across the requirements of the early stages of the RIBA PoW.

Approaching the stadium design task from a performance-based perspective and working across methods and methodologies from both the architectural and structural engineering fields enabled a comprehensive representation, analysis, and optimisation of stadium design in terms of spectator experience. The two primary focal points of this research from the field of engineering – parametric modelling and modular design – were successfully deployed along with methods from the architectural field, such as Space Syntax, shape grammars, and typological studies. This approach highlighted the benefits of a more holistic approach to evaluating stadium design through computational means – the quantification of layout relationships, circulation simulation, and sightline quality can be utilised to produce a comprehensive design representation that reflects the legislative environment, along with current advances in computational design technology. The research objective of a better understanding of the provision of different events in multi-use stadiums was also enriched through the parametric representation and evaluation of sightline quality.

The pipelines developed improve the existing workflows in professional practice through the reduction of subjective design decisions. The proposed data-rich environment of the parametric model allows both new types of data to be analysed and for the resulting design performance to be benchmarked and optimised. The design framework builds on current developments in modern building procurement strategies highlighted in the RIBA's BIM (Sinclair, 2013) and Design for Manufacture and Assembly (Thompson, 2021) trying to enrich the analytical and optimisation process during design. This approach allows the design process to be streamlined, reduces the coordination required across design disciplines, and enables input from all stakeholders into the design development.

Utilising methods from academic research allowed for an alternative reading of existing practices in stadium design, such as layout and circulation analysis. This approach simplifies the otherwise computationally expensive agent-based arrival and egress simulations and improves the traditional measurement of exit distances as described in the Metric Handbook (Buxton, 2018). The approach to simulating circulation further enhances our understanding of stadium design by combining the spectator seating bowl circulation, internal circulation, and paths in the masterplan into a single model. This model offers greater detail in understanding how the circulation of different sections of the building relate to each other and has the potential to improve their design in terms of safety.

The data-rich environment of the parametric model for the training of machine learning models that can reduce design time and overall project cost and can highlight previously unattainable design solutions. The ability of the parametric model to generate an unlimited number of design solutions within a design space requires a tool which can analyse this information, as the sheer number of analytical factors is beyond the human ability to recognise and evaluate patterns. Further, the multi-objective optimisation evaluate the weight of each design feature in the overall project delivery.

The methodology of this research is grounded in methods from the three major themes – architecture, structural engineering, and data science. Starting from the point of view of enhancing existing workflows with machine learning, the research has aimed to create a framework in which stadium design, modularity, and adaptability for different functions can be translated into a set of automated workflows. The research has built on the work of earlier researchers such as Hudson (2008), Turrin (2012), and Pan (2021), but has also introduced stadium space planning, masterplanning, and circulation as features of multi-objective optimisation, along with existing research on sightline quality and morphology.

An expectation at the outset of the research was that the machine learning analysis would result directly in generative design output through direct control of the inputs of the parametric model. The method of design space development, however, proved more effective in terms of legal compliance verification, performance evaluation, and multi-objective optimisation. A partial exception was the evolutionary optimisation, as the training was carried out automatically within the algorithm. Another exception was the multi-objective layout optimisation, which resulted in heat maps that can inform space planning directly.

## 6.2 Future work

The implementation of machine learning in architecture is still in its infancy, and both professional practice and academic research are exploring and trying to define impacts on the overall design delivery process. This research attempted to bring all the major layers of design constraints and external inputs into a set of workflows that can establish a novel performance-based design solutions. As an explorative research project, this thesis presents the core elements of the workflow –design drivers, parametric relationships, design space, and the consequent reduction of the design space with machine learning. This research started to define an alternative application of machine learning in architecture, but each step can be elaborated and revised further to increase its relevance to a specific project or increase the level of detail to bridge the gap between design development, the tender process, and actual manufacture and building assembly.

Design drivers and parametric relationships were based in this research on circulation, layout, and sightlines but can be expanded in future to include various other design considerations, such as player accommodation, hospitality provision, maintenance, and sustainability. The identification of shared typological characteristics and design drivers can be targeted at various aspects of design. The comparison of typologically related case studies presented in this research can identify solutions that are prevalent in one building type but less well explored in another. An example of this is the characteristics of transformable theatre spaces and their application to stadium or arena design.

The identification of shared design drivers can benefit the design and delivery process by standardising design elements across building types. Currently this process of standardisation is largely limited to engineering and manufacturing: by adopting the ideas expressed in RIBA's DfMA overlay (Thompson, 2021) a step further, this research challenges the scale of standardised elements – from the current focus on small- to medium-scale prefabrication. The scales described in the parametric model allow for prefabricated interchangeable building sections based on shared design drivers. This process of scaling up and unifying design elements has the potential to expand on the DfMA (Thompson, 2021) overlay and reduce cost, increase efficiency and performance, and improve the sustainability of design, manufacture, and assembly. The application of methods from the field of engineering such as parametric modelling to architectural design has tremendous potential to improve the space planning of future designs and to bring previously unattainable design solutions. Grounding the layout development in quantifiable design characteristics can further improve the overall legislative environment by setting building performance objectives instead of adopting the current rule-based compliance system. This process can be further enriched by increasing the detail in the simulations and the number of functions included in the optimisation. Further, this representation and simulation path can accommodate many different layout configurations which will result in better-informed designs. In terms of the parametric model itself, the workflows presented in this thesis are adaptable to various design situations and are applicable across building types. The parametric model for this research was based on typological study, but could be applied to restraints or conditions specific to other building types.

Tailoring the application of existing machine learning algorithms to specific RIBA PoW (2020) stages creates a new link between machine learning and architecture that has the potential to revise the entire project delivery process and the industry as a whole. The understanding of project delivery as a data transformation process can inform a new conceptualisation of how we deliver buildings. This process has already begun through the introduction of the early RIBA stages (2013) and the BIM (Sinclair, 2013) and DfMA (Thompson, 2021) overlays, but its scope is still limited due to its slow adoption by the construction industry. Moving beyond our current understanding of the practice of architectural design enables the identification of new data-based tasks, which will require new specialists in the field. This will reduce the project delivery tasks such as space planning, coordination, and value engineering to the evaluation of the output of the analysis by a machine learning algorithm. With the rapid development of computational technology, the complexity and speed of machine learning analysis will increase and enable more extensive and complex simulations of much larger sections of the built environment. Policy makers should therefore develop a more holistic way of controlling a building, a city, or a national development, that is rooted in data science and performance evaluation.

The process of the development and reduction of design space with machine learning is a workflow that can also transform the design process from the perspective of data science. This research presents the approach as a series of steps targeted at specific design tasks. The next step in this process is the adaptation of the workflows in professional practice by automating and encapsulating the entire process in a single software application. The ideas developed in Grasshopper (Robert McNeel & Associates, 2020) could be translated into a lower-level programming language and packaged as a software application that generates and reduces a design space. This process has the potential to make the current concept development and detailing processes obsolete, as it will be based on textual or numeric input from the designer and the output will be directly deployable on BIM platforms (Thompson, 2021) like Revit. Going further, this workflow can be extended across the entire RIBA PoW (2020) and radically challenge our understanding of the architectural profession and that of other design disciplines.

## 6.3 Contribution to knowledge

The main contribution that this research makes to both academic and professional fields is the development of much-needed integrated typological and engineering analytical and design methodology. This innovative approach bridges the gap between a qualitative understanding of space design from an architectural perspective and its quantified reading from structural and computer science points of view.

Related to this is the use of machine learning in typological analysis. Classification algorithms play a key role in the development of pattern recognition and prediction, but until now they had been rarely used for architectural typological analysis. Previous work by Kelle et al. (1995) described the basic methodology of how to construct typologies and Kluge (2000b) delineated the methodology for such analysis in the social sciences, but there is no prior research that uses precise architectural spatial data to construct types. The shift towards the use of tools that are commonly used in professional environment allows for the research to be directly applicable in practice and in the construction industry.

Parametric modelling is widely used in structural engineering and occasionally in specialised architectural offices (R. Hudson, 2008). The contribution to knowledge, both academically and professionally, is the parametric representation of structural topologies for the design and analysis of architectural space. The research creates a direct link between the functional and circulation properties of architectural space and its supporting structure within a 3D model that can be used for both academic and professional design and analysis. The research developed new structural engineering methods in its parametric model capturing issues of layout, circulation, infrastructure, safety, and experience, although similar strategies have been developed before, for example in Buro Happold's Venue Performance Rating (Pottinger, 2020).

In terms of the architectural discourse, this research project is the first to map the entire evolution of stadium modularity through the 2700 years since the emergence of the type in Ancient Greece. Stadium design has rarely been discussed in academia, and through an architectural and structural interpretation of archaeological and legislative data this research for the first time creates a comprehensive overview of what the stadium design drivers are, how they developed, how they relate to each other and how they can be combined in order to create a parametric model that can be utilised across RIBA PoW (2020) stages for analysis and optimisation. Exploring the subject from architectural, structural, legislative, and historical perspectives creates an overview of the most significant properties of these buildings and establishes the basis for the creation of multi-dimensional datasets.

In terms of multifunctionality and adaptability in stadium design, the only previous academic research that has been undertaken is that by Bader (2008). His thesis has an archival nature and maps all the adaptable areas within those buildings. Bader (2008) goes no further than cataloguing the properties of the stadium, while this research builds on these ideas and repackages modular design within a framework that works with machine learning, and the analysis is directly applicable in a professional setting within the construction industry.

Another contribution of this project is the creation of a stadiums dataset. This addressed the problem of lack of available 3d data for analysis by developing a parametric model to translate available data in 2d drawings into 3d models that can be measured. The data was further used to define the relationship between design parameters, machine learning, and statutory requirements. The multi-dimensionality of the information and the elements identified for performance analysis have direct applicability to professional stadium design, construction, and operation. This dataset also can incorporate structural data along with architectural and performance data. Through combining such material and structural properties the dataset can bring further information on the economical aspect of design and construction.

## 6.4 Relevance of research to practitioners

Stadium design is a specialist area in architectural practice. The approach to identification of design drivers, parametric simulation, and analysis and optimisation deployed in this research can be adapted in real-life projects. Automating aspects of the design workflow allows for more efficient design development, lower cost, better building performance, and better integration with the rest of the design disciplines. Rapidly changing building procurement environment creates a new set of requirements, challenges, and opportunities for the construction sector, as set out by the UK government in its support for design automation and off-site manufacturing as defined by the Industrial Strategy Construction Sector Deal (2018). The focus on offsite manufacturing and design automation (Sinclair, 2013; Thompson, 2021) creates new rules for the design process. The traditional approach towards sequentially adding more detail to a design is no longer the case as the tender phases are shifting towards the initial stages and the focus of identifying the construction systems as early as possible dominates the current procurement environment. This process radically challenges the traditional design practice. For the novel approaches to work, large sections of the design process must be automated.

This research responds to the challenges by proposing a framework that allows for working across the RIBA PoW (2020) stages through automating sections of the traditional workflows and allowing the optimisation of designs based on performance metrics and benchmarks. The workflows developed have the potential to streamline and optimise the work of practitioners in the construction and sports industries. Furthermore, policy makers and regulators can benefit from the workflows that offer a new performance-based approach to licensing, design, and compliance beyond the current reference-based approach.

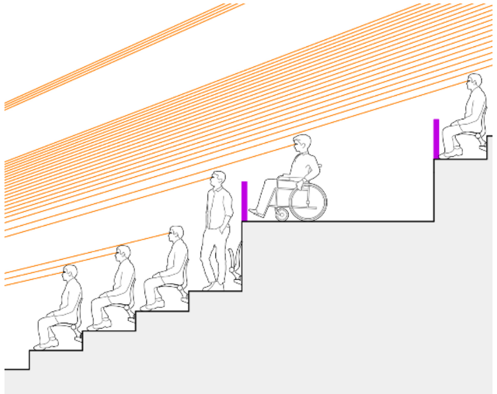
## 2D Section Generation Python Script for Grasshopper in Rhino based on 'C' value Formula

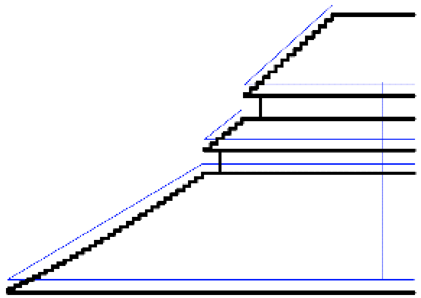
```
import Rhino.Geometry

def compute_step_height(c_value, r_value, d_value, t_value): num = (r_value + c_value)

* (d_value + t_value) denom= num/ d_value

step_height = denom- r_value return step_height


# Define inputs

c_value = float(c_value)

r_value = float(r_value)

d_value = float(d_value)

t_value =  float(t_value)

num_rows = int(num_rows)


for i in range(num_rows):
step_height = compute_step_height(c_value, r_value, d_value, t_value)


step_heights.append(step_height)

r_value += step_height d_value += t_value


z = 0

for i, height in enumerate(step_heights): x1 = (i - 1) * t_value

x2 = i * t_value

y = 0

z += height

point1 = Rhino.Geometry.Point3d(x1, y, z - height) point2 = Rhino.Geometry.Point3d(x2, y, z)

points.append(point1)

points.append(point2) z += t_value

polyline = Rhino.Geometry.Polyline(points)

a = polyline
```

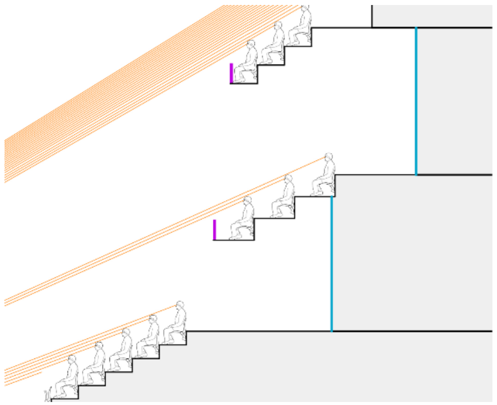
# Parametric model inputs

## *2D Section*

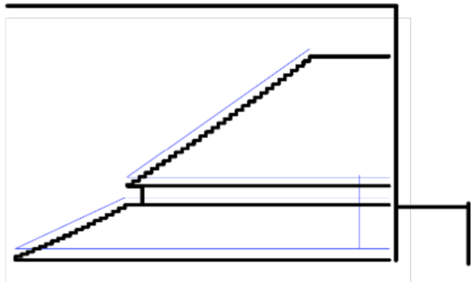
*Table Appendix.1. Parametric model inputs 2D Section scale*

| | | | | |
|---|---|---|---|---|
| **Section - Bowl -- Seats** | **C-Value** [0 - 180]<br><br>**Depth** [400mm - 500mm]<br><br>**Location on row** [back - front] | BS EN 13200-4:2006 Spectator facilities. Seats. Product characteristics<br><br>Multiple types of spectators sightline with the same C-Value requirements | Department for Culture, Media and Sport, 2008. Guide to safety in sports grounds. The Stationery Office, London. | **C-Value –** most widely used formula to estimate sightline quality. Used to generate parabolic 2D seating stand section.<br>**Depth –** seat depth. Included because it allows measurement of the clearway on the row and indicates seating comfort<br>**Location on row –** seats are located at the back of the row in modern stadium design, but historically they were also located at the front. Include to expand the scope of existing case study representation<br>**Accuracy -** Comprehensive digital representation |

| | | | | |
|---|---|---|---|---|
| **Section - Bowl -- Rows** | **Depth** [700mm - 1200mm]<br><br>**Super riser** [0-1] | BS EN 13200-1:2019 Spectator facilities. General characteristics for spectator viewing area<br><br><br><br>Typical section generated by parametric model | Department for Culture, Media and Sport, 2008. Guide to safety in sports grounds. The Stationery Office, London.<br><br>Fédération Internationale de Football Association, 2011. FIFA Stadium Safety and Security Regulations, 5th ed. FIFA, Zurich.<br>Wimmer, M., 2016. Stadium buildings: Construction and Design Manual, 1. Auflage. ed, Construction and design manual. DOM publishers, Berlin.<br>Association of British Theatre Technicians, Adams, D., Chartered Institute of Environmental Health, District Surveyors Association of England & Wales, Institute of Licensing (Great Britain), 2019. Technical standards for places of entertainment. | **Depth –** the depth of the seating row. Primary seating bowl parameter that affects morphology and circulation.<br>**Super riser** – added to include horizontal bowl circulation<br>**Accuracy -** Comprehensive digital representation<br><br>Row depth is measured from 2D sectional drawings.<br><br>Locations of super risers are extracted from the same drawing |

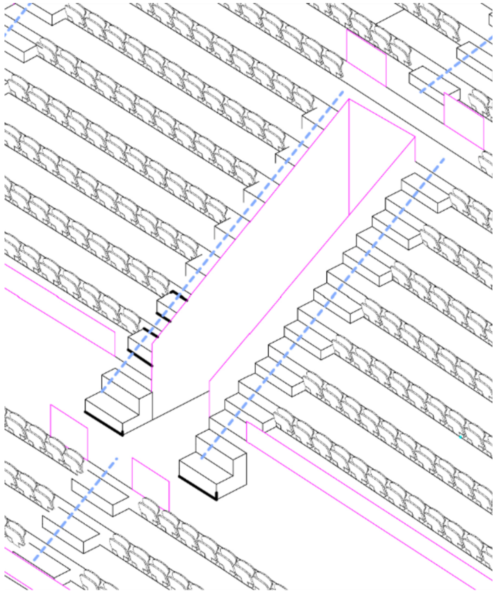
| | | | | |
|---|---|---|---|---|
| **Section - Bowl -- Tiers** | **Number** [0-10]<br><br>**Number of rows per tier** [0-60]<br><br>**Cantilever** [0mm - 12000mm]<br><br>**Landing** [0mm - 12000mm]<br><br>**Starting point** | BS EN 13200-1:2019 Spectator facilities. General characteristics for spectator viewing area<br>BS 9999: Code of practice for fire safety in the design, management and use of buildings Annex D<br><br>Multi-tier configuration with sightlines | Department for Culture, Media and Sport, 2008. Guide to safety in sports grounds. The Stationery Office, London.<br>Nixdorf, S., 2008. StadiumATLAS: technical recommendations for grandstands in modern stadia. Ernst und Sohn, Berlin.<br>John, G., Campbell, K., Sports Council (Eds.), 1981. Handbook of sports and recreational building design. Vol. 3: Outdoor sports. Architectural Press [u.a.], London.<br>Building Regulations and Approved Documents index [WWW Document], n.d. . GOV.UK. URL https://www.gov.uk/guidance/building-regulations-and-approved-documents-index (accessed 6.1.22). | **Number –** number of seating tiers in a stand. Included because it is a basic morphological and organisational feature.<br>**Number of rows per tier-** input for how many rows are in each tier. Included because it is a basic morphological and organisational feature.<br>**Cantilever** – overhang of upper tier above lower tier. Included because it is a basic morphological and organisational feature.<br><br>**Landing** – circulation zone at the top of each tier. Included because it is a basic morphological and organisational feature.<br>**Starting point** – bottom point of stand in reference to playing field. |

| | | | | |
|---|---|---|---|---|
| | [-<br>2500mm-<br>5000mm] | | | Included because it is affects sightline calculation.<br>**Accuracy -** Detailed digital representation of sightline relationships, diagrammatic structural representation |
| **Section - Interior -- Slabs** | **Height**<br>[-<br>2500mm-<br>60000mm]<br><br>**Depth**<br>[10mm-<br>3000mm] | BS 9999: Code of practice for fire safety in the design, management and use of buildings Annex D<br><br>All standards from UK Building Regulations Approved document A | Department for Culture, Media and Sport, 2008. Guide to safety in sports grounds. The Stationery Office, London.<br>Culley, P., Pascoe, J., 2009. Sports facilities and technologies. Routledge, New York.<br>Culley, P., Pascoe, J., Institution of Civil Engineers (Great Britain) (Eds.), 2015. Stadium and arena design, Second edition. ed. ICE Publishing, London. | **Height** – location of slab in the vertical. Included because it affects circulation and layout.<br>**Depth** – thickness of slab. Included because it affects amount of structure<br>**Accuracy -** Diagrammatic digital representation |
| **Section - Exterior** | **Location from ground** | All standards from UK Building Regulations | Department for Culture, Media and Sport, 2008. Guide to safety in sports grounds. The Stationery Office, London. | **Location from ground** – height of podium from ground. Included because it affects circulation. |

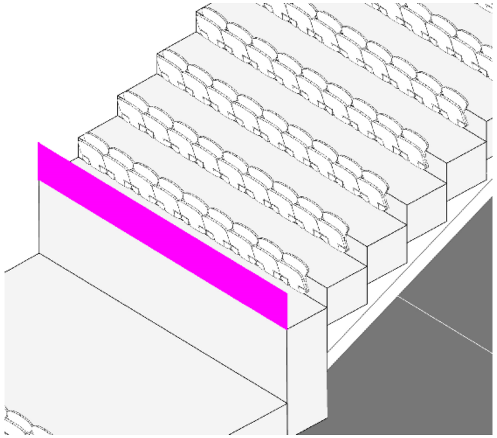
| | | | | |
|---|---|---|---|---|
| **-- Podium** | [0mm-30000mm]<br><br>**Width** [0mm-70000mm] | <br>Typical section generated by practice side | Building Regulations and Approved Documents index [WWW Document], n.d. . GOV.UK. URL https://www.gov.uk/guidance/building-regulations-and-approved-documents-index (accessed 6.1.22). | **Width** – podium width. Included because it affects circulation and amount of structure.<br>**Accuracy** - Diagrammatic digital representation |

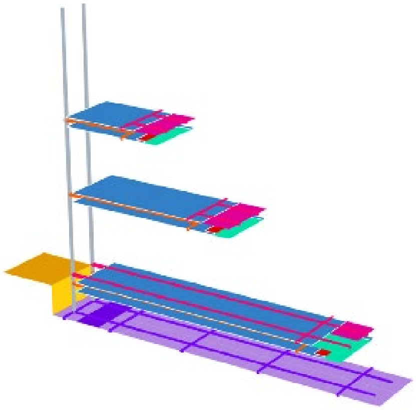
## *Bay*

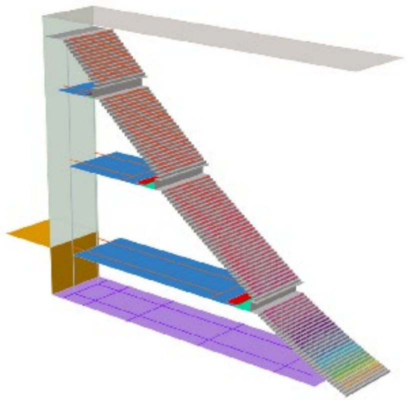
*Table Appendix.2. Parametric model inputs Bay scale*

| | | | | |
|---|---|---|---|---|
| **Bay -Bowl -- Vomitories** | **Location**<br>Bay number<br>[0 - ∞]<br><br>**Start row**<br>Row number<br>[0 - 100]<br><br>**Height**<br>Number of rows<br>[3 - 10]<br><br>**Width**<br>[1000mm - 8000mm] | BS EN 13200-1:2019 Spectator facilities. General characteristics for spectator viewing area<br><br>BS EN 13200-3:2018 Spectator facilities. Separating elements. Requirements<br><br>Vomitory and bowl circulation | Department for Culture, Media and Sport, 2008. Guide to safety in sports grounds. The Stationery Office, London.<br>Safety of Sports Grounds Act 1975 [WWW Document], 1975. URL https://www.legislation.gov.uk/ukpga/1975/52/enacted (accessed 10.26.20).<br>Fédération Internationale de Football Association, 2011. FIFA Stadium Safety and Security Regulations, 5th ed. FIFA, Zurich.<br>Nixdorf, S., 2008. StadiumATLAS: technical recommendations for grandstands in modern stadia. Ernst und Sohn, Berlin. | **Location –** bowl entry point locations. Included because they affect circulation<br>**Start row** – vertical position of vomitory in reference to the row total. Included because it affects circulation.<br>**Height** – height of vomitory in rows. Included because it affects circulation.<br>**Width** – vomitory width. Included because it affects circulation.<br>**Accuracy -** Comprehensive digital representation<br>The vomitories (bowl exits) are located based on their module bay number on the |

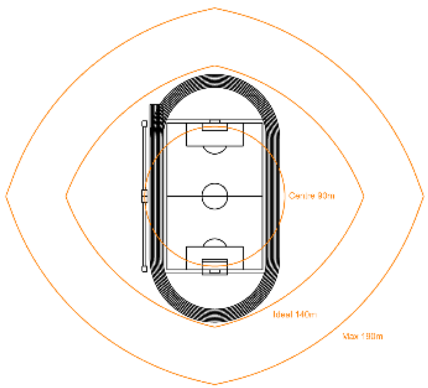
| | | | | |
|---|---|---|---|---|
| | | | | plan, the row where they connect to the bowl circulation. Their height is calculated in rows. |
| **Bay -Bowl --Seats** | **Spacing** [400mm - 700mm] | BS EN 13200-1:2019 Spectator facilities. General characteristics for spectator viewing area<br>BS EN 13200-3:2018 Spectator facilities. Separating elements. Requirements<br>BS EN 13200-4:2006 Spectator facilities. Seats. Product characteristics | Department for Culture, Media and Sport, 2008. Guide to safety in sports grounds. The Stationery Office, London.<br>Safety of Sports Grounds Act 1975 [WWW Document], 1975. URL https://www.legislation.gov.uk/ukpga/1975/52/enacted (accessed 10.26.20).<br>Fédération Internationale de Football Association, 2011. FIFA Stadium Safety and Security Regulations, 5th ed. FIFA, Zurich.<br>Nixdorf, S., 2008. StadiumATLAS: technical recommendations for grandstands in modern stadia. Ernst und Sohn, Berlin. | **Width –** seat width. Included because it affects circulation<br>**Spacing** – distance between seats. Included because it affects circulation<br>**Accuracy -** Comprehensive digital representation |

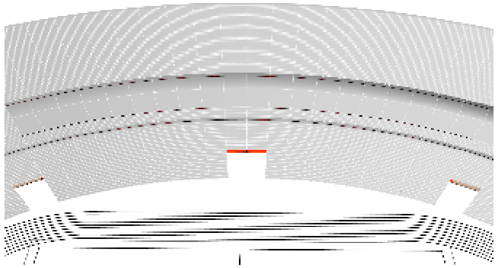
| | | | | |
|---|---|---|---|---|
| | | <br>Seat spacing within bay module | Wimmer, M., 2016. Stadium buildings: Construction and Design Manual, 1. Auflage. ed, Construction and design manual. DOM publishers, Berlin. | |
| **Bay -Interior --Vertical circulation** | **Location** Relative to slab grid | BS EN 13200-1:2019 Spectator facilities. General characteristics for spectator viewing area<br>BS EN 13200-3:2018 Spectator facilities. Separating elements. Requirements<br>UK Building Regulations Part B | Department for Culture, Media and Sport, 2008. Guide to safety in sports grounds. The Stationery Office, London.<br>Nixdorf, S., 2008. StadiumATLAS: technical recommendations for grandstands in modern stadia. Ernst und Sohn, Berlin.<br>John, G., Campbell, K., Sports Council (Eds.), 1981. Handbook of sports and recreational building design. Vol. 3: Outdoor sports. Architectural Press [u.a.], London. | **Location -** on plan. Included because it affects layout and circulation.<br>**Accuracy -** Comprehensive digital representation within typological framework Circulation is represented as areas in plan and as line in the vertical |

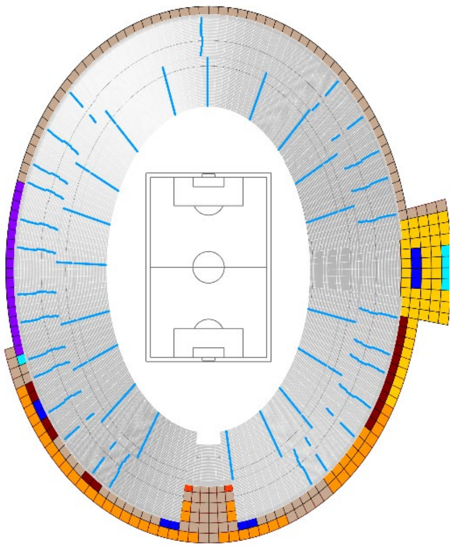
| | | | | |
|---|---|---|---|---|
| | | <br>Bay unit circulation | Building Regulations and Approved Documents index [WWW Document], n.d. . GOV.UK. URL https://www.gov.uk/guidance/building-regulations-and-approved-documents-index (accessed 6.1.22). | |
| **Bay**<br>**-Exterior**<br>**--Façade**<br>**--Roof** | **Coverage**<br>Percentage<br>[0 % - 100%]<br>**Panelisation**<br>U<br>[0 - 100]<br><br>**Panelisation**<br>V<br>[0 - 100] | BS EN 13200-1:2019 Spectator facilities. General characteristics for spectator viewing area<br>BS EN 13200-3:2018 Spectator facilities. Separating elements. Requirements | Department for Culture, Media and Sport, 2008. Guide to safety in sports grounds. The Stationery Office, London.<br><br>Nixdorf, S., 2008. StadiumATLAS: technical recommendations for grandstands in modern stadia. Ernst und Sohn, Berlin.<br><br>Building Regulations and Approved Documents index [WWW Document], n.d. . GOV.UK. URL https://www.gov.uk/guidance/building- | **Coverage -** percentage of façade area covered. Included because it informs amount of structure.<br>**Panelisation -** number of façade panels per bay. Included because it informs amount of structure.<br>**Accuracy -** Limited digital representation that allows allocation of BIM families at later stage |

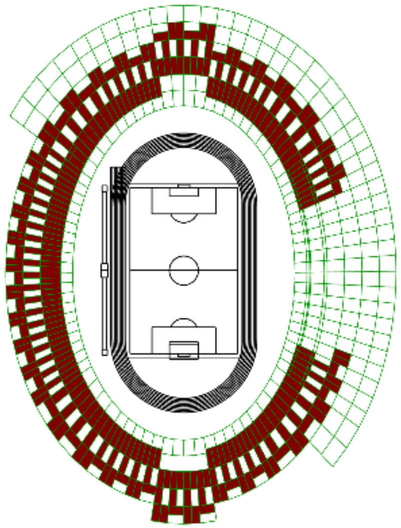
| | | | | |
|---|---|---|---|---|
| | |  Bay unit façade at back | regulations-and-approved-documents-index (accessed 6.1.22). | |

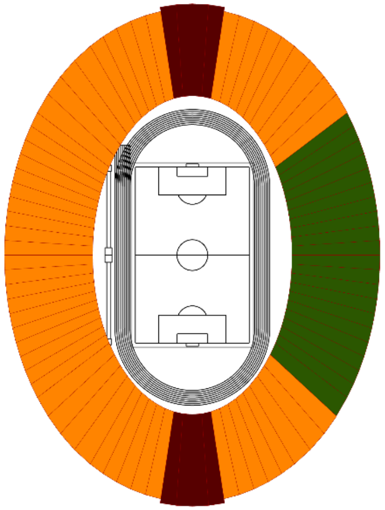
### *Sector*

| *Table Appendix.3. Parametric model inputs Bay scale* | | | | |
|---|---|---|---|---|
| **Stand -Bowl --Viewing distance** | **Maximum viewing distance** [100m - ∞mm] |   | Department for Culture, Media and Sport, 2008. Guide to safety in sports grounds. The Stationery Office, London.<br><br>John, G., Sheard, R., 1994. Stadia: a design and development guide, Butterworth Architecture design and | **Maximum viewing distance -** outer limit for stadium bowl. Included because it affects the amount of structure and circulation.<br>**Accuracy -** Comprehensive digital representation |

| | | | | |
|---|---|---|---|---|
| | | Proximity to centre of playing field, ideal and maximum viewing distances | development guides. Butterworth-Architecture, Oxford [England] ; Boston. Fédération Internationale de Football Association, 2011b. Football Stadiums Technical recommendations and requirements, 5th ed. FIFA, Zurich. | The maximum viewing distance can be adjusted based on the specific case study. |
| **Stand<br>-Bowl<br>--Tunnels** | **Bay number**<br>[0 - ∞]<br><br>**Height in rows**<br>[0 - 20] | <br>London Stadium pitch access tunnels | Department for Culture, Media and Sport, 2008. Guide to safety in sports grounds. The Stationery Office, London. John, G., Sheard, R., 1994. Stadia: a design and development guide, Butterworth Architecture design and development guides. Butterworth-Architecture, Oxford [England] ; Boston. | **Location based on bay number-** Included because it affects the amount of structure and circulation.<br>**Height in rows** -Included because it affects the amount of structure and circulation.<br>**Accuracy –** Typological constraints |
| **Stand<br>-Bowl<br>--<br>Gangways** | **Location**<br>Bay number<br>[0 - ∞]<br>**Location** | BS EN 13200-1:2019 Spectator facilities. General characteristics for spectator viewing area | Department for Culture, Media and Sport, 2008. Guide to safety in sports grounds. The Stationery Office, London. | **Location –** bowl vertical circulation. Included because it affects circulation<br>**Location relative to vomitory** – gangway |

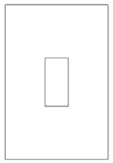
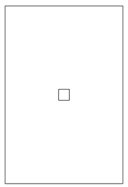
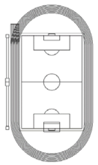
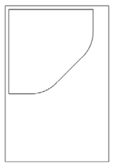
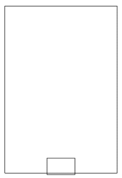
| | | | | |
|---|---|---|---|---|
| | Relative to vomitory [Left, Centre, Right, Left and right]<br>**Start row**<br>Row number [0 - 100]<br>**Height**<br>Number of rows [0 - 20]<br>**Width**<br>[1000mm - 8000mm] | BS EN 13200-3:2018 Spectator facilities. Separating elements. Requirements<br><br>Olimpiastadion, Berlin bowl cirulation | Safety of Sports Grounds Act 1975 [WWW Document], 1975. URL https://www.legislation.gov.uk/ukpga/1975/52/enacted (accessed 10.26.20).<br><br>Fédération Internationale de Football Association, 2011. FIFA Stadium Safety and Security Regulations, 5th ed. FIFA, Zurich. | location in reference to the bowl entry point. Include because it affects circulation.<br>**Start row** – vertical position of gangway start in reference to the row total. Included because it affects circulation.<br>**Height** – length of gangway in rows. Included because it affects circulation.<br>**Width** – gangway width. Included because it affects circulation.<br>**Accuracy –** Typological constraints<br>The gangways (bowl vertical circulation) are located based on their module bay number on the |

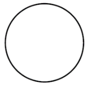
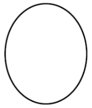
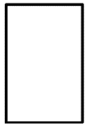
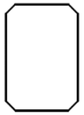
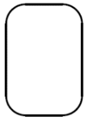
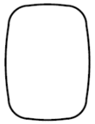
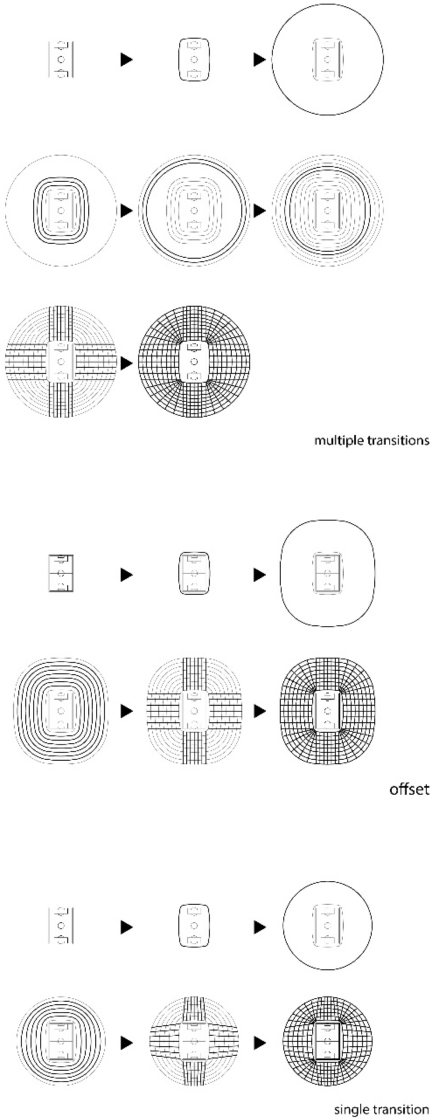
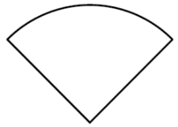
| | | | | |
|---|---|---|---|---|
| | | | | plan in reference to the vomitory position, the row where they connect to the bowl circulation. Their height is calculated in rows. |
| **Stand** **-Interior** **--Layout** | **Floor level** [-10 - ∞] **Grid offset** [1 - 6] **Cell number** [1 - ∞] **Type** [Vertical circulation, WC, Commercial, Service, Performers, Hospitality, Media, Other, |  London Stadium Concourse practice side representation | Functions are located on a simplified plan based on the cells of the structural grid. The function of each cell is input as a number. If a cell has more than one function it can be split in two either horizontally or vertically. | **Floor level -** Included because it affects the layout and circulation. **Grid offset / cell number** – functions are allocated to grid cells based on their U and V coordinates in reference to the structural grid **Accuracy -** Limited digital representation within typological framework – distortion may result if there are more than two functions per cell - any additional functions are omitted |

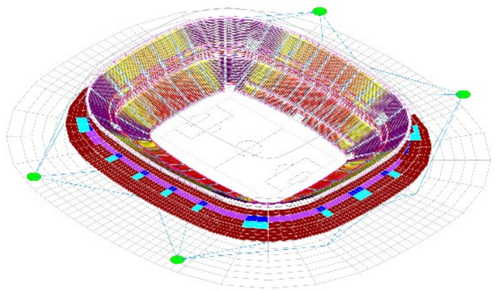
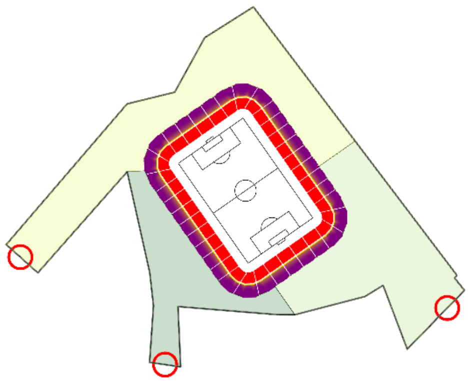
| | | | | |
|---|---|---|---|---|
| | Parking, Concourse] | | | |
| **Stand - Interior** | **Bay distribution** |  London Stadium bay distribution | Department for Culture, Media and Sport, 2008. Guide to safety in sports grounds. The Stationery Office, London. <br><br> Nixdorf, S., 2008. StadiumATLAS: technical recommendations for grandstands in modern stadia. Ernst und Sohn, Berlin. | **Allocation of module types per individual bay -** each radial bay is allocated a specific type of bay defined at the previous scale. This step is crucial in the process of representing case studies and generating 3D model. <br><br> **Accuracy -** Comprehensive digital representation within typological framework |

### *Stadium*

*Table Appendix.4. Parametric model inputs Stadium scale*

| | | | | |
|---|---|---|---|---|
| **Stadium -Field of play** | **Length** [0mm - ∞mm]<br>**Width** [0mm - ∞mm]<br>**Shape**<br>Type [Sport specific]<br><br>Tennis<br><br>Boxing | FIFA /UEFA football pitch guidance<br>WBC – boxing ring guidance<br>ATP – tennis court size<br>IOC, IAF – athletics configuration<br>BS 7370 - Grounds maintenance<br><br>BS8461 Football Goals - Code of Practice for their procurement, installation, maintenance, storage and inspection<br><br>Football / athletics<br> <br>Baseball Concert | Field Dimensions \| Glossary [WWW Document], n.d. . MLB.com. URL https://www.mlb.com/glossary/rules/field-dimensions (accessed 6.2.22).<br>World Boxing Council, 2015, Rules & Regulations of the World Boxing Council, Mexico City<br>ATP Official Rulebook \| ATP Tour \| Tennis [WWW Document], n.d. . ATP Tour. URL https://www.atptour.com/en/corporate/rulebook (accessed 6.1.22). | **Length / Width –** playing field dimensions. Included because they affect all research areas.<br>**Shape** – based on the findings from he typological study in Chapter 03, the research focuses on stadiums with rectangular playing filed which accommodates additional sports and their respected playing filed shapes<br>**Accuracy -** Comprehensive digital representation within typological framework |

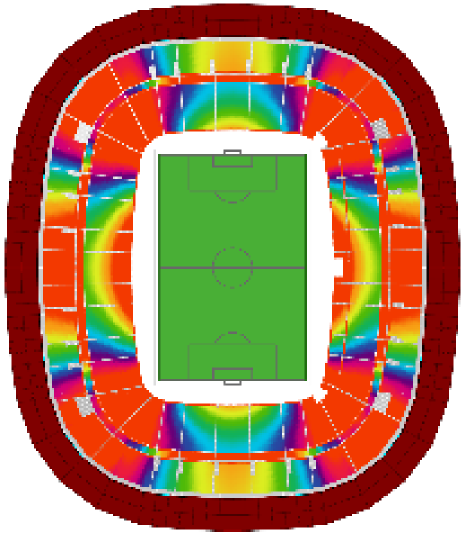
| | | | | |
|---|---|---|---|---|
| **Stadium**<br>**-Bowl**<br>**-Façade**<br>**--**<br>**Outlines** | <br>Circle<br><br>Ellipse<br><br>Rectangle<br><br>Chamfer<br><br>Fillet edges<br><br>Tangent arc | <br> | Knight, T., Stiny, G., 2015. Making grammars: From computing with shapes to computing with things. Design Studies 41, 8–28. https://doi.org/10.1016/j.destud.2015.08.006<br><br>Lee, J., Mueller, C., Fivet, C., 2016. Automatic generation of diverse equilibrium structures through shape grammars and graphic statics. International Journal of Space Structures 31, 147–164. https://doi.org/10.1177/0266351116660798<br><br>Stiny, G., Gips, J., 1972. Shape Grammars and the Generative Specification of Painting and Sculpture. Information Processing 1460–1465.<br><br>Sun, Y., Xiong, L., Su, P., 2013. Grandstand Grammar and its Computer Implementation. | **Type –** shape based on previously identified stadium morphologies from the typological study. Included because it affects all research areas.<br>**Accuracy - Accuracy –** Limited digital representation within typological framework All major outer trims in the seating bowl are captured in the model through their specific bay module type and/or the building outline<br><br>Hippodrome<br><br>Baseball |

| | | | | |
|---|---|---|---|---|
| **Stadium -- Stadium entry point** | **Location** Bay number [0 - ∞]<br><br>**Location** Level [-10 - ∞] | <br>Masterplan entry points and paths to stadium entrances | Department for Culture, Media and Sport, 2008. Guide to safety in sports grounds. The Stationery Office, London.<br>Safety of Sports Grounds Act 1975 [WWW Document], 1975. URL https://www.legislation.gov.uk/ukpga/1975/52/enacted (accessed 10.26.20). | **Location** - based on bay number. Included because it affects layout and circulation.<br>**Location** – associated building level. Included because it affects layout and circulation.<br>**Accuracy -** Comprehensive digital representation within typological framework |
| **Stadium -Exterior -- Masterplan Entry Points** | **Masterplan Entry Points** [ X;Y;Z] | <br>Masterplan entry points and Zone 4 subdivision | Department for Culture, Media and Sport, 2018. Guide to safety in sports grounds. The Stationery Office, London. | **Masterplan Entry Points –** entered as positions in reference to centre of playing field<br>**Accuracy -** Comprehensive digital representation |

# Analytical categories

## *Sightlines*

*Table Appendix.5. Analytical categories related to sightline evaluation*

| | | | | | |
|---|---|---|---|---|---|
| **Sightlines** **-Formulas** **--Planar analysis** | **C-value** **-Football / Rugby** **-Baseball** **-Tennis** **-Box** **-Concert** **-Athletics** Point Cloud [0 - 180] | **Maximise value** |  Arena da Amazonia by gmp, from practice side – note the higher resolution and contrast between this study and that by Bianconi et al. (2020) | Russell, J.S., 1938. Elementary considerations of some principles in the construction of buildings designed to accommodate spectators and auditors. *Edinburgh: New Philosophical Journal* 27, 131-136. Ham, R., 1987. *Theatres: planning guidance for design and adaptation*. Rev.ed. London: Architectural Press. UK Government. Department for Culture, Media and Sport, 2008. *Guide to safety in sports grounds*. London: The Stationery Office. John, G., Sheard, R., 1994. *Stadia: a design and development guide*, Butterworth Architecture design and development guides. Oxford; Boston, MA: Butterworth-Architecture. | **Measurement** – all distances and angles are measured within the model, as per the formula in *Guide to Safety in Sports Grounds* (Department for Culture, Media and Sport, 2008) **Evaluation** - design practice, performance criteria, research papers, benchmarks Evaluation is based on the percentage of seats with C-value above 120 **Accuracy** - Each seat is evaluated individually based on input spatial data. The point clouds contain every |

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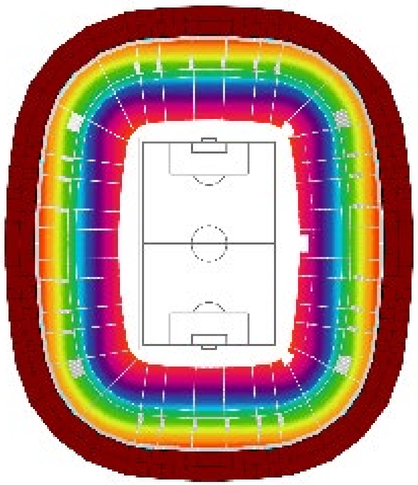
| | | | | | individual seat centre location and C-value.<br>The C-value calculation is based on the outline of the playing field / stage for each individual type of performance. |
| **Sightlines -Physical features -- Quantifiable elements** | **Distance to touchline**<br>Point Cloud<br>[0mm - 200000mm]<br>**Horizontal angle**<br>Point Cloud<br>[0 - 90]<br>**Vertical angle**<br>Point Cloud<br>[0 - 90] | **Minimise value**<br><br>**Minimise value**<br><br>**Minimise value**<br><br>**Maximise value** | <br>Arena da Amazonia distance touchline | Shepherd, P., Hudson, R., 2007. Parametric definition of Lansdowne Road stadium. Presented at the *IASS Symposium 2007 - Structural Architecture*.<br>Rafailaki, E., Dritsas, S., 2007. A computational framework for theatre design. In: *Embodying Virtual Architecture: The Third International Conference of the Arab Society for Computer Aided Architectural Design (ASCAAD 2007*) 165–182.<br>Appleton, I., 1996. *Buildings for the performing arts: a design and development guide*. Oxford: Butterworth. | **Measurement** – all distances and angles are evaluated within the model as per the analysis methodology described by Rafailaki and Dritsas (2007)<br>**Evaluation** – no published benchmarks or regulations, evaluated against benchmark case studies<br>Evaluation is based on minimalisation for distance to touchline, horizontal and vertical angle and |

| | | | | | |
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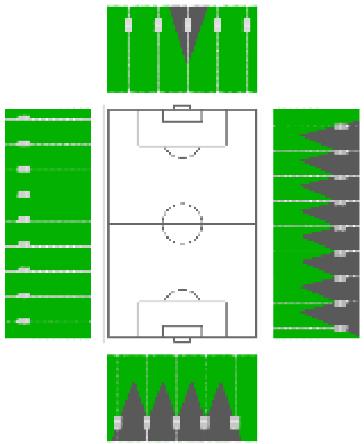
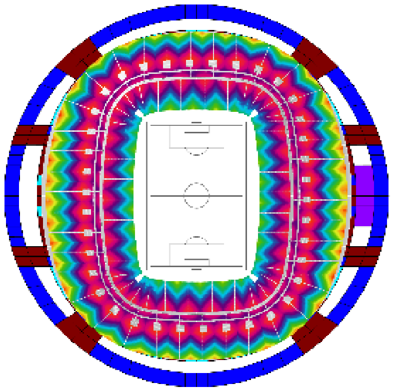
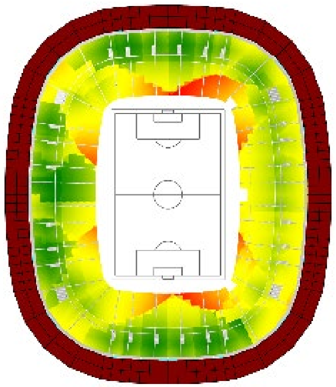
| | **Field of view**<br>Point Cloud<br>[0 - 180] | | | | maximalisation for field of view.<br>**Accuracy** - Comprehensive digital representation – each seat is evaluated individually based on input spatial data |
| **Sightlines -Physical features -- Obstructions** | **Seats with restricted views**<br>Point Cloud<br><br>[0 - 1] | **Minimise value** | <br>Craven Cottage London, Restricted views | UK Government. Department for Culture, Media and Sport, 2008. *Guide to safety in sports grounds*. London: The Stationery Office. | **Measurement** – any obstruction in the field of view classifies the seat as one with a restricted view<br><br>**Evaluation** –Minimise total<br><br>**Accuracy** - Comprehensive digital representation – each seat is evaluated individually based on input spatial data |

## *Circulation*

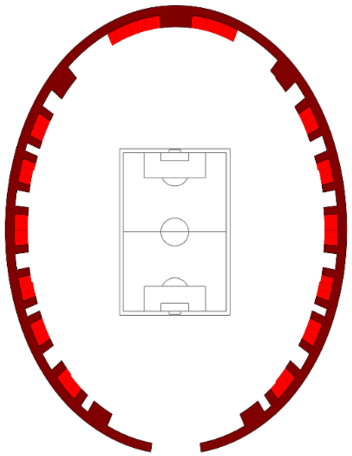
*Table Appendix.6. Analytical categories related to circulation evaluation*

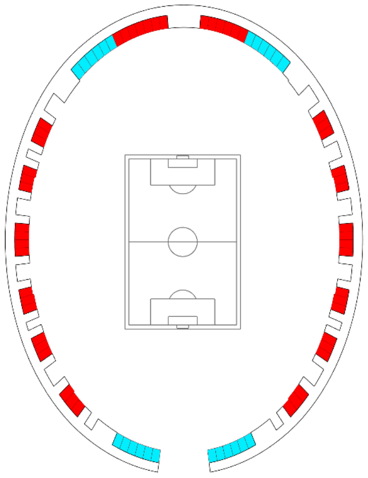
| | | | | | |
|---|---|---|---|---|---|
| **Circulation - Euclidean distance -- Distance** | **Distance seat to vertical circulation** Point Cloud [0mm - 200000mm] | **Minimise value** |  Mane Garrincha Stadium, Brazil, Seat to gangway | UK Government. Department for Culture, Media and Sport, 2008. *Guide to safety in sports grounds*. London: The Stationery Office.. Hillier, B., 2015a. *Space is the machine: A configurational theory of architecture*. CreateSpace Independent Publishing Platform. Hillier, B., Hanson, J., 2005. *The social logic of space.* Cambridge: Cambridge University Press. Hillier, B., Hanson, J., Graham, H., 1987. Ideas are in things: an application of the space syntax method to discovering house genotypes. *Environ. Plann. B* 14, 363–385. https://doi.org/10.1068/b140363 | **Measurement** – direct distance from seat to centre of gangway Distance to vomitory is also direct. **Pathfinding on the concourse is based on a grid, and using shortest path component in Grasshopper, shortest path on the grid is identified. The length of that path is then added to the groups of distances coming from the bowl exit.** **Evaluation** – limited to 7500mm for distance seat to gangway and limited to |
| | **Distance seat to stadium entrance** Point Cloud [0mm - 200000mm] | **Minimise value** | | | |
| | **Distance seat to gangway** | **Minimise value** | | | |

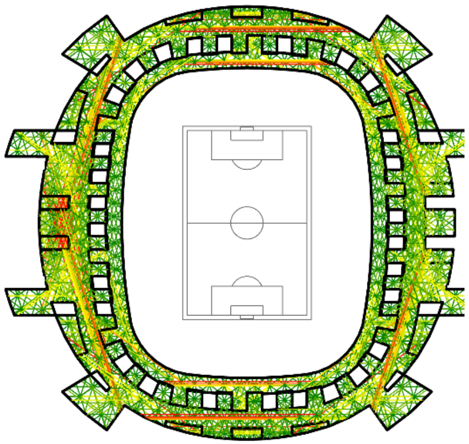
| | | | | | |
|---|---|---|---|---|---|
| | Point Cloud [0mm - 8000mm] **Distance seat to vomitory** Point Cloud [0mm - 80000mm] **Distance seat to WC / Commerciak** Point Cloud [1000mm - 200000mm] | **Minimise value** **Minimise value** **Minimise value** |  Mane Garrincha Stadium, Brazil, Seat to commercial | | 38000mm for seat to gangway based on Department for Culture, Media and Sport, 2008. *Guide to Safety in Sports Grounds.* The Stationery Office, London. The rest is based on benchmarks from the case studies. **Accuracy** - Comprehensive digital representation – each seat is evaluated individually based on input spatial data A point cloud of the basic distances from seat to bowl circulation and bowl exit. Distance is calculated in full based on the actual circulation layout. |

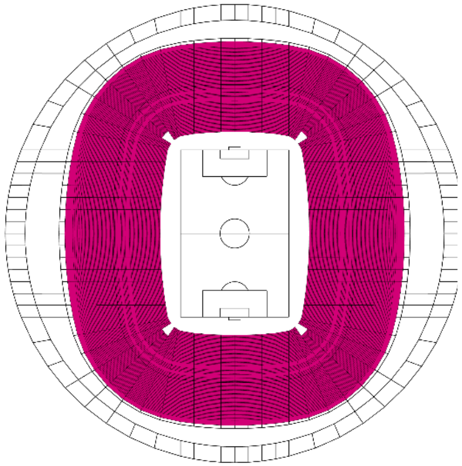
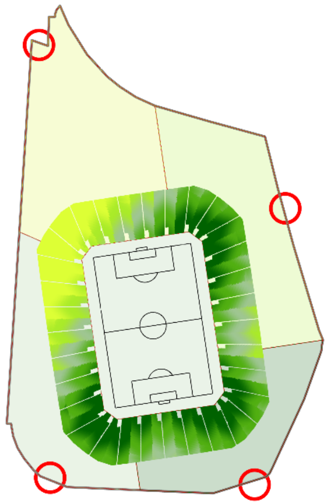
### *Layout*

*Table Appendix.7. Analytical categories related to layout evaluation*

| | | | | | |
|---|---|---|---|---|---|
| **Layout -Areas --Areas per seat** | **Concourse area per seat** [0.1m² - ∞ m²]<br>**Commercial area per seat** [0.1m² - ∞ m²]<br>**WC area per seat** [0.1m² - ∞ m²] | **Maximise value**<br>**Maximise value/case specific**<br>**Maximise value** | <br>Olympiastadion Berlin: relationship between concourse and commecial, GA concourse | UK Government. Department for Culture, Media and Sport, 2008. *Guide to safety in sports grounds*. London: The Stationery Office.<br>.<br>John, G., Sheard, R., 1997. *Stadia: a design and development guide*. Second ed. Oxford; Boston, MA: Architectural Press. | **Measurement** – from model<br>**Evaluation** – based on legal requirements in the *Guide to safety in sports grounds*<br>The analysis is extended to commercial areas per seat as it informs the commercial performance of the building<br>**Accuracy** - Comprehensive digital representation within typological framework |

| | | | | | |
|---|---|---|---|---|---|
| **Layout**<br>**-Areas**<br>**--Ratios** | **WC to concourse**<br>Area ratio<br>[0 - 1]<br>**WC to commercial**<br>Area ratio<br>[0 - 1]<br>**Concourse commercial**<br>Area ratio<br>[0 - 1]<br>**Service to commercial**<br>Area ratio<br>[0 - 1]<br>**Service to players**<br>Area ratio<br>[0 - 1] | **case specific** | <br>Olympiastadion Berlin: relationship between toilets and commecial, GA concourse | Castro, A., 2020. Geometry and digital technologies in the architecture of Herzog & de Meuron. The project for the Stamford Bridge Stadium in London, in: Viana, V., Murtinho, V., Xavier, J.P. (eds.), *Thinking, drawing, modelling* (Springer Proceedings in Mathematics & Statistics). Cham: Springer International Publishing, pp. 13–28. https://doi.org/10.1007/978-3-030-46804-0_2<br><br>UK Government. Department for Culture, Media and Sport, 2008. *Guide to safety in sports grounds*. London: The Stationery Office.<br>John, G., Sheard, R., 1997. *Stadia: a design and development guide*. Second ed. Oxford; Boston, MA: Architectural Press. | |

| | | | | | |
|---|---|---|---|---|---|
| **Layout -Internal views --Isovist** | **Isovist** Concourse visibility – viewing rays longer than 50m [0 - ∞] | **Maximise value** | <br>Mane Garrincha stadium, Brasilia, lower concourse isovist | Benedikt, M.L., 1979. To take hold of space: Isovist fields. *Environment and Planning B: Planning and Design* 6, 47–65.<br><br>Turrner, A., Penn, A., 1999. Making isovists syntactic: isovist integration analysis. In: *Proceedings of the 2nd International Symposium on Space Syntax*, Universidad de Brasil, Brazil.<br><br>Standfest, M., 2017. *Applying emergent features of architectural geometry*. Zurich: ETH Zurich | **Measurement** – from model with 2D isovist simulation algorithm<br><br>**Evaluation** – based on benchmarks<br><br>This analysis is included because it defines the internal views in the concourse – the higher percentage of long vies (rays) means that spectators can see further into the building and it will be easier for them to find their way.<br><br>**Accuracy** - Comprehensive digital representation |

| | | | | | |
|---|---|---|---|---|---|
| **Layout**<br>**-**<br>**Structure** | **Rows width distribution**<br>Average width<br>[600mm - ∞] | **Maximise value** | <br>Seating bowl width distribution | BS EN 13200-1:2019 Spectator facilities. General characteristics for spectator viewing area<br><br>BS EN 13200-3:2018 Spectator facilities. Separating elements. Requirements<br><br>UK Building Regulations Approved Document A | **Measurement** – from 3D model<br>**Evaluation** – based on benchmarks<br>This analysis describes the comfort in the viewing stand and the dimensions of the dimensions of the seating bowl .<br>**Accuracy** - Comprehensive digital representation |
| **Layout**<br>**-Masterplan** | **Zone 4 access zones**<br>Area ratio<br>[0 - 1] | **Equal distribution** |  | Based on Zone 5 as described at<br>UK Government. Department for Culture, Media and Sport, 2008. *Guide to safety in sports grounds*. London: The Stationery Office. | **Measurement** – from 3D model<br>This analysis is included because it allows crowd movement in external zone simulation. |

# Case study benchmarks


*Figure Appendix .1. Full set of case studies benchmarks*


*Figure Appendix .1. Full set of case studies benchmarks*

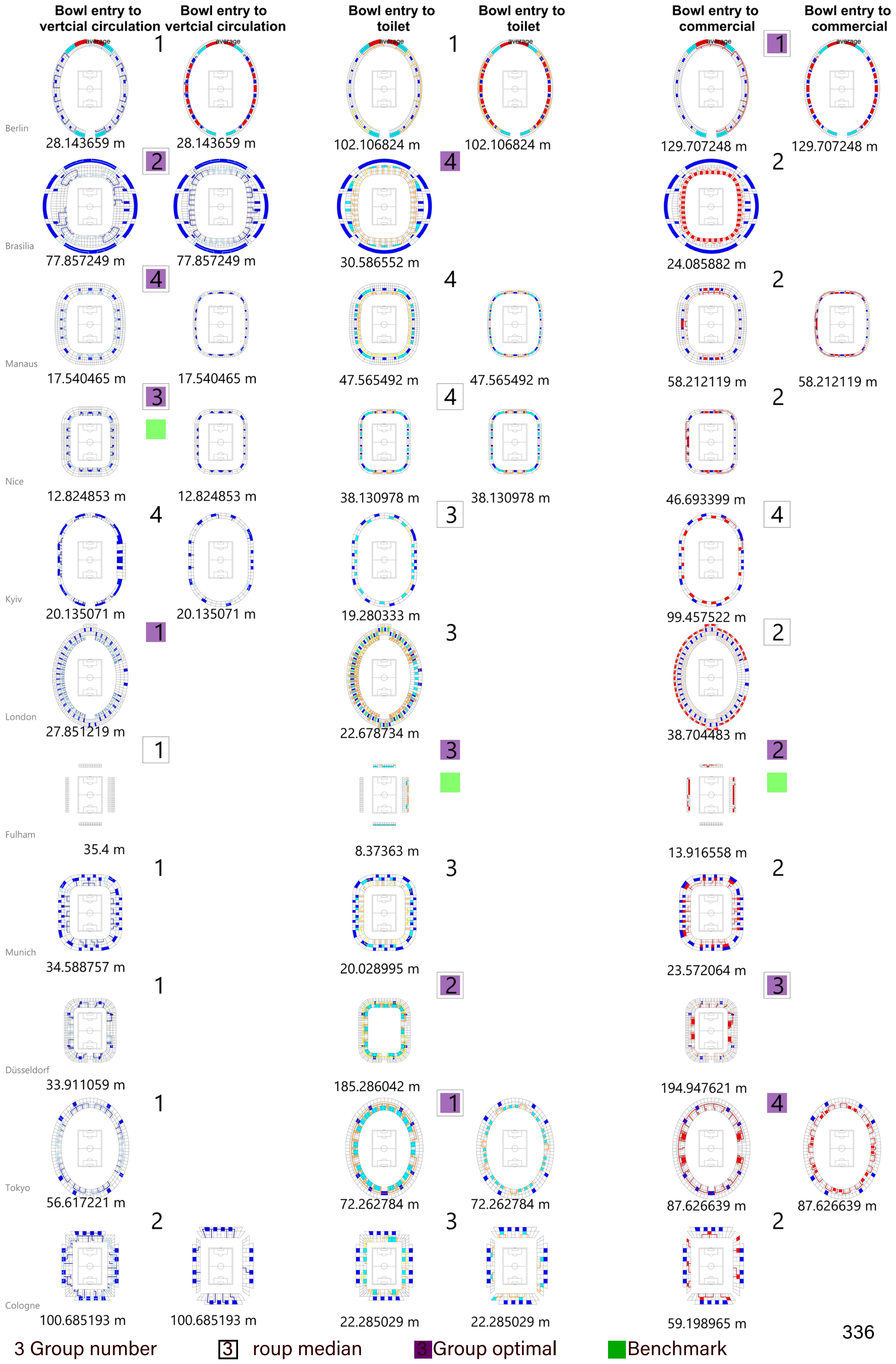





*Figure Appendix .1. Full set of case studies benchmarks*


*Figure Appendix .1. Full set of case studies benchmarks*




*Figure Appendix .1. Full set of case studies benchmarks*

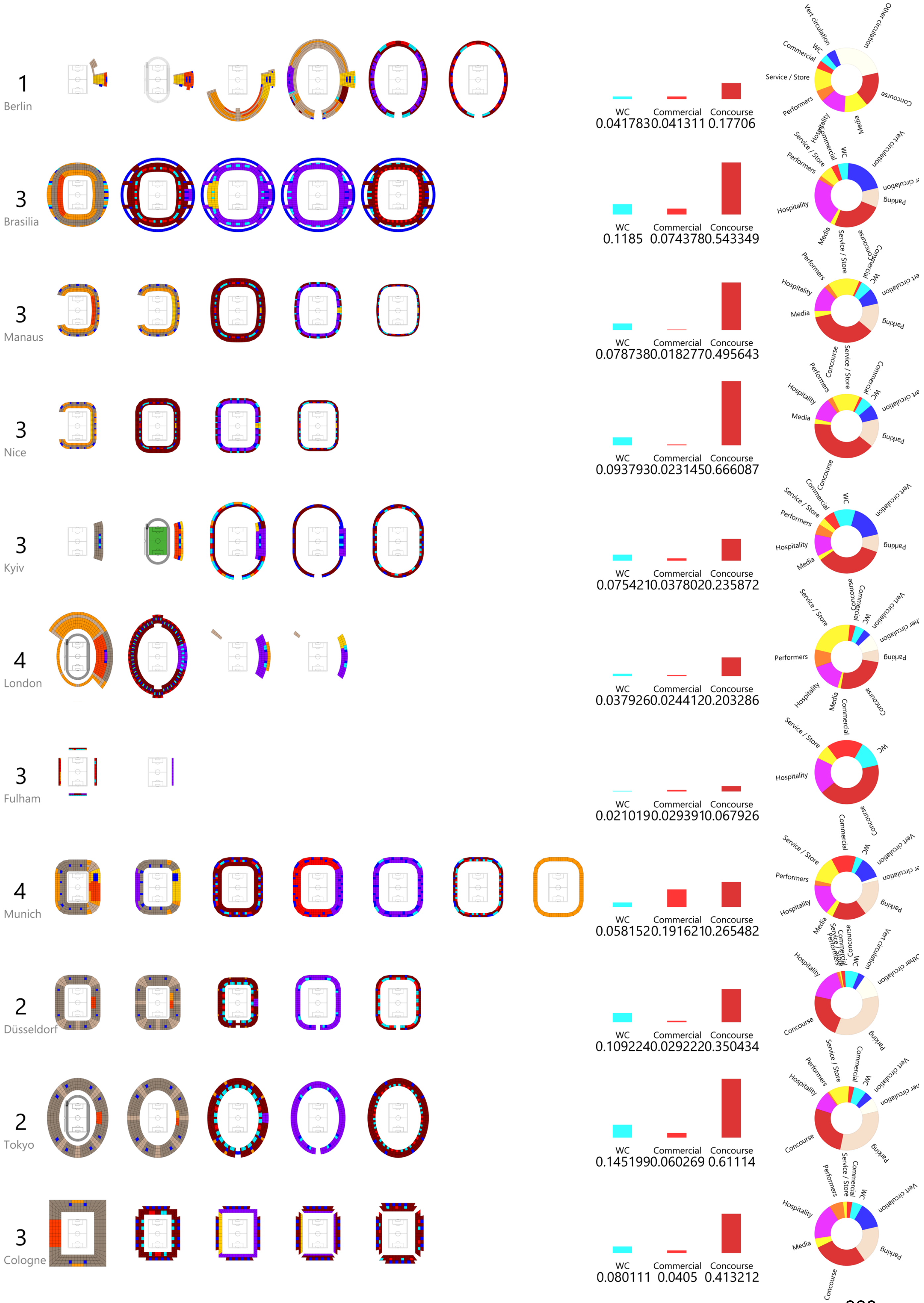





*Figure Appendix .1. Full set of case studies benchmarks*

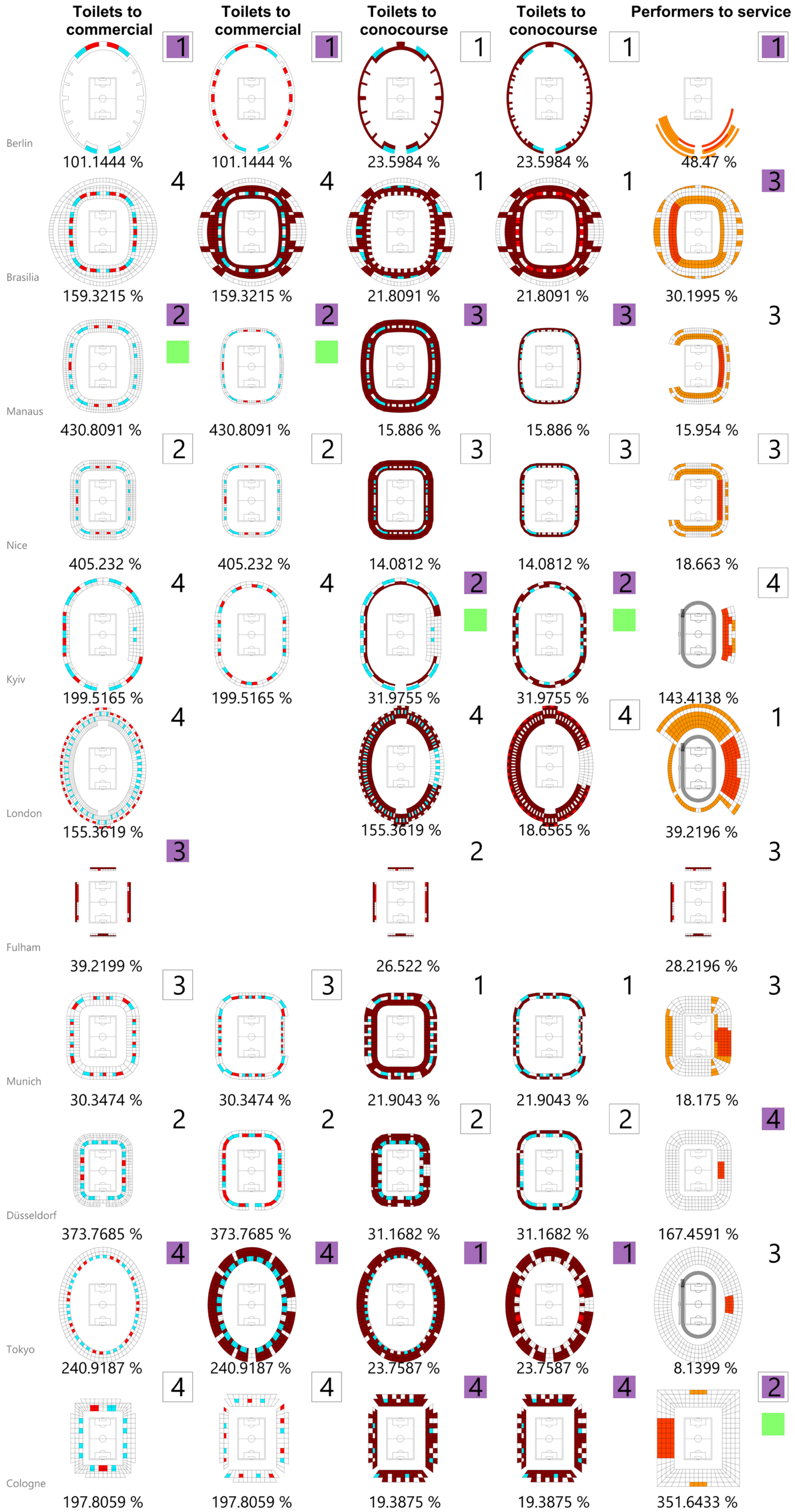





*Figure Appendix .1. Full set of case studies benchmarks*

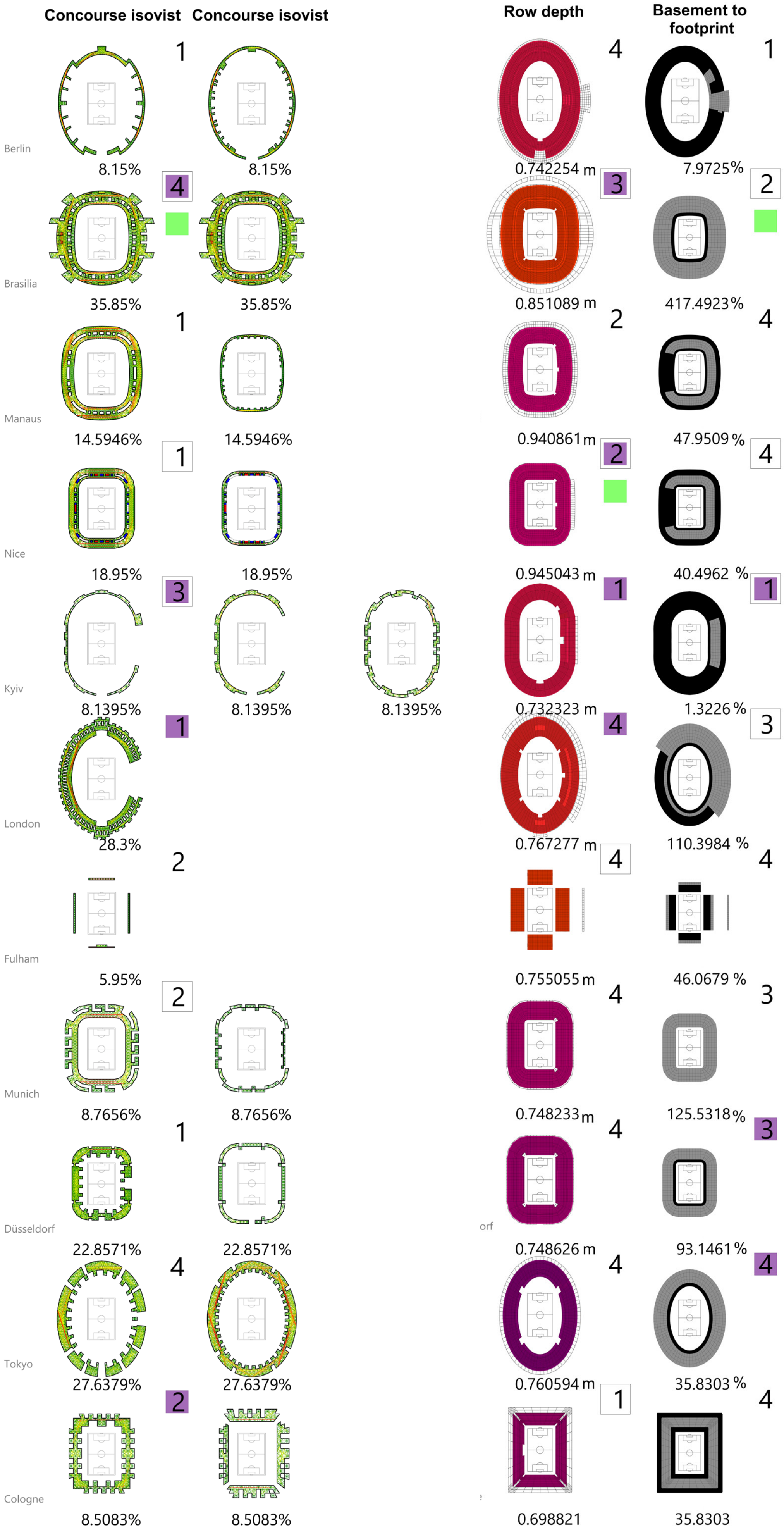





*Figure Appendix .1. Full set of case studies benchmarks*

## Typological parametric variations benchmarks

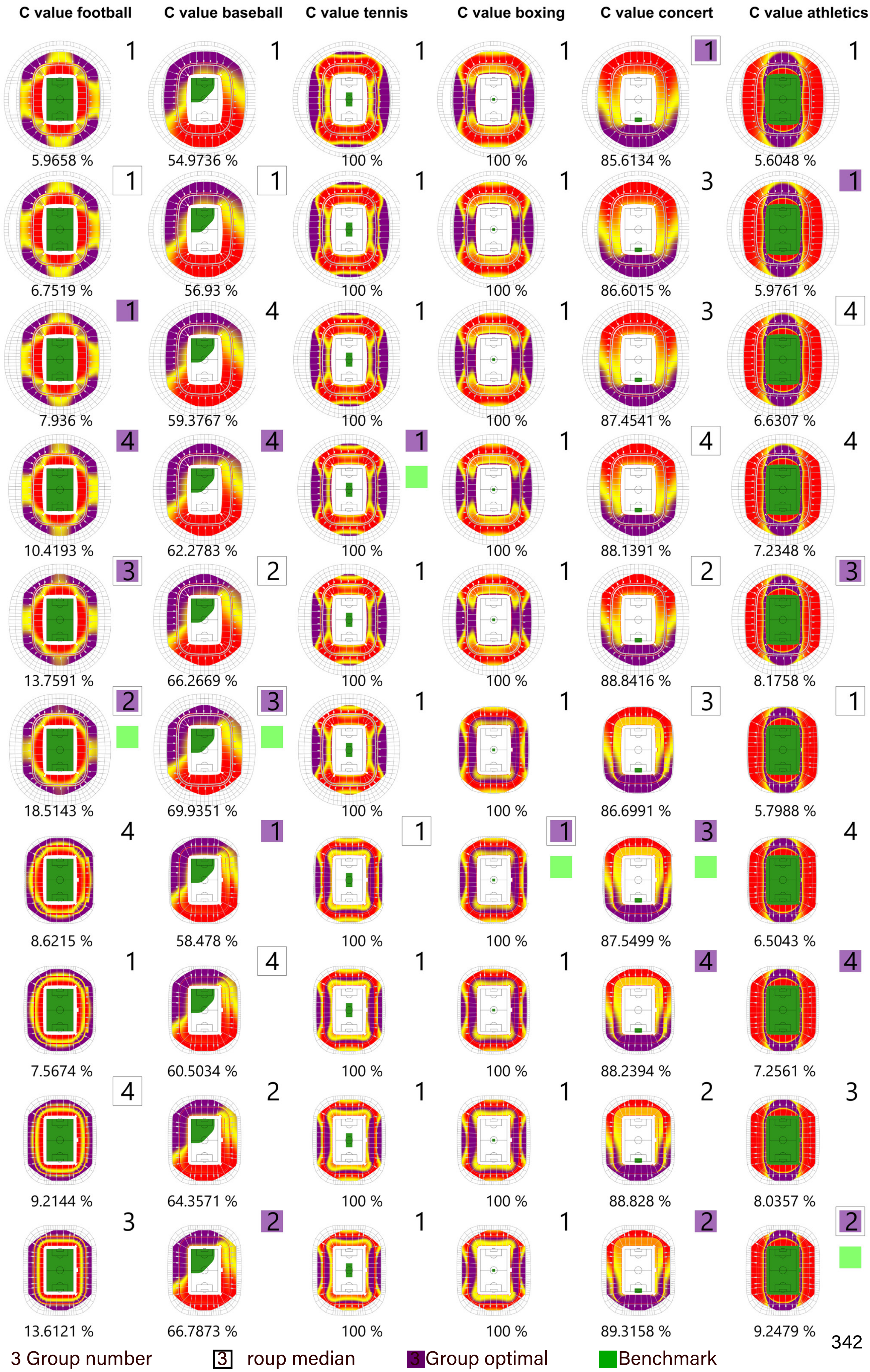





*Figure Appendix.2. Full set of typological parametric variations benchmarks*




*Figure Appendix.2. Full set of typological parametric variations benchmarks*

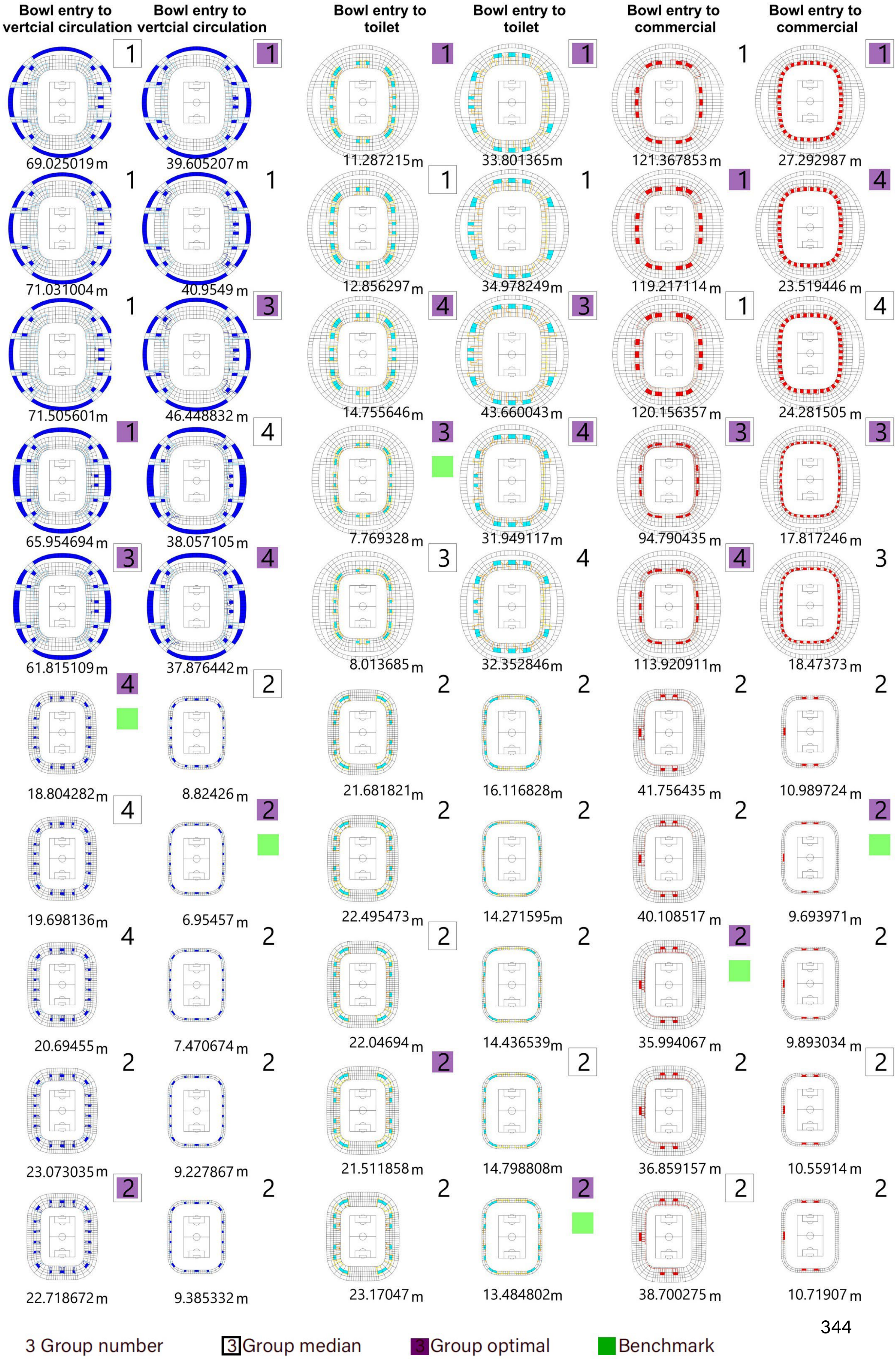





*Figure Appendix.2. Full set of typological parametric variations benchmarks*

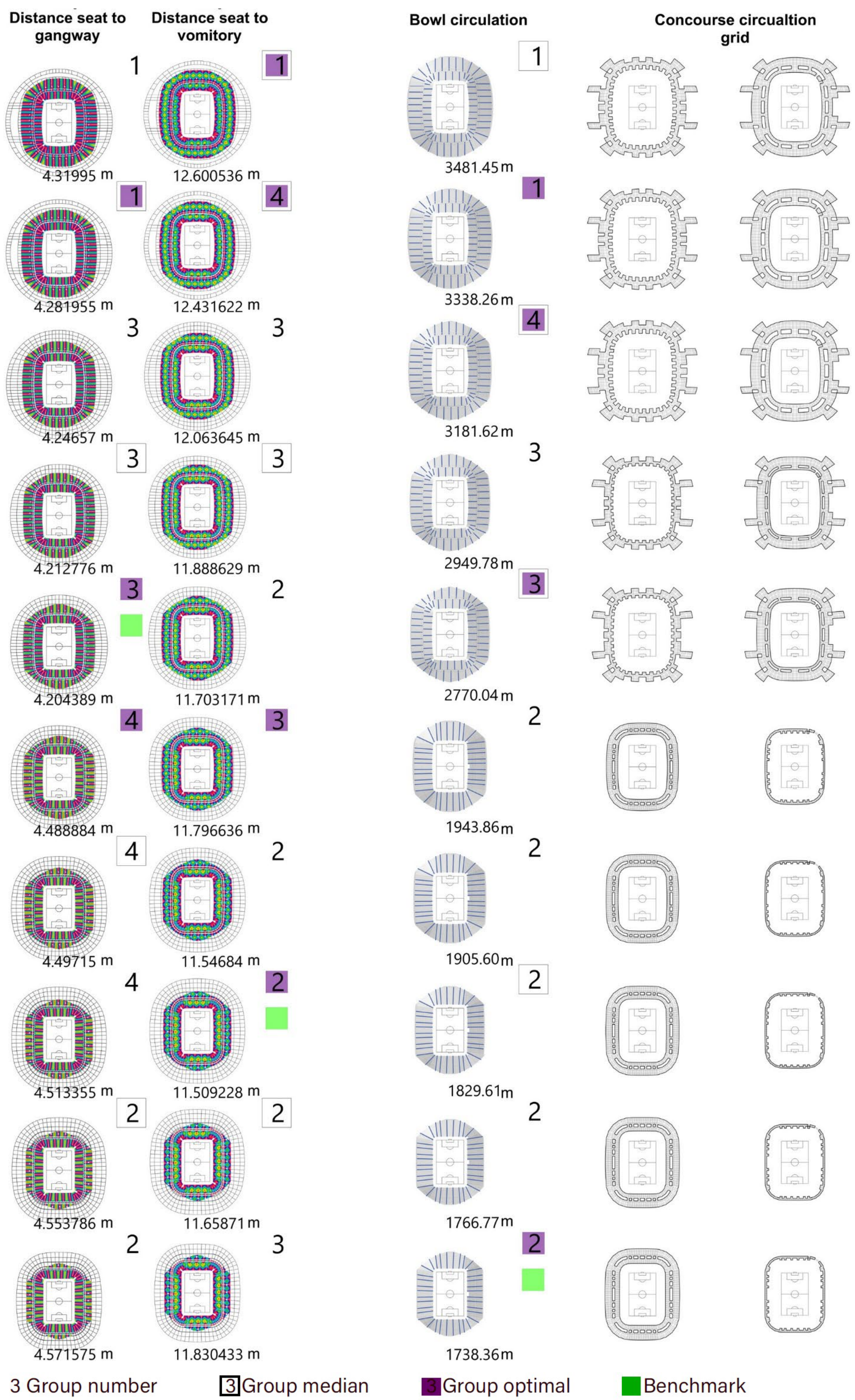





*Figure Appendix.2. Full set of typological parametric variations benchmarks*



*Figure Appendix.2. Full set of typological parametric variations benchmarks*




*Figure Appendix.2. Full set of typological parametric variations benchmarks*

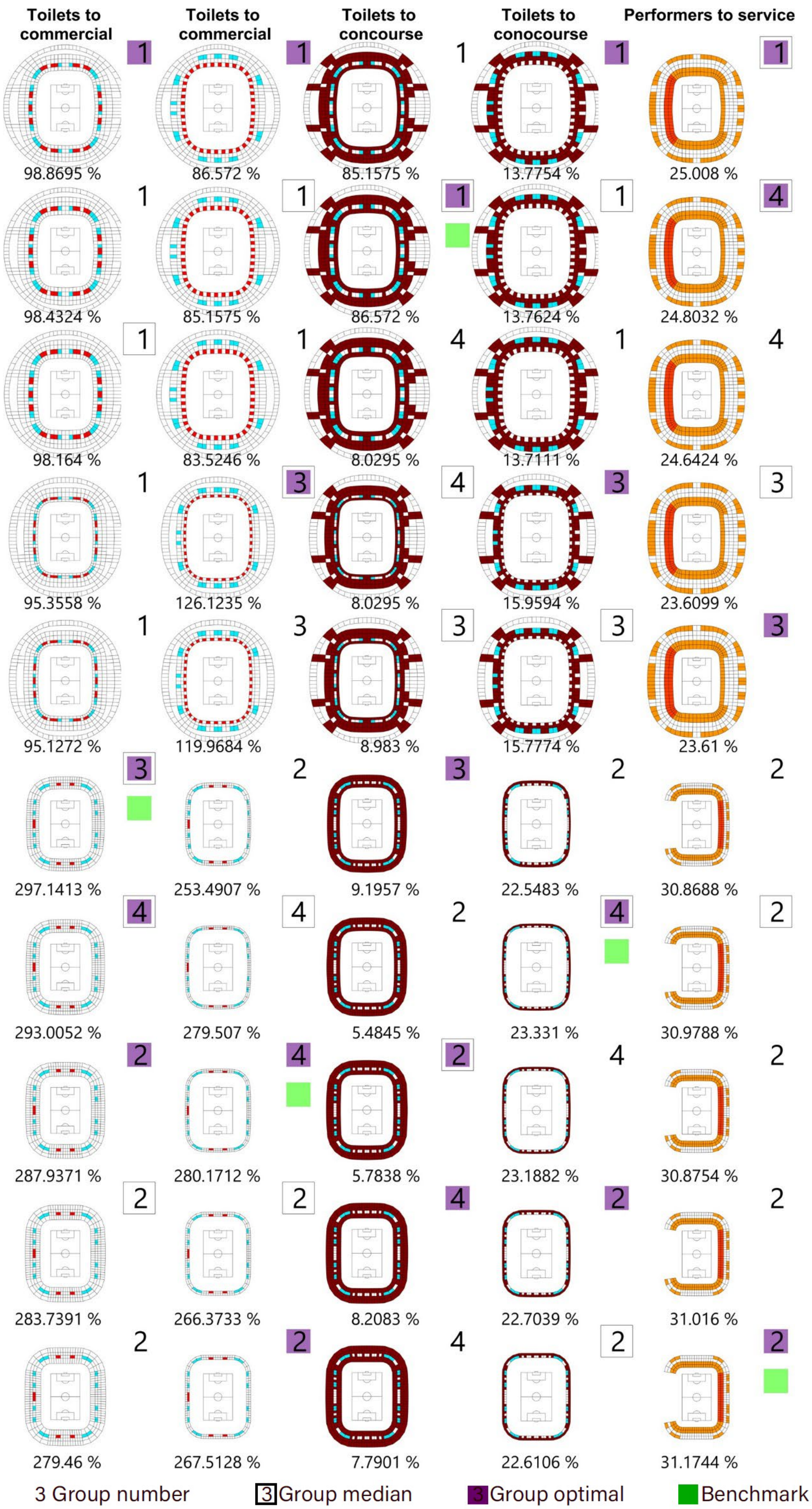





*Figure Appendix.2. Full set of typological parametric variations benchmarks*

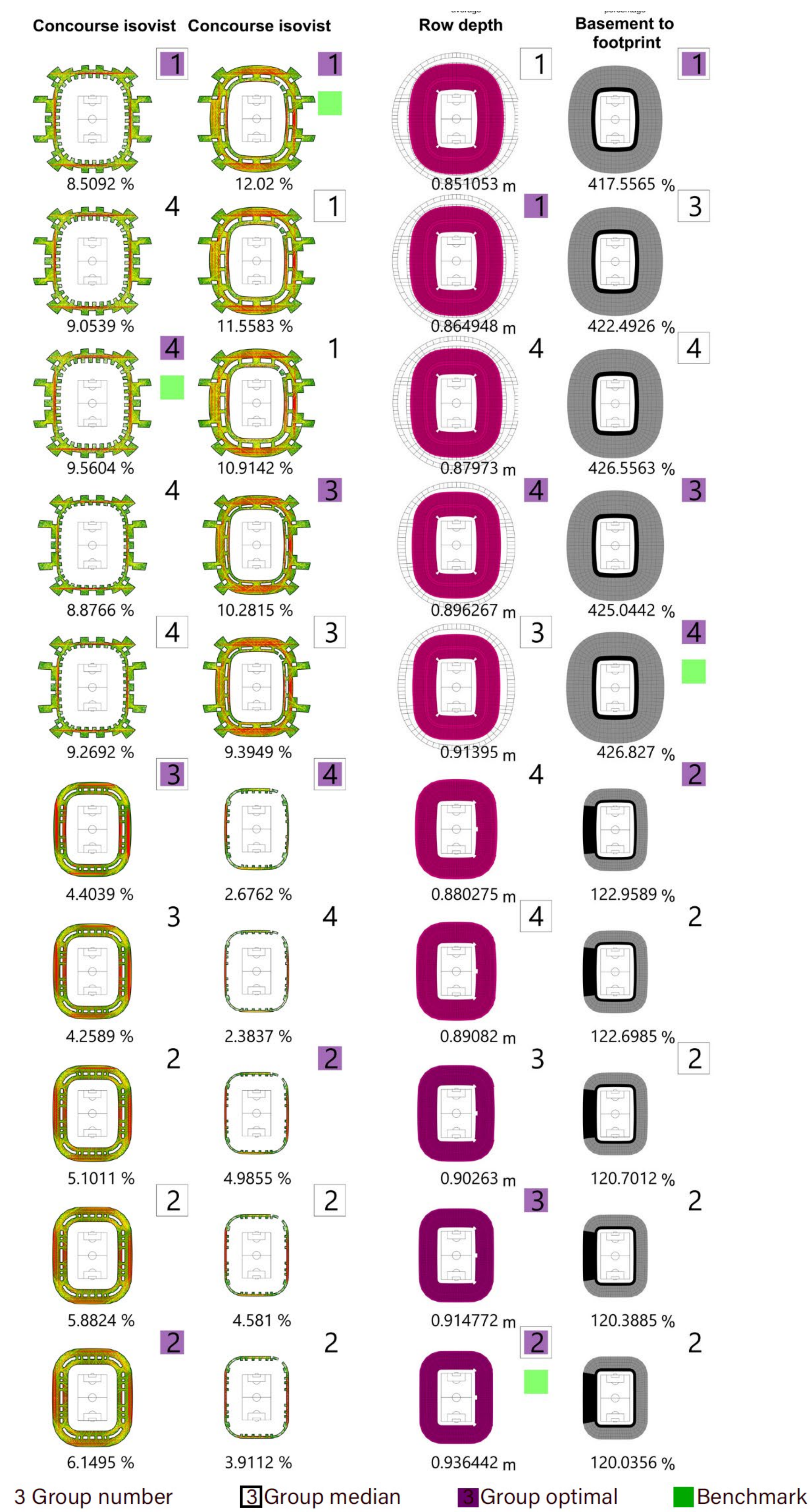



*Figure Appendix.2. Full set of typological parametric variations benchmarks*

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