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ESCOLA DAS ARTES
PORTO

THE EVOLUTION OF ACOUSTICAL DESIGN IN FOOTBALL STADIA IN THE LAST 60 YEARS

Dissertação apresentada à Universidade Católica Portuguesa
para obtenção do grau de Mestre em Som e Imagem

Pedro Gonçalo Magalhães Bacelar

Porto, Novembro de 2019

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Design de Som

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Trabalho efetuado sob a orientação de

Pedro Pestana

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ABSTRACT

Stadia acoustics have seen tremendous evolution in the last decades. Ranging from their geometry and consequent impact on sound propagation to state-of-the-art sound system designs. In fact, the way sound will function in these stadia will have a profound impact on the spectators and surrounding community. It will influence the spectators' enjoyment and determine the successful outcome of a newly inaugurated stadium, as it will reshape the soundscape its inserted in. Careful acoustical design will determine the quality of speech intelligibility in the advent of needed announcements and improve overall atmosphere.

This dissertation will strive to understand past and current trends of stadia acoustics and engineering so we can understand where we are heading. We will be discussing the origins of the football stadium, its conceptual and construction phases, choice of materials and different installation approaches. These aspects will then be supported by diverse case studies made on stadia acoustical properties throughout these last couple of centuries. Several interviews were also conducted with experts in the field of stadia design and engineering so that their methodology and vision can be further discussed. A sustainable and environmentally friendly mindset is clearly a 21st century phenomenon and football stadia do not stray away from it. This is a predicted trend for future stadia design and also applicable to their acoustical capabilities.

Keywords: acoustics, stadia, intelligibility, atmosphere

Palavras-chave: acústica, estádio, inteligibilidade, atmosfera

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GLOSSARY OF TERMS

AI – Artificial Intelligence

dB – Decibel

dBA – A-weighted Decibel

EDT – Early Decay Time

ETFE – Ethylene Tetrafluoroethylene

HVAC – Heating, Ventilating and Air-Conditioning

PTFE – Polytetrafluoroethylene

RIBA – Royal Institute of British Architects

RT – Reverberation Time

SPL – Sound Pressure Level

TL – Transmission Loss

1. Chapter One: Introduction

Stadia are important buildings in our society, offering an escape from the daily life of the spectator. They offer a venue for like-minded individuals in society to gather and share a common interest (Jenaway, 2013). The importance of these edifices to society is evident, hence the high significance of providing expert design and construction. A dissatisfactory design can compromise efficiency, safety, revenue and public opinion. Therefore, in order to properly design and construct a new stadium, we need to understand how they have evolved and why, permitting a greater understanding of modern stadia and their technological innovations.

Sound is a vital component of the football stadium. It interacts with the players, performers and spectators which will ultimately set the atmosphere for the event. As we will investigate further in this project, there are key aspects to have in mind for a successful atmosphere in the bowl. Announcements, music, emergency statements, among others, need to be properly understood by the audience. For that to happen, stadia need a proper sound system design and installation. Football stadia are subject to high sound pressure levels that need to be diffused, reflected, absorbed and contained properly within the structure. Hence, enter stadia acoustics.

Large stadia, whether enclosed or open-air, present many acoustical design challenges including excessive reverberation, echoes from surfaces distant from the sound system loudspeakers, sound absorption by air, refraction, difficulty achieving acceptable speech intelligibility, and synchronization of the sound reinforcement system to the video boards (Marsh, 2007).

This dissertation will delve into the significance and functionality of proper stadia acoustics whilst analysing its history and debating current methods and future trends. Enabling a search for improvement, we can understand mistakes from the past and use them as lessons for future projects.

1.1. Need for Research

Stadia engineering is a well-developed research topic. However, when it comes to stadia acoustics, there is lack of literature to investigate. This text will try to contradict that tendency whilst offering an amplified view of stadia acoustics methodology. As we will see onwards, the acoustics of a stadium will essentially revolve around acceptable speech intelligibility through careful sound system design and high sound pressure level control and coverage. Hence, it is important to grasp an understanding of stadia structure and form. Looking at past strategies and, sometimes, mistakes, as well as having a truly evolutive mindset will fuel a need for research that drives progress. The acoustics of these enormous buildings will have a direct impact on the stadium atmosphere which will consequently have a direct impact on the revenue of the space and determine the desire of the spectator to come back for more events.

The multi-functionality aspect of modern stadia is a relatively recent trend that requires proper overall acoustics. Hopefully, this will be a major driving force for future research in the behaviour of sound in stadia.

1.2. Research Aim and Objectives

This paper will present a theoretical analysis of the acoustical thought-process of stadia design since the 20th century and onwards. It will discuss the associated problems in the field and how these were overcome through natural and evolutionary design and construction developments.

By investigating aged and modern stadium design and construction methodologies, understanding the adaptability of acoustical enhancement solutions throughout the years is made possible. Architectural acoustics will be discussed and several case studies of acoustic measurements in stadia shall be presented in order to provide comparisons and establish a guideline amidst progressive technological advancements throughout the last sixty years. Interviews were also made with experts in the area of stadia design, engineering and acoustical consultancy with hopes to further investigate that guideline.

Upon reading this dissertation, the reader should have an understanding of the methodologies behind stadia acoustical design and where it is likely to head in the future. It involves review of available literature and consequently aims to further increase it. The ultimate aim, however, is to provide a base of understanding for the reader about stadia design and construction so acoustic considerations can be further discussed and how evolutionary changes could take stadia in the future, highlighting issues in past and present stadia.

1.3. Research Project Methodology

As aforementioned, the methodology of this dissertation follows a theoretical analysis. This is due to the fact that the topic in discussion is broad and accessibility is problematic. Therefore, available literature and other documentation will be discussed, and several interviews were arranged with those involved in the field of large-scale acoustics to better grasp past and current demands.

A list of European stadia was arranged, composed of stadia in different environments with different designs and choice of materials. Online research was extensive, and several books were thoroughly analysed in the fields of stadia design, engineering and acoustics. Available literature in this field is not abundant, so contacting the ones involved would prove resourceful. Providing a contextualization of architectural acoustics and sound behaviour in large spaces, assessing key terminologies and definitions intends to present a generalized view of acoustics and their function in such spaces.

There was a clear intent to present the evolution of acoustics in European stadia with the objective of analysing that precise evolutionary process. To learn what was done in the past, how public demand has changed and how any problems encountered were dealt with and what lessons derived from them. Several case studies will be presented for that purpose. Being a desktop study, resources are limited. Hence, further investigation is welcome.

1.4. Structure of this Dissertation

The format of the research project is presented as follows. Chapter One briefly describes the outline of the research project and introduces the research, the need for it and the ultimate goals of this dissertation.

Chapter Two will focus on the state of the art when it comes to stadia acoustics. Starting at the 20th century with the birth of the modern stadium, this chapter will discuss the evolution of the stadium environment and how it fuelled a need for acoustical awareness in these spaces, providing the stadiums of today.

Delving into the world of architectural acoustics, chapter three will present some insight into the principles of acoustics and hearing. Some notions, terms, languages and concepts are introduced so we can better understand sound in any given space.

Chapter Four will introduce us to the main research topic of this dissertation, stadia acoustics. We will investigate the structure and form of modern stadia, its materials and how they are treated to benefit the atmosphere of the stadium through sound reflection, diffusion, absorption and isolation. Here we will deepen the importance of the natural acoustics of the bowl, speech intelligibility and sound system design as well as the environmental noise impact of stadia.

With aims to further demonstrate the acoustical thought-process of football stadia through a chronological list of case studies developed in stadiums all over the world, chapter five intends to illustrate the evolution of technology in assisting stadia acoustic design throughout the 20th and 21st century.

Chapter Six will present a carefully organized chapter featuring the input of several engineers and acousticians referring to an enquiry elaborated by the author. The enquiry consists of broad topics such as current stadia design trends and more concise matters such as the use of specified materials.

Concluding the dissertation, chapter seven offers the reader a discussion of the research in a final manner. It will discuss the implications of this project and its future application to stadia acoustical design and construction for the present and future.

2. Chapter Two: State of the Art

Since Wallace Clement Sabine's work in the late 19th century, architectural and psychoacoustics have come a long way. Sabine's equation is considered one of the first steps in understanding the way sound behaves in a room. Since then, technological evolution has helped grasp a better understanding of the concept.

What are 'good acoustics'? Whilst being used regularly throughout the world, it is a truly subjective notion. The acoustics of a given room will always rely on the importance of absorption and reflection control (especially in large and loud volume environments), how the space shares and handles the frequency content of the sound, and how the space is shaped to accommodate the proposed activities (Adelman-Larsen, 2014). Also, designers will have to pay special attention to building materials, desired sound levels, distance of listeners to the source, its power, and so on (Boeck, Navvab, Heilmann, & Bisegna, 2012).

It was the failure of the design for the New York Philharmonic Hall that sparked a new generation of effort to understand what makes a good concert hall. (Barron, 2010). Scale modelling would become an interactive design aid and prevent such mishaps. Theatre design is based on hard facts and is rarely a matter of inventing new kinds of theatre. The architect works within many constraints, some of which are self-imposed, and if inventiveness comes into it at all, it is in the way that theory is put into practice. (Moro, 1982).

Studies in the 1970s were productive and work in Canada, Europe and Japan have contributed greatly. Indeed, in the 21st century acoustics came to be recognized as a science as well as an art. (Long, 2006). The development of electroacoustic devices flourished and may soon provide an equivalent or superior experience at home.

> "A sports stadium, however, also has to meet other expectations. It has to fulfil all the criteria for sustainable development. Its design and development have to be based on the latest economic, social and environmental standards. It has to be part of an urban development plan which integrates the stadium into an overall concept.

This underlines that neither stadia, nor sport, can live in isolation. They have to be part of everyone's life and society."

(Rogge, 2007)

2.1. The Evolution of the Stadium in the 20th and 21st Century

Pierre de Coubertin (1863 – 1937) was the founder of the International Olympic Committee and is known as the father of the modern Olympic Games. 1896 saw the rebirth of the Olympic Games in Athens, Greece. With it, came the renovation of the Panathenaic Stadium to accommodate for the expected visitors. This marked a critical point in the history of sports and stadia as it led to the construction and development of sports stadia all over the world (Jenaway, 2013).

By 1908, London was selected to host the 1908 Olympic Games and with it came the precursor for the modern generation of stadiums: The White City Stadium. It had initial influences of the Panathenaic Stadium due to its success, employed the use of a steel structure as opposed to the common use of materials such as stone and marble and presented itself as a pioneer in the ideology of the seated stadium (Yaroni, 2012). Through the White City Stadium, we see a will to accommodate for a high number of spectators and different activities: highlighting one of the predominant reasons for the first-generation stadia.

Figure 2. 1.: The White City Stadium, England (Tomizawa, 2016).

Rod Sheard (2005) states there are five generations of modern stadia that can be classified, each marking a new step in the evolutionary process. He defines these as:

- First generation — emphasis on accommodating large numbers of spectators.
- Second generation — increasing spectator comfort and improving support facilities.
- Third generation — the family stadium, with a focus on safety and reducing anti-social behaviours.
- Fourth generation — multi-functional stadiums, funded by corporate sponsorship and media.
- Fifth generation — catalyst for urban regeneration.

As we have seen, White City Stadium can be highlighted as an example of a first-generation stadium since its focus was the seating of a high number of spectators and little regard for comfort or integrated facilities.

The invention and diffusion of television through the 1930s and 1940s led to two important evolutions in stadia design. The first of those influenced spectator experience to continue attracting audience. This led to improved seating, incorporation of toilets and food and beverage facilities. The second evolution intended to provide a better experience also for those at home which led to, among other things, artificial lighting and the possibility of nightly events, advertising and improved appearance on television.

Reaching the third generation, stadia would start to be developed focusing on safety and family-friendly environments which would start to attract a more diverse crowd to the stadium. This generation had a high commercial focus and enjoyed increased revenue via the marketing and communication aspects of stadia. It further improved stadia lighting, acoustics, sound reinforcement and advertising.

The fourth generation focused on the multiple uses of stadiums and inherent flexibility to host a variety of events. Functionality and flexibility are key aspects to this generation and further enhanced investigation of acoustics for multipurpose use.

The fifth and last generation starts to target unique ideas and designs for stadia that make it stand out in the surrounds of the city to aid in urban renewal. Some recent stadiums (e.g., New Tottenham Hotspur's Stadium) aren't just that, they are entire sporting and entertainment precincts. The focus of this generation is creating sustainable and integrated environments where stadia often act as catalysts for diversity, vibrancy and regeneration within a city (Jenaway, 2013).

2.2. Stadium Environment

> "Stadiums and outdoor venues present designers with a set of challenges which are not usually encountered in interior spaces. The leading challenge is the immense distance over which sound of an appreciable level must be projected. This is followed by the fact that the sound is not propagating in a stable medium – i.e., outdoors the air temperature and relative humidity are erratic variables and the air is hardly ever still. Lastly, in addition to the normal 6 dB loss for doubling of distance from a point source in a free field, there exists an additional attenuation from atmospheric absorption whose value is a function of frequency and depends on both temperature and relative humidity."
>
> (Patronis Jr., 2008)

The first 50 years of the 20th Century saw a combination of materials start to take shape in stadium construction, including wood, concrete and steel. But as the sizes of stadia continued to grow, so did their use, leading us into an age in the U.S. by the '50s and '60s where large concrete structures were built plain and abstract enough to welcome basically any event, no matter the use (Newcomb, 2015). This line of thinking also created the domed stadium, first seen in 1965 when the nearly 68,000-seat Astrodome became the first in line.

With the evolution in construction and engineering technologies, the acoustic qualities of such a large space would also start to be frequent subject for investigation. The article *Acoustical Design of the Houston Astrodome* by Theodore J. Schultz (1966) is one of, if not, the first acoustical design analysis for a sports arena.

> "It was recognized early in the preliminary planning for this building that its extraordinary size would perhaps present acoustical problems which had never been faced before in the realm of room acoustics. There was no question here of attempting to achieve the refined acoustics of a large conventional auditorium, yet the scale of this building was so far beyond our experience at the time that we found it hard even to conceive what difficulties might arise."
>
> (Schultz, 1966)

Figure 2. 2.: Houston Astrodome, USA (CNN International, 2018)

It involved model-scale acoustical measurements using the Charlotte Arena in North Carolina whose dimensions would be close to half of the Houston Arena. Following this procedure, it would be possible to predict the effectiveness of the absorbing treatment intended, predict reverberation time, any peculiar effects of the dome, crowd noise and its variation throughout the seating area and if a similar sound system installation to the one in Charlotte would be worthwhile.

By this time, sound system reinforcement was already largely considered. In this case, the sound system was primarily designed to ensure high speech intelligibility and good reproduction of music in a large space with less than optimal conditions. Sound system design remains a critical component of stadia acoustics as of today and often investigated throughout the years (Schultz, 1966; Figwer & Philbrick Jr., 1977; Papanikolaou, Pergantis, & Trochidis, 1983; Jones & Griffiths, 1991; Willsallen & Cabrera, 2004). Another important scope of this research was the evaluation of noise levels. Up until now, attenuating these noise levels would often infer means of site isolation from mostly external sources. In the case of sports arenas, where the spectators can generate levels in excess of 100 dBA, noise would now become a sizeable concern (Alton Everest & Pohlmann, 2015).

Reaching the 1980s and 1990s, stadiums started do develop multi-functionality characteristics. They would now host music concerts, conferences and other sport activities like never before. This would motivate further sound system and speech intelligibility research (Somek & Strizic, 1987; Jones & Griffiths, 1991). Furthermore, in the advent of progressively increased revenues from television and investors, enhancing the spectator experience in the stadium continued to be worthwhile.

> “However, the effects of sport stadium atmosphere on consumer behaviour have received comparatively little attention from researchers to date. Our understanding of the construct of sport stadium atmosphere is still at a rudimentary stage. It remains unclear what specific factors contribute to the stadium atmosphere. There are no attempts in the literature to develop sport stadium atmosphere as a theoretical construct and to operationalize it for use in empirical studies. It is therefore impossible at present to investigate adequately the relationship between stadium atmosphere and variables with important financial implications, such as on-site food and beverage consumption, spectator satisfaction, and positive word-of-mouth. (…) Sport stadium atmosphere can be tentatively defined, then, as the relationship between perceptions of the specific environmental features of a sport

stadium and the elicited affective responses of the spectators."

(Uhrich & Benkenstein, 2010)

Over the last twenty years, modern day stadia have become unique structures that highlight the urban landscape of a town and are often a focal point in a city. They strive to incorporate new and different ideas to enhance the experience of the players, spectators and home television viewers. Modern day stadia enhance the local economy, boost tourism and provide an opportunity for spectators to witness their local sporting heroes in action. Modern day stadia also have new ideologies, from sustainability to environmentally friendly and zero-emission contributors. This has led to amazing evolutionary advancements in stadia technology, design, construction and utilisation (Jenaway, 2013).

Today, stadium uses are predicted and defined, playing surface and pitch selection is possible, site selection, structural materials and structural support systems for stadium roofs are clinically considered factors. A recent trend in the last two decades is the incorporation of EFTE[1] panels in stadium construction. These usually contribute more towards the aesthetic or cladding of these buildings. They are often based on the availability near the stadium (e.g., lower costs in materials in some countries will attract architects and engineers).

Some materials such as the ETFE panels are chosen more for a unique design and to create something truly spectacular, such as the Allianz Arena in Munich, Germany. In this present day, materials are also selected based on environmental and sustainability factors. Materials that present environmental advantages or represent sustainable efforts such as ETFE panels, which absorb solar radiation and reduce thermal loss, are highly regarded as viable construction materials in modern stadia (Jenaway, 2013). Thanks to Jung Joong Kim, Jeong Ho Jeong and Jang-Yeul Sohn (2009), the sound absorption qualities of these materials have already been investigated.

[1] Ethylene Tetrafluoroethylene

Figure 2. 3.: The Allianz Arena, Germany (Bundesliga, 2019)

There are downsides to utilising this material, however. It requires a sophisticated design and a series of steel networks to achieve the desired outcome. They also require very careful detailing of rainwater guttering and maintenance which can be time consuming.

Amidst all evolution, stadium acoustics have become vital towards an enveloping stadium atmosphere. Thanks to the digital era, scale models are developed via computer which allows more reliable predictions. The environmental impact of stadiums is weighed and enhancing the spectator's experience is a mission. Today, designers and engineers involved with stadia design and construction are increasingly looking towards new technologies in order to improve stadium functionality, design, overall look, environmental footprint and long term sustainability. This has led to incorporation of many new and unique elements in modern stadia as engineers look to create the most memorable, sustainable and environmentally sensitive stadiums. Research efforts in the area of stadium acoustics and atmosphere continue today (Navvab, Heilmann, & Sulisz, 2008; Boeck, Navvab, Heilmann, & Bisegna, 2012; Sarwono, Prasetiyo, & Natanael, 2016).

3. Chapter Three: Architectural Acoustics

3.1. Introduction

The arts of music, drama and public discourse have both been influenced and been influenced by the acoustics and architecture of their presentation environments (Long, 2006). In the architectural world of stadia, the patent atmosphere of such buildings is deeply interconnected to the acoustical response of the edifice. Ranging from a seating capacity of a few hundred to several thousands, the nature of the application determines the acoustical priorities of the space. For example, in a place of worship, the building may require a specific design enhancing speech intelligibility, whereas a concert hall may demand longer reverberation times even at lower frequencies. Very generally, we may consider the design of large spaces in two aspects: spaces primarily intended for speech and those primarily intended for music (Alton Everest & Pohlmann, 2015). Stadia, as we will see in future chapters, will require a blend of both these aspects.

3.2. Principles of Acoustics and Hearing

3.2.1. Nature of Sound

Sound is the sensation perceived by the human ear resulting from rapid fluctuations in air pressure (Ginn & Sc., 1978). A passage of a sound wave causes air particles to move forwards and backwards parallel to the direction of motion of the wave. Therefore, whilst travelling in the air medium, sound waves are longitudinal.

When an air particle is displaced from its original position, elastic forces of the air tend to restore it to its original position. Because of the inertia of the particle, it overshoots its resting position, bringing elastic forces into play in the opposite direction and revealing the critical importance of sound in elastic mediums. It is readily conducted in gases, liquids and solids and travels at different speeds for each due to different properties of mass and elasticity. Without a medium, sound cannot be propagated (Alton Everest & Pohlmann, 2015).

When the amplitude of the sound is not compromised, it will travel at a fixed speed of sound of 343 m/s (or 1125 ft/sec) at 20ºC. However, its speed, as with light, is dependent of the medium through which it transverses, as well as other factors such as the medium's molecular structure, temperature, humidity, and so on.

3.2.2. Frequency and Wavelength

A frequency is a steady state sound produced by the repeating back and forth movement of an object at regular intervals (Long, 2006). It specifies the number of cycles per second and it is expressed in Hertz (Hz), named after Heinrich Rudolf Hertz. The wavelength is the distance a wave travels in the time it takes to complete one cycle.

Frequency intrudes into all aspects of acoustics. Typically, almost all musical instruments cannot produce a pure tone, instead producing more complex sounds with the harmonics of that tone. The lowest of these perceived frequencies normally determines the pitch of the sound. The human ear can perceive frequencies between 20 and 20,000 Hz although the upper limit decreases with age.

Frequency is also perceived in a logarithmic fashion by our ear. Audio engineers, acousticians and musicians refer to the octave for measurements. An octave is defined as a 2:1 ratio of two frequencies. Acoustic measurements are also made over octave intervals, with centre frequencies of 125, 250, 500, 10000 Hz etc.

3.2.3. Sound Levels and the Decibel

The decibel is one of the most important units of measure in audio. Named after Alexander Graham Bell, the decibel can be used to measure differences or to measure sound amplitudes (Barron, 2010). It employs a logarithmic scale because logarithms are both practical and proportional. Logarithms are particularly useful to audio engineers because they can correlate measurements to human hearing and allow large ranges of numbers to be expressed efficiently (Alton Everest & Pohlmann, 2015). Sound levels expressed in this fashion, underline the wide range of sensitivity in the human hearing.

We can measure sound pressure using the decibel. Sound pressure is usually the most readily parameter to measure in acoustics, hence, the sound-pressure level (SPL). It consists of a logarithmic value of the sound pressure. The reference value is chosen to be close to the quietest sound we can hear. So, 0 dB sound level correlates roughly to the threshold of hearing. Conversational speech has a level of around 50 dB and a very loud sound of 120 dB causes pain in the ears if experienced regularly (Barron, 2010).

Sound-level meters are used to evaluate sound-pressure level. Since the human hearing response is not flat across the audio band, sound-level meters often offer a selection of weighting networks. The A-weighting factor is widely used because it approximates our human hearing frequency response. These measurements cannot accurately represent loudness, as will see in future chapters.

3.2.4. Sound Propagation

In a free field, sound travels in straight lines and is unimpeded. The sound waves are not affected by any obstacles and presents itself as unabsorbed, undeflected, undiffracted, unrefracted, undiffused, and not subject to resonance effects (Alton Everest & Pohlmann, 2015). The intensity of the sound decreases as the distance from the sound source increases. The human voice can reach at least 50 m in a free field (Adelman-Larsen, 2014). In ancient Greek theatres, the walls behind the performers would reflect the sound back to the audience, permitting a higher sound level for both the performer and the audience.

The wavelengths of sound are sometimes comparable to the dimensions of common room surfaces and objects. At high frequencies, frequency wavelengths may be blocked if comparable to the size of the obstacle. At low frequencies with large wavelengths, sound waves commonly bend around objects. This phenomenon is called diffraction and it often related to low-frequency sound waves.

In enclosed spaces, most of the sound we hear is reflected of the surfaces and other objects in the room. The geometries of reflection for light and sound are identical (Barron, 2010). For sound, however, larger surfaces would be mandatory for reflection of the larger wavelengths we perceive. When the reflecting surface is large compared to the wavelength of an impinging sound wave, the sound will be reflected like light in a mirror. This phenomenon is called *specular reflection*. An acoustic mirror is a large, plane surface of, for instance, concrete or plastered masonry (Adelman-Larsen, 2014).

As light hits a white piece of paper, the paper will scatter the light evenly in all directions from the scattering surface. A *diffusing surface* can be employed when dealing with sound as it will evenly scatter the sound back into the room. Conversely, as light hits a black piece of paper, most of the light will be absorbed. The same happens for sound as some materials are made for the absorption of a predetermined frequency band. In practice, some absorption of sound energy occurs for reflections from all surfaces, while some materials are highly absorbent (Barron, 2010). Typical porous absorbers such as fabrics, carpets and drapes are somewhat efficient. The most efficient absorbers such as mineral wool, fibreglass and acoustic open-cell foam are widely used for various applications.

3.2.5. Audience and Air Absorption

Audience in an enclosed space has the ability of absorbing sound. The people comprising a concert-hall audience can account for as much as 75% of absorption for a full house (Alton Everest & Pohlmann, 2015). This absorption is predominant at middle and higher frequencies. An audience can also be subject to distinct type of attenuation, as it scatters the sound around the room and can provide a greater absorption coefficient. The angle of incidence also plays a role. When an audience is seated on a relatively flat floor, the low angle of incidence provides good absorption. In stadia, such is not the case with higher angles of incidence and, hence, less absorption.

Air absorption plays a significant role at higher frequencies and can account for as much as 20 to 25% of total room absorption. It becomes apparent at 2 kHz and above and is the reason why reverberation times at that frequency or above tend to be reduced in large auditoriums (Barron, 2010). Therefore, it is considered a high-frequency phenomenon. Dry air is a more efficient absorber than humid air (Adelman-Larsen, 2014).

3.2.6. Reverberation

Reverberation is considered one of many measurable parameters that defines the acoustical quality of a given space. In psychoacoustics and acoustics, it is defined as the persistence of sound after the sound is produced (Valente, Hosford-Dunn, & Roeser, 2008). Reverberation must be accounted for when designing rooms for speech or music since it has the power of enhancing the sound or otherwise mask it.

When designing rooms where speech intelligibility is prioritised, the reverberation must not be excessive, or the masking of lower consonants may occur. In normal speech, the syllables follow each other with rapidity. Unless each syllable decays quickly, it will tend to mask those following. Therefore, reverberation must not be too long (Ginn & Sc., 1978).

If designing a room for music is the objective, considering the adequate reverberation may become a more subjective concern. Reverberation for one type of music may not be suited for another type of music. The best that can be done is to establish a range based on subjective judgment (Alton Everest & Pohlmann, 2015). Parameters such as clarity, definition and sound level will influence the reverberation design.

In all designs, special care must be taken in order to avoid echoes. An echo is what we perceive when a reflection is delayed by more than 50 ms compared to the direct sound. Whereas *distinct echoes* involve long path lengths, *flutter echoes* are likely to occur at shorter distances between parallel walls (Adelman-Larsen, 2014). These acoustics defects are perceived by almost every person with normal hearing.

3.3. Terms, Languages and Concepts

Throughout the twentieth century, acousticians have introduced a number of words that characterize a set of acoustical attributes that have proven to be of importance when seeking to describe halls for symphonic music, opera, and other classical music genres (Adelman-Larsen, 2014). Not all those attributes will be of relevance to this paper given their musical nature, but it is worthwhile to remember that they were elaborated to qualify the sound based on the perception of listeners. All these subjective parameters are a sum of all sound properties discussed earlier, fusing pitch, the sound in the soundscape, how it disperses through the room, and so on. They help us identify and characterize a specific room. The following terms, languages and concepts are commonly used in acoustics.

Term	Definition
Balance	Equal loudness among the various orchestral and vocal participants
Blend	A harmonious mixture of orchestral sounds
Brilliance	A bright, clear, ringing sound, rich in harmonics, with slowly decaying high-frequency components
Clarity	The degree to which rapidly occurring individual sounds are distinguishable.
Definition	Same as clarity
Dry or dead	Lacking reverberation
Dynamic range	The range of sound levels heard in the hall (or recording); dependent on the difference between the loudest level and the lowest background level in a space.
Echo	A long, delayed reflection of sufficient loudness returned to the listener.
Ensemble	The perception that musicians can easily play together.
Envelopment	The impression that sound is arriving from all directions and surrounding the listener.
Glare	High-frequency harshness, due to reflection from flat surfaces
Immediacy	The sense that a hall responds quickly to a note. This depends on early reflections returned to the musician.
Liveness	The same as reverberation above 350 Hz.

Presence/Intimacy	The sense that we are close to the source, based on a high direct-to-reverberant level.
Reverberation	The sound that remains in the room after the source has been turned off. It is characterized by the reverberation time.
Spaciousness	The perceived widening of the source beyond its visible limits. The apparent source width is another descriptor.
Texture	The subjective impression that a listener receives from the sequence of reflections returned by the hall.
Timbre	The quality of sound that distinguishes one instrument from another.
Tonal colour	The contents of harmonics or overtones and their strength relative to the fundamental of a tone.
Tonal quality	The beauty or fullness of tone in a space. It can be marred by unwanted noises or resonances in the hall.
Uniformity	The evenness of sound distribution.
Warmth	Low-frequency reverberation, between 75 Hz and 350 Hz.

Table 3. 1.: Commonly employed musical and acoustical terms and their definitions (Adelman-Larsen, 2014).

3.3.1. Reverberation Time and EDT

As mentioned earlier, reverberation is a key measuring parameter that defines the acoustical quality of a room. Generally, the reverberation time (RT) of an enclosed space refers to the amount of time it takes for a loud sound to become inaudible. In more technical terms, reverberation time is the time it takes for a loud sound to decay 60 dB after being radiated (Beranek, 2004), abbreviated as RT_{60}. The idea that there is a specific period of time for sound to die out in a room originated with Wallace Clement Sabine in 1900.

The early decay time (EDT) is also an expression of reverberation time, but based on the decay from 0 to -10 dB. EDT has proven to be better correlated with a test person's judgment of reverberation time (Adelman-Larsen, 2014). A 60-dB decay will be seldom encountered in a football match environment. While a match may not be entirely made of goals and passionate celebrations, there will always be the sound of thousands of people talking, clapping hands and chants from the supporters. In this case, the EDT of the loudest sound in the stadium would be better perceived than its reverberation time. EDT is a good descriptor of *reverberance*, used to describe the subjective experience of reverberation.

3.3.2. Early Reflections, Definition and Spaciousness

Early reflections encompass the reflections from a direct sound that reach our ear in the first 80 ms (Beranek, 2004). It is often associated to the quality of definition or clarity and can positively influence intelligibility.

Assuming a reflection delay in the 10- to 20- ms range, as it is increased above the threshold of audibility, spatial effects dominate. As the reflection level is increased 10 dB above that threshold, image effects dominate creating a sense of image size and shifting of position of the image (Alton Everest & Pohlmann, 2015). With another 10 dB increase, the reflections would now be superimposed as discrete echoes which are undesirable. This sense of spaciousness imparts a great sense of size to a given room and can be adjusted through careful manipulation of lateral and early reflections.

3.3.3. Acoustical Gain

Acoustical gain, or room gain, can be thought of as the difference in sound-pressure level between the sound-pressure level in the centre of the hall from an arbitrary source in an anechoic environment (Long, 2006). Therefore, it depends on the volume of the room and its reverberation time.

3.4. Essential Design Criteria

For any room, there is always a predetermined set of characteristics we intend for its acoustics. Characteristics such as low ambient noise levels from internal and external sources, reasonable levels of acoustical gain and reverberation times and the abstain of echoes are features we expect from a room. This is no different from the design of sound sensitive rooms, concert halls and stadiums. Above all, criteria must be evaluated for the structure's desired purpose (Barron, 2010).

3.4.1. Room Design for Speech

First considering the power of speech, it lies in mid-to-low frequencies with 80% of power below 500 Hz and relatively no power below 100 Hz. At higher frequencies lie the power of consonants which are of great relevance for the intelligibility of speech.

There are four factors that affect the clarity of speech in a room (Ginn & Sc., 1978). Firstly, the background noise level can eventually mask the desired sound. An acceptable level of background noise would be kept below 30 dBA. Secondly, one must consider the sound pressure level produced at the listener's ear which depends on the distance between the speaker and the listener and the room volume. Thirdly, the crucial factor of the reverberation time. If too long, some pronounced syllables may mask the following ones. However, if too short, it will compromise the speeches' abilities to be heard at a sufficiently high intensity for good speech intelligibility. Lastly, the shape of the room can be designed to avoid acoustical defects such as echoes and other artefacts as well as provide good sightlines. The way a room is acoustically treated will create a compromise where one must balance loss of sound intensity through absorption and loss of definition due to excessive reflected sounds.

3.4.2. Room Design for Music

Designing a room for music is much more complex due to the variety of subjective and emotional judgments involved. Criteria are almost totally subjective, making them very difficult to define and often impossible to measure (Ginn & Sc., 1978). There are several acoustical parameters that help qualify the sound in a room for music which have already been reviewed previously.

In relation to room designs for speech, room designs for music also require acceptable background noise levels, reasonable amount of acoustical gain and a specific room shape. Reverberation time, however, plays the decisive role as music typically demands longer reverberation times.

3.4.3. Reverberation and Echo Control

Rooms designed for speech have shorter mean reverberation times than rooms designed for music mainly because of intelligibility concerns. Furthermore, reverberation is much more than reverberation times. The frequency response of the reverberant field must also be considered (Alton Everest & Pohlmann, 2015). Music often requires significantly longer reverberation times at low frequencies which would impact warmth to the sound. The converse is applicable to speech since it would improve intelligibility.

Large enclosed spaces can be subject to discrete echoes which can damage the quality of sound in a room. Architects and acousticians must always be aware of excessive reflections of sufficient level and delay and how they can be controlled. When these reflections are carefully controlled, they can give a sense of spaciousness to the room which is sometimes desirable. The reverberation of the room will affect the audibility of echoes.

3.5. Reinforcement of Sound Sources

In some cases, the sound source may need reinforcement for a variety of reasons. A sound system is a functional arrangement of electronical components designed to amplify sound. It is employed when people need to hear something better, to make sound louder for artistic reasons (e.g., musical performances) and to enable people to hear sound in more remote locations (David & Jones, 1990).

Sound systems are an integral part of big events where sound amplification is procured. In order to obtain sound patterns both aesthetically satisfactory and functional, it is necessary to take findings of auditory psychophysiology into account (Ahnert & Steffen, 1993). For example, for a sound system to be effective, proper frequency response calibration must be ensued for the system to be perfectly integrated in the space. This will improve intelligibility and proper distribution of the sound.

Given the present state of the art, sound reinforcement systems are made available for various purposes such as information systems, sound reinforcement systems with and without playback reproduction, sound reinforcement systems for improving room-acoustical parameters, sound reinforcement systems serving as means of artistic expression, among others (Ahnert & Steffen, 1993).

3.6. Criteria for Noise Control and Sound Insulation

Noise is characterized as a loud or unpleasant sound that causes disturbance and can be most incongruous in many scenarios. Sound sensitive rooms such as recording studios, concert halls and others, should operate with minimized noise inside the structure and properly isolated from outside sources. Sound insulation characterizes the ability of building elements or structures to reduce sound transmission, hence its close relationship to noise control.

"Noise can:

- Damage hearing
- Interfere with speech communication
- Disturb concentration thus causing a decrease in efficiency
- Annoy."

(Ginn & Sc., 1978)

Before construction, one should analyse the environmental ambient noise where the building will be located and determine what level goal is forecast for the inside of the room (Crocker, 2007). Controlling interfering noise is one of the most challenging problems in architectural acoustics and it is a major concern in stadium design.

3.6.1 Approaches to Noise Control

There are five basic approaches to reducing noise in sound sensitive spaces (Ver & Beranek, 1992):

- Locating the receiving room in a quiet place
- Reducing the noise output of the offending source
- Interposing an insulating barrier between the noise and the room
- Reducing the noise energy within the source room and/or receiving room
- Minimizing both airborne and structureborne noise

Locating stadia in quiet places would be an efficient solution but a somewhat unattainable one due to a variety of reasons such as availability. The common environmental noise output level produced by these edifices can be problematic, especially in city centres. Reducing the noise output of the source is the most logical and efficient approach. Sometimes it is possible, other times it is not. In most cases, however, it is more productive to work on the offending source and try to reduce its output than to partake on corrective measures for the builduing. On a larger scale, it may not be the case.

Another common solution would be to construct a noise-insulation[2] barrier although often difficult and costlier. A barrier with a specific transmission loss[3] will only reduce the noise level by its stipulated amount. Sometimes, it is viable to apply corrective treatment within the noise-receiving room. Controlling reverberation and careful placement of absorbent materials will dictate the noise level reduction.

Noise can also be controlled by minimizing the intrusion of airborne and structureborne sound in the room. Even the most efficient barrier can be easily outperformed if there are any leaks in the space. As for structureborne noise, it can be easily transmitted through solid structures through vibrations.

3.6.2. Airborne and Structureborne Noise

Sound can propagate through any medium; for example, it can pass through air and through solids. The former is airborne transmission and the latter can occur as structureborne transmission (Alton Everest & Pohlmann, 2015). Airborne sound is a high-frequency phenomenon whereas structureborne sound is a low-frequency one and sometimes felt as vibrations.

Airborne noise can pass through the smallest crack or aperture because those air leaks would have a transmission loss of zero. Any flanking path would allow sound to travel around obstacles and compromise the integrity of a structure. Careful construction is vital for a great design to become great.

Structureborne sound refers to the generation and propagation of time-wise varying motions and forces in solid bodies (Cremer & Heckl, 1973). It is usually associated to noise control due to its common intrusion via outside traffic, HVAC[4], or even the impact of footsteps. Thus, structureborne noise is most efficiently controlled at the source.

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[2] Noise insulation refers to the ability of building elements or structures to reduce sound transmission.
[3] Transmission Loss (TL) refers to the loss of sound as it passes through a barrier.
[4] Refers to Heating, Ventilation and Air-Conditioning systems.

3.6.3. Site Selection

As stated earlier, locating a sound sensitive room in a quiet location is an elegant solution but a quite rare one. Whatever location is selected, understanding the surrounding noise levels is essential.

Site selection will depend on the intended purpose of the building since not all spaces demand the same levels of noise output. Economically, one must always compare the cost of locating the building in a quiet area to the cost of acoustically treating it. Architects and acousticians should also be aware of possible future building projects in the area that may constitute an increase in noise levels.

> "In some unique cases, people can create very loud unwanted noise levels. In particular, the spectators in sporting events venues can generate levels in excess of 100 dBA[5]. For example, a crowd's noise level in an outdoor football stadium might reach 111 dBA (…)."
>
> (Alton Everest & Pohlmann, 2015)

3.7. Acoustics for Multipurpose Use

> "There's no single acoustical "solution" that can be universally applied to building design. Each built environment offers its own unique set of acoustical parameters. The acoustical design for a business conference room, for instance, differs greatly from the design needed for a kindergarten classroom. Understanding these differences and knowing how to utilize building materials, system design and technologies are key factors behind successful acoustical design."
>
> (Janning)

[5] dBA refers to an expression of the relative loudness of sounds in air as perceived by the human ear. In the A-weighted system, the decibel values of sounds at low frequencies are reduced, compared with unweighted decibels, in which no correction is made for audio frequency. This correction is made because the human ear is less sensitive at low audio frequencies.

When designing a room with various objectives and having in mind that hopefully those varied purposes will be somewhat similar, a compromise must be found amid the variabilities of the ultimate acoustical quality of the room. In some cases, means of adjustable acoustics[6] may help but recent literature shows that those are mostly used on a smaller scale (Alton Everest & Pohlmann, 2015). Stadiums and other multipurpose auditoria are likely to host a variety of events, diverse in their nature, that can demand different acoustics. Researching an efficient way of accounting for this compromise could be advantageous.

[6] E.g.: draperies, hinged panels, portable units, among others.

4. Chapter Four: Stadium Acoustics

With a more heightened understanding of the behaviour of sound in any given space, one can look into the acoustic properties of stadia. The main bowl area will be the loudest out of all remaining areas so it is wise to investigate how sound is meant to be contained and controlled. This chapter will expand on how the stadium comes to life and divulge common constructing and engineering techniques which will be important towards understanding the role of acoustics and atmosphere in football stadia.

4.1. Stadium Structure and Form

> "Design excellence is achieved in stadia when structure, enclosure and finishes express at all scales – from overall form right down to the smallest detail – a single concept which functions well, is rich and expressive, and avoids jarring conflicts. (…) complete success is rare: the first step towards higher architectural standards must be the identification of those particular problems which make it so difficult to achieve functional and beautiful stadium designs nowadays."
> (John, Sheard, & Vickery, 2007)

Generally, those problems revolve around:

- **Inward-looking form of stadiums**
  Turning our backs on the surroundings, being elevated from the ground, facing the street tends to be unwelcoming
- **Car parking**
  Unattractive and usually separates the stadium off its surroundings
- **Gigantic scale**
  Reconciling the scales of stadia with its environment is a difficult challenge

- **Inflexible elements**
  Such as seating tiers, stairs and ramps or entrances and roof forms which tend to assert themselves on the building
- **Tough finishes**
  Stadia must have tough and highly resilient surfaces to be able to stand up. This usually comes across as ‘tough’, ‘brutal’ and ‘anti-human’
- **Periods of disuse**
  Which inflicts upon the stadium and its surroundings massive effects of both under-use and over-use.

Whilst impossible to set rules which will guarantee a good stadium, some suggestions may be helpful:

- Designers should carefully consider each and any more problem considered above which are key architectural concerns
- They should look at existing stadia in which these or any other problem has been solved and try to identify precedents to their own case. Many good designs are an intelligent modification of an existing model.
- Bear in mind the approaches outlined below which may be helpful but serve only as suggestions.

4.1.1. Roof and façade

Stadia can benefit of a low profile. Techniques such as dropping the pitch below ground level and raising the surrounding landscape could help achieve this. Munich’s 1972 Olympic Stadium is a great example of such low-profile stadia. Conversely, roofed stadia are a recurrent case in Europe. The most important step towards achieving a satisfying architectural solution is to avoid an assertive façade competing with an equally assertive roof.

Dominant Roof

An example of a ‘dominant roof’ design is, again, Munich’s *Olympiastadion* with a translucent roof made dominantly out of acrylic panels. In this case, the wall has been virtually eliminated and replaced with graceful roof forms hovering green landscape.

Figure 4. 1.: Munich *Olympiastadion*, Germany (Augsburger Allgemeine, 2019)

Dominant façade

A successful example of the ‘dominant façade’ approach is found in London with the Mound Stand at Lord’s Cricket Ground. It has a light roof floating above a dominant and well-composed façade, providing a progression from the heavy to the light tent roof at the top.

Figure 4. 2.: The Mound Stand at Lord’s Cricket Ground, England (Hopkins Architects, 1987).

Dominant structure

A third possible approach could involve making the whole structure dominant where, for instance, both façade and roof be contained behind a dominant cage such as the *Parc des Princes*, in Paris or Kenzo Tange's masterpiece twin gymnasia for the 1964 Tokyo Olympics.

Figure 4. 3.: Yoyogi National Gymnasium, Japan (Go Tokyo, 2019)

Corners

The problem of gracefully handling the stiff corners of the pitch has defeated many designers, especially in roofed stadia. Some stadiums such as the Turf Moor Stadium in Burnley, England, simply dodge this problem by placing stands on all four sides of the pitch and leave the corners as gaps. This measure helps save money, helps avoid awkward structural and planning problems and the grass is provided with good ventilation. However, the results are often inelegant. One solution would involve erect towers on the corners which could help crowd movement, accommodate offices or other functions.

Figure 4. 4.: Turf Moor Stadium, England (Line-Up, 2019)

Designs in which both the stands and roofs are swept around have also produced good results. Such is the case with the Aviva Stadium, in Dublin. In these designs, a fluidly-shaped roof floats free above the seating areas, highest along the length of the pitch where most people sit, and lowest in the corners where the pitch ends.

Figure 4. 5.: Aviva Stadium, Ireland (Stadia Magazine, 2019)

4.1.2. Materials

The use of unfinished concrete in stadium design is widely used but presents itself as unattractive by the general public. Exposed concrete is best avoided in rainy regions, especially in industrial areas where the rainwater is contaminated with pollutants and stains the surface. If used in these environments, expert help should be sought to avoid surface staining. Painting the surfaces are also a typical solution, but can pose a great maintenance burden.

Stadia have been built from every conceivable material throughout the ages. From the Roman Colosseum made from brick and stone, to the typical concrete, steel and aluminium stadiums of today. The cost of the structure and, therefore, chosen materials can be significant thus presenting itself as a major factor in stadia design due to its large scale. Other performance characteristics such as durability and sound handling abilities must also be thoroughly investigated.

Concrete

Reinforced concrete, along with steel, is one of the most widely used structural material for stadia. It is naturally fireproof and cheaper in some countries but is unpopular when left unfinished or unmaintained. There are different approaches to deploying the concrete structure on the site. *In situ* concrete has been widely exploited to produce enigmatic stadia. However, recent use has diminished in favour of more lightweight structures. Pre-cast concrete has the advantage of being prefabricated away from the building site, reducing construction costs. Such approach tends to be favourable when the stadium is being remodelled or reconstructed, minimizing disruptions. Pre-stressed and post-tensioned concrete are also useful in stadium construction and often used when the structure is to be built as two independent units. It helps with jointing, offering a reduction of movements through the structure.

Steel

Steel can be cheaper in some parts of the world and allows its prefabrication off-site. It is lighter than concrete, physically and visually, and allows for more graceful structures. Steel will implicate fire safety precautions and normally implicates its encasing, spraying with mineral fibre or vermiculite cement. This factor could cause steel to lose its advantage to the use of concrete structures.

Brickwork

In stadia, brickwork is likely to be used to clad a structure rather then a structural material. It can help the stadium blend in with its surroundings.

4.1.3. Playing surface

Sinking the stadium below ground level can help it blend in the landscape and help reduce construction costs. However, this approach can also lead to poor soil conditions and endanger said savings.

Natural grass is the preferred playing surface for European stadia. Its feasibility, nonetheless, depends on whether or not the stadium is enclosed. Completely open stadia will allow any type of playing surface. Such is not the case for partly or totally roofed stadia. Partly roofed stadia, through a combination of shading, sunlight and wind effects may damage the grass. Careful guidance is vital. For completely roofed stadia, the use of natural grass pitches is unviable. The use of synthetic turfs would have to be investigated.

Today, some stadia possess rolling pitches which can be substituted and relocated at any time. These can be kept inside the structure, or beside it on the outdoors. In Europe, designers are more inclined to supplement the stadium with translucent roofing and artificial light, or supply a retractable roof to provide sufficient light. Synthetic surfaces are unlikely to have any adverse effect on any particular stadium, but whilst often used in colder climates, it is undesirable in central and southern Europe.

4.1.4. Foundations

Give the scale and sheer weight of stadia, sometimes the soil may be too poor to withstand such structures. In these cases, much of the construction budget may be used for ground improvement operations. A full geotechnical report should be commissioned before the final construction budget is agreed upon. Without site investigation, the construction may present itself as a hazard.

4.1.5. Seating tiers

The seating tiers of the stadium have key influences on the overall stadium form and structure. These are commonly constructed in pre-cast concrete and follow a series of desired specifications:

- Spectators should preferably not look into the sun. Stadium orientation is essential in dealing with this matter
- Be close enough to the pitch so that they can see the movement of the ball
- Be given a clear view of the pitch over the heads in front of them, which involves 'raked' angles for the seating tiers
- The stands may not be too steep (34 degrees will normally be the maximum incline)
- There must be no obstruction to the spectators' view of the pitch, such as columns or low roof edges.

4.1.6. Concourses, stairs and ramps

As with seating tiers, there are several aspects which should be accountable for when designing a stadium:

- The pattern of concourses, stairs and ramps must allow for the smooth inflow of spectators

- The layout must allow for fast, safe, emptying of the stadium in panic conditions
- Access to toilets and catering facilities should be facilitated
- Subdividing the total capacity of the stadium into sectors of about 2.500 to 3.000 spectators is usual and should allow easier crowd control and even distribution of other facilities

Surface finishes also pose an important design development. Ill-behaved crowds should be expected, henceforth finishes must be tough enough to withstand wear and tear, maintenance, temperature, rain and so on. Concrete finishes, as noted, are relatively inexpensive and durable, but unpleasant in the eyes of the public. Natural concrete block surfaces with anti-graffiti coatings are useful and coated steel claddings have improved greatly, becoming very durable and easily cleanable. These are examples of recent surface finishes.

4.1.7. Roofs

Open or partially covered arenas are prevalent throughout the world, from cold countries, to hot ones. Recent trends, however, specify partial or even total covering on the account of spectators demanding better protection from the climate. As mentioned previously, covering the arena may also have implications on the playing surface.

For afternoon matches, the main stand should face east with a minimum of spectators having to look to the sun from a west-facing position. Evidently, the efficiency of a roof in shading its occupants and the pitch will always be dependent on the position of the sun. Its effects should be digitally modelled and thoroughly investigated.

As for wind and rain effects, in open and partially covered stadia, not all spectators can be effectively protected. The spectators seated higher and further away from the pitch are the best kept protected, whilst spectators seated closer to the pitch tend to have relative to no roof protection. This depends on the design of the stadium and its roofing intentions. Roofs arranged in round or elliptical forms, as opposed to separate roofs, tend to create a calming effect on the air inside the stadium which contributes to the performance of the athlete and the atmosphere in the arena.

Several special parameters are taken as first steps in the design of such structures. Through scale modelling and wind tunnel experiments, the engineers investigate:

- Prevailing wind directions and velocities
- Usual air temperatures and frequency of rain or snow
- Local patterns of air turbulence created by surroundings and the stadium itself
- Conflicts between needs of the spectators (wanting protection from the climate whilst desiring a natural grass pitch)
- Height of the roof edge so most of the spectators maintain sight of the ball when it is high in the air.

Different elements of the stadium will have different durability abilities. Roof coverings tend to be replaced in a 15- to 20-year period depending on their type. Elements with such short replacement dates should be designed to facilitate said replacement and a definite maintenance cycle should be decided for the roof.

4.1.7.1. Roof types

Eight commonly used structural forms of roofing are described below. These are not exclusive as there are many variations and possible combinations of the following.

Post and beam structures

This system comprises a row of columns parallel to the pitch, supporting a series of beams which, in turn, carry the roof. It is a simple and cheap system but outdated by today's standards. The row of columns would disrupt the spectator's viewing to an unacceptable level. This is no longer recommended given the availability of better alternatives.

Figure 4. 6.: Craven Cottage, England. An example of post and beam structures (Stadium Journey, 2019).

<u>Goal post structures</u>

This system employs a post and beam roof with posts only at the two ends of the entire length of the roof and being spanned by a single girder. This implies regular inspection and maintenance. A variant of this approach involves combining the post and beams into an arch along the front of the roof. These have the advantage of providing unobstructed viewing to the spectator but works best when little or no seating is provided in the corners of the stadium, which in turn restrains seating capacity.

Figure 4. 7.: *Estádio da Luz*, Portugal. An example of goal post structures (SL Benfica, 2019).

<u>Cantilever structures</u>

A cantilevered roof is a structure supported on of its sides, while the opposite one hangs free and unsupported. This design can be a dramatic one, exploiting the excitement provided by no apparent means of support. It can also provide virtually no impediment to viewing and is as suitable for continuous and separated stands. However, other than cost, uplift wind can present a destructive disadvantage for cantilevered roofs.

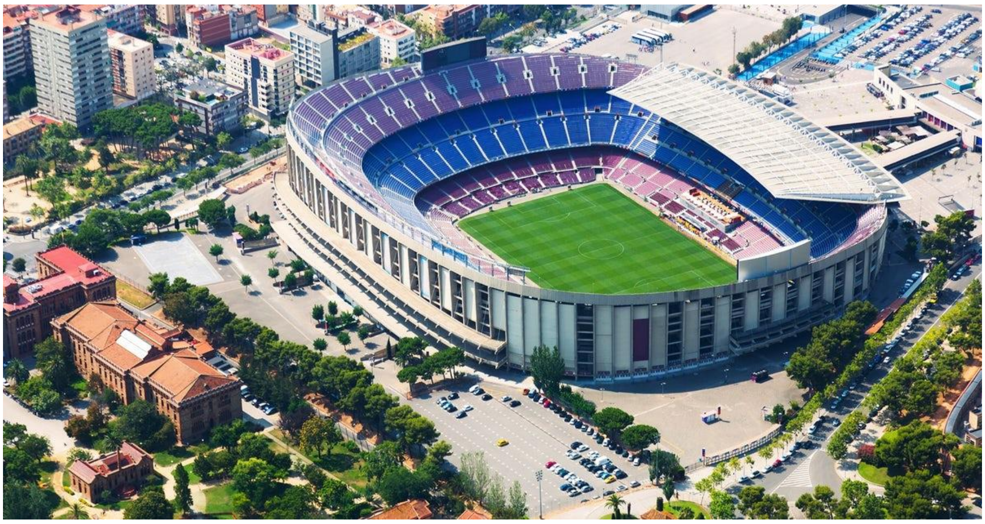

Figure 4. 8.: *Camp Nou* Stadium, Spain. An example of a cantilevered roof (Musement, 2019).

<u>Concrete shell structures</u>

These roof designs are made with thin shells curved in one or two directions whose structural integrity derive from their geometrical shape rather than the thickness of the material. Concepts deriving from this approach include cylindrical, domed, conoid and hyperbolic shapes. Shell structures can be visually appealing through their elegant shapes but must be subject to thorough computer modelling and further investigation. If carefully detailed, these shells could be self-finished on both the upper and lower surfaces.

Figure 4. 9.: *Estádio do Algarve*, Portugal. An example of concrete shell roofs (Football Tripper, 2019).

Compression/tension ring

Consists of an inner and outer ring, connected by radial members, maintaining the geometry and integrity of the structure. Greater stand depths become possible, the roof appears to be a lightweight construction and transparent or translucent roofs are common with this particular design. The only limitation is that it can only be employed on bowl stadia.

Figure 4. 10.: *Ernst-Happel-Stadion*, Austria. An example of a compression/tension ring (Sport-Österreich, 2017).

Tension structures

With this design, all primary forces of the roof are taken by members acting in tension alone, such as cables. These are typical and may be more economical in terms of materials. There are three principal deviations from this design: catenary cable, cable net and membrane structures. Catenary cable structures use a compression arch (or arches) supporting one or more cables hanging in catenary shape. While aesthetically pleasing, it can be a rather heavy form of a heavy structure when compared to the following examples. Cable net structures employ a net of steel cables usually covered by translucent plastics such as acrylic, PVC or polycarbonate. Membrane structures, unlike the previous ones, are designs in which the roof covering material forms both the structure and enclosure. These structures often utilize light materials such as PVC-coated polyester or PTFE-coated glass fibre. Tension structures can give an airy appearance to the stadium but are dependent of a very sophisticated design and regular intensive maintenance.

Figure 4. 11.: *Olimpiyskiy* National Sports Complex, Ukraine. An example of a tension-structured roof (Schlaich Bergermann Partner, 2011).

Air-supported roofs

Consists of an enclosure made with a plastic membrane. These are regularly made of PVC polyester and, in the case of a large roof, assisted by cable reinforcement. Air-supported roofs are usually cheaper but more vulnerable to damage. This design also depends on the use of air-systems to maintain the interior of the arena adequately pressurised.

Figure 4. 12.: *Stadion Narodowy w Warszawie*, Poland. An example of an air-supported roof (Wikipedia, 2019).

Space frames

Space frames form a grid of structural members which bring stability to the structure. These can be made of any material but are commonly made of steel. These can span large distances but are more efficient when only spanning in two directions. Therefore, space frames are typically employed when the roof structure is geometrical in its design. These also tend to be quite expensive.

Figure 4. 13.: *Stadio Giuseppe Meazza*, Italy. An example of space frames *(Rappo, 2019)*

Retractable roofs

The use of opening and closing roofs has been increasingly popularized throughout the globe. Retractable roofs enable the bowl area to be protected from the climate and allows the stadium to host a bigger variety of events. These are typically constructed with transparent or translucent material which provide some light to the arena.

Figure 4. 14.: Johan Cruijff Arena, Netherlands. An example of a retractable roof (Holland Online, 2018)

4.1.7.2. Roof coverings

When considering the materials for roof coverings, designers should seek lightweight, tough, water-tight, incombustible, aesthetically acceptable, cost-effective and durable materials to withstand outdoor weather (Bardhan-Roy, 1992). Roof construction may also require additional thermal and acoustic insulation.
Opaque coverings such as profiled metal sheets and aluminium are commonly used. These should be regularly maintained to avoid corrosion. Concrete would be hardly used as a roof covering given its weight and unattractiveness. However, when dealing with shell structure roofing, concrete may well be used. Furthermore, one should be careful of the concrete staining over time.

Translucent coverings generally employ rigid plastics such as acrylic or polycarbonate sheeting and are regarded as strong, waterproof materials with reasonable impact resistance. PTFE-coated glass fibre roofs are a modern trend in stadium design and is considered a non-rigid plastic, lighter than previous materials.

4.2. Stadium Site Appraisal

4.2.1. The Ground

With the possibility of urban regeneration and ease of transport issues, stadia tend to be constructed on brownfield sites such as former industrial zones. Many of the major risks lie on the ground as any other building projects, but stadia are different than any other structure:

- Because some columns are exceptionally heavy loaded
- Large cantilever roofs may impose high horizontal loads
- Most of stadiums' loads are live, being induced by crowds, wind, and others. These effects need to be considered whereas a failed a design may kill hundreds of spectators.

When designing stadia, one should also be aware of the presence of desired utilities for the project and their efficiency, the possibility of clearing and reengineering the area and if the local transport network is capable of dealing with increased demand.

Geotechnical risk reduction is vital and addressing the particular types of foundations desired can outline some particular issues. The extent of earthworks need to be fully considered and when the pitch level is chosen, the requirements for excavation and filling operations become clearer. Defining the approximate foundation locations and how much load they will carry must also be assessed.

Several authors have already emphasized the high risks involved with the ground and how investigating and treating problems at the source can be more fruitful (Littlejohn, Mellors, & Cole, 1994). The average costs of delays in construction projects are much large larger than the cost of thoroughly investigating the building site. Proper ground site investigation is critical and may be the main factor towards the completion of the building on schedule. The most effective way to control geotechnical risks is to investigate these in a timely manner and try to mitigate them whenever possible. The Royal Institute of British Architects (RIBA) provide a list of work stages which are universal in stadia design and should be analysed prior to construction.

4.2.2. Masterplanning

> "The art of planning large stadium sites hinges on the correct zoning of the available land and the separation of incompatible uses which must be accommodated within the site boundaries."
>
> (John, Sheard, & Vickery, 2007)

A masterplan helps ensure the ultimate design is consistent, aesthetically pleasing and efficient whilst clarifying the successive phases of the development to be carried out. It will include the direct sporting functions and surroundings such as parking areas, pedestrian and vehicular routes, among others.

A starting point for such a design would start at the playing surface, determining its shape, dimensions and orientation. Next, seating capacity would be discussed. This is a very delicate factor for the owners as it will dictate much of their revenue. Given the multi-purpose feature of recent stadia, the capacity design should express maximum attendance around the area of the pitch, and maximum attendance around the smallest space users (such as concerts or boxing matches). Another design factor would be pitch orientation which depends on various aspects such as the hemisphere where the stadium is located, the period of the year in which the sport will be played, the times of day of these events and specific local environmental conditions. Finally, zoning should be resolved. It helps arrange all the elements of the stadium from the pitch, to the parking areas outside.

Traditionally, the sports stadium was a modest facility embedded in the local community. As communities grew larger and became more mobile, the stadia drew further away from city centres to open land on the town periphery. This way, larger crowds could be more easily controlled and would cause less disturbance to the lives of those not attending the event. The increased distance from city centres would also mean a reduction in land costs and easier road access as well as dedicated security and safety measures. Already existing stadia built in-town have the advantage of being steeped in the tradition and communities which support them. This would also mean that providing these places with the necessary safety, comfort and variety of other facilities would prove to be challenging.

Decisive locational factors depend on the stadium's client base, land availability and land cost and regulations. Stadia should be easily accessible to its clients. Therefore, careful analysis of who the projected customers are, where they live, and how they will travel to the stadium is convenient. Fifteen acres, plus parking space, can be required for a stadium location and land costs are kept to a minimum. This is why stadiums are usually built on low-grade land such as former industrial areas or reclaimed land. Today, it is viable to build a safe, comfortable and efficient stadium in any location, provided that there is enough land and the stadium's use is compatible with its surroundings.

Stadia are major developments which can enhance the surrounding environment or otherwise undermine it. Attitudes to such environmental impact vary around the world, with the most protective approach found in Europe partly because of its limited amount of green space. Most countries now have environmental protection legislation for both town and country. They also have increasingly aware and assertive communities who will object to massive new buildings, especially if these are likely to generate traffic and noise. They could go as far as even preventing their construction, or at least forcing expensive modifications to the design.

4.3. Bowl Acoustics

The successful integration of the behaviour of sound in acoustic environments is achieved through:

- Providing effective sound reinforcement throughout the building.
- Allowing each activity in a given space to operate without interference

- Providing the appropriate natural acoustics (atmosphere) to enhance the experience of the event
- Minimising the risk of environmental noise impact to local communities.

The main acoustic disciplines are environmental noise (construction, transportation, façade insulation, sound system, building services) and sound quality/clarity (sound system, building services, architectural acoustics, internal sound insulation). The design and impact associated with these disciplines need to be coordinated with the design team and, in particular, the architect, structural engineer, mechanical and electrical engineer, and the quantity surveyor (Griffiths, 2015).

The natural acoustics of the bowl play a big role in the architectural acoustics of the stadium. It controls the atmosphere and enhances the enjoyment of the spectator, assists sound system speech intelligibility, shapes music quality and helps reflect sound onto the pitch. Bowl acoustics are defined by their size, shape and building fabric of the stadium. These can be varied since some roofs can be retractable and video screens may be moved, altering the acoustic environment.

Given the multipurpose feature of modern stadia, acoustical design may create conflicts between the ultimate enjoyment of the spectators and speech intelligibility requirements. Technological advancements have enabled analysis through digital scale modelling which allows for more accurate studies and optimised acoustics. Most models use ray-tracing techniques, approximating wave behaviour through multiple ray reflections. Other factors such as sound source characteristics, air absorptions, reflections, diffraction edges structureborne transmissions, among others, are taken into account. A detailed model study should identify problems and promote the most effective treatments. Stadia atmosphere is becoming an important feature of the stadium bowl and directly affects the team, supporters and sound system.

Bowl sound insulation is also a critical factor in the acoustic behaviour of the space. It is determined by considering two main variables, source noise levels and acceptable receptor noise levels. Again, since a multitude of events is likely to be considered, sound insulation needs to guarantee satisfactory results for all scenarios. In most cases, noise generated by the audience will be the one to reach high peak sound pressure levels. For music concerts, on the other hand, the performers tend to generate the highest peaks and for a continuous amount of time, containing an unbalanced frequency spectrum. Henceforth, determining the appropriate composite bowl sound insulation must take into account the source noise level, its pattern, characteristics, additional reverberant sound energy and how the sound propagates.

There are three main areas that will contribute directly to the overall sound insulation of the stadium. Firstly, the main wall of the seating the tier, which essentially forms the interface between the stadium and the exterior, will be the single most effective barrier of sound in the building. Concrete is commonly used for reasons explained previously. Secondly, a roof, or partial roof, will help prevent leakage to the exterior of the building. It may also help redirect sound onto the pitch and prevent exterior noises, such as aircrafts flying above, from breaking in. Lastly, penetration through either of the previously mentioned for the purposes of personnel access, vehicular access, ventilation, or others will have a negative effect on overall sound insulation. Sound will be able to travel through room divisions and change the acoustics of the bowl.

The acoustics of internal rooms within the stadium also requires careful consideration. Space planning with respect to acoustic separations between low- and high-noise environments is an essential first debate. Areas such as television and radio broadcast rooms, presentation and conference areas will always require special acoustic treatment whereas public access areas will be considerately reverberant and loud due to their size. The performance for most areas is usually specified by surface finishes with convenient absorption coefficients and sound insulation values whilst accounting for noise rating values.

4.4. Sound Systems

Besides the traditional performance requirements of sound systems (life-safety announcements and commentary), sound systems for modern venues are often required to perform the following functions:

- Relay important messages to all public areas of the venue

- Provide commentary related to the event
- Be suitable for the reproduction of a full range music to enhance the fan experience to convey messages from sponsors and advertisers to interface with screens and other visual equipment
- Interface with concert sound systems to provide direct sound to the more distant parts of the stadium
- Provide the full audio requirements for the venue attractions (tours, museums, etc.)
- Provide a communications system for the hard of hearing.

These systems will need to serve all public areas and also provide emergency evacuation communications for civil commotion and bomb alerts. The sound system design should be incorporated within the architectural acoustic modelling, so that the optimum quantity and types of loudspeakers can be established for each given acoustic space to meet the necessary performance criteria. As already discussed, the designs must also have due regard to the environmental impact.

The Wembley Stadium sound system (Jones & Griffiths, 1991) was the first of its kind to be fully integrated with concert touring systems, and has been used by every artist performing at the stadium. The system, using digital signal processors for equalisation, signal delay and routing, improved the external environment. The sound quality in the stands was also generally improved, as the sound was focused into the seating areas by local speakers designed for the acoustic space rather than being served by a multi-purpose concert system located some distance from the audience.

To be effective, a sound system must be heard over the background noise of the crowd by a significant margin. As a guide, the sound system should be in the order of 6 dB louder than the crowd noise level. The next step would be to determine the uniformity of the sound distribution in the stadium. The degree of uniformity should, as a rough guide, be in the order of +6 dB and -3 dB for at least 95% of the spectator area, but perhaps for only 75 or 80% of less important areas such as entrance concourses and turnstiles. However, having enough sound volume does not necessarily ensure intelligibility. It is necessary to measure, specify and calculate sound levels. Emergency messages often need to be complex and must not be misunderstood, therefore any testing of a sound system should replicate real use.

If a stadium is intended for multi-purpose use (which is now common), it must be suitable for hosting musical events and music sets the most demanding criteria for sound quality. Designing the permanent sound installation to these criteria will be expensive – probably too expensive if the stadium is not often used for musical events. In that case temporary systems may have to be brought in for such events, but then very careful thought must be given as to how these temporary systems will be installed. Many acoustic problems arise from lack of forethought about these matters (John, Sheard, & Vickery, 2007).

4.4.1. Sound System Design

Sound system design begins not with the audio system, but with the shape and materials of the stadium itself. In completely open stadia the influence of shape and materials will be small, but in fully or extensively roofed stadia, to which the following notes are principally addressed, the effects of sound reflection and of noise build-up could be severe. As an obvious example, hard surfaces that are parallel to each other (such as an acoustically reflective roof over a hard floor; or two parallel walls facing each other) may generate echoes and/or excessive reverberation which reduce or destroy intelligibility.
Particularly problematic acoustic areas are the corners of the stadium bowl, the seats below overhanging tiers (where sound intensities can build up even in open stadia) and the area under the roof of a fully covered stadium. If such a roof is domed the problem may be even worse because of the focusing effect of the curved surface. Generally, the underside of enclosed stadium roofs must always have acoustically absorbent surfaces, perhaps (if the roof is solid) as panels fixed to the soffit or suspended some distance below it, or (if it is a double-layer fabric roof) by inserting an absorptive material between the two layers.

When planning fully enclosed stadia it is helpful to note that irregularly shaped plans may create fewer acoustic problems than rectangular or curved ones. Surfaces that are broken up by mouldings or irregularities probably create fewer problems than smooth flat ones. The careful location of acoustically absorbent materials is essential for reverberation control and the avoidance of echoes. It should be noted that the ideas above are only generalizations, and expert help should be sought.

One aspect with which stadium designers will get directly involved is the pattern of sound distribution. There are three layouts: centralized speakers, partial distribution of speakers, and a completely distributed system of speakers. A centralized system collects all the speakers together in one location, which makes it the cheapest of the three options. The disadvantage of this configuration is that there is less control over sound distribution if all sound comes from one point. A usual location in open stadia is at the end of the bowl, often adjoining or as part of a video display. In covered stadia a usual location is centrally above the pitch, suspended under the roof, and this may well be the most appropriate use of the centralized system – though such a central placement may exacerbate problems of reverberation time.

A partially distributed system has several clusters of speakers placed around the bowl at regularly spaced intervals. The fully distributed system, which is more popular in Europe, has an even distribution of speakers dispersed throughout the spectator areas. It is the most expensive of the three options because of, but not restricted to, the extensive cabling that is required. However, this system does provide the best general sound quality of the three options as well as the best control. Speakers can be located on each tier of the bowl and serve each section of the seating area separately.

> “A sound system for a sports stadium may typically contain the following criteria.
>
> 1. The statement should set down the basis upon which the design is undertaken and on which its performance will be judged when installed.
> 2. It should state the standards and codes of practice upon which the design should be undertaken.
> 3. The systems function should be stated as:
>   i. To communicate emergency messages
>   ii. To provide public address messages
>   iii. To be used for other specific messages
> 4. The frequency response should be stated. The following is an example. General public areas:
>   i. Frequency response pre-equalization. Total system 100Hz-6kHz +6-3dB (essentially smooth).

   ii. Frequency response post-equalization. Total system 100Hz-6kHz ±3dB. Concourses, turnstiles and entrances.
   iii. Frequency response pre-equalization. Total system speech only 200Hz-6kHz +6-3dB (essentially smooth)
   iv. Frequency response post-equalization. Total system speech only 200Hz-6kHz ±3dB

5. The intelligibility rating should be stated with a given occupancy noise.
6. Sound pressure levels and coverage should be quantified, such as the following example:
   i. Sound pressure level 6dBA >L10 for 95 per cent of public
   ii. Coverage to be within ±2dB for 95 per cent of public areas where L10 is sound pressure level which is exceeded 10 per cent of the time
7. Different zones should be identified, and the system should allow access to the different areas identified independently or as a group of areas. A typical range of zones is given below for guidance:
   i. North side stand
   ii. North concourses
   iii. North turnstiles
   iv. South side stand
   v. South concourses
   vi. South turnstiles
   vii. East side stand
   viii. East concourses
   ix. East turnstiles
   x. West side stand
   xi. West concourses
   xii. West turnstiles
   xiii. Executive suites
   xiv. Car parks
   xv. Restaurants
8. A priority system should be indicated, with the police and security services give the highest priority. A typical order of priority might be as follows:
   i. Police announcer in police control room

ii. Management announcer in event control room
iii. General announcer and commentator
iv. Pre-match events commentator
v. Musical entertainment and 'Disc-Jockey'
vi. Advertising.

9. Any additional requirements should be stated."

(John, Sheard, & Vickery, 2007)

4.5. Environmental Noise Impact

Noise generated by HVAC sources can affect both the internal and external environment. These sources can create a great amount of airborne and structureborne noise so it is important that these are properly constricted. Therefore, vibration isolation and the use of acoustic attenuators are required for the mechanical plant. Noise ratio criteria are normally provided and should, in this case, determine the appropriate size of the attenuators.

The issues that are normally covered in such as assessment for stadiums include:

- Operational noise (e.g., sporting, concerts)
- Stadium sound systems
- Plant and machinery
- Noise from patrons when going to and from the stadium and while in the stadium
- Transportation noise
- Construction noise.

Transportation noise on event days can also be a significant problem and should be assessed and dealt with accordingly. When assessing the impact of noise from transport it is necessary to establish the breakdown of attendance patterns into car, bus, rail, foot, among others, which is usually provided by specialist highway planners. Using this information and knowledge of the baseline situation, the impact in terms of increases in or absolute levels of noise can be determined. The frequency and number of events held at the stadium should be kept in mind when selecting an appropriate standard, recognising that events are normally held relatively infrequently at major stadiums.

> “With patrons’ increasing expectations of good standards, which include those of the sound and acoustics, coupled with the general emphasis on environmental enhancement and sustainability, the need to properly address all aspects of sound, noise and acoustics for stadiums is becoming of greater importance in order to complement the traditional engineering and architectural disciplines required for this type of development.”
>
> (Griffiths, 2015)

5. Chapter Five: Case Studies

In an effort to further understand the acoustic aspirations and methodologies in stadiums in these last sixty years, several case studies from different decades are presented. Henceforth, we will witness the evolution of the stadium's engineering technology, flexibility and overall possibilities.

What links these case studies are the methods used for evaluating reverberation times, improving speech intelligibility through sound system design and placement, considerations on materials used and eventual absorption necessities, problem detecting and achievable solutions.

5.1. Houston Astrodome, USA - 1966

> "The Harris County Domed Stadium, involving the largest room in the world and having the worst possible shape for sound control, was an inherent acoustical albatross."
>
> (Talbot, 1966)

The dome shape of the arena could be subject to sound focusing qualities which would be undesirable. Only one third of the dome could be subject to acoustical treatment given that the other two thirds were to be translucent. Hanging absorptive pads from the trusses was discussed but their frightening expenses would eventually turn down the plan. The dome was to be compensated with strips of fibreglass and the exposed decking would consist of a 3-inch fibre and cement board with good acoustical qualities.

For the time, it could be the largest enclosed single space in the world. Having in mind the space would serve various kind of spectacles, some acoustical attention in the form of a speech reinforcement system would be necessary.

The acousticians turned to a model scale study to investigate the acoustical capabilities of the future Astrodome. They used the Charlotte Colosseum in North Carolina as a near half-scale model. It was intended to check the effectiveness of absorbing material, minimizing general room reverberation, treat any peculiar focusing effects of the dome and evaluate the success of an eventual central loudspeaker cluster.

Time-scaling studies were also employed and included “double-speed” examples of speech, music and other measurement signals. The tape recorder that included these signals would be played over the sound system in Charlotte’s Arena and recorded stereophonically as it was heard in the stadium. Measurements of the average and peak crowd noise levels would also be recorded.

Acoustical problems likely to arise in the Houston Arena were now predictable. Knowing the reverberation times would be greater than Charlotte’s Arena, a system of distributed speakers was installed to complement the central loudspeaker cluster. The dome of the arena would require enough sunlight so that grass could grow on the field, leaving a reduced amount of dome available for placement of acoustical absorption. Controlling reverberation times in these conditions could prove to be challenging. Although, accounting for the possible uses of the arena at the time, reverberation times were deemed satisfactory. It presented a boost on the low-frequencies due to the lack of absorption efficiency of the materials used in the arena but was not objectionable.

The sound system was designed primarily to ensure high speech intelligibility and good reproduction of music in a large place with less than optimum acoustical absorption. Time-delay tape loops would be used to synchronize sound arriving at different seat positions and additional loudspeakers and amplifiers would be provided for coverage of the concourse and miscellaneous areas surrounding the stadium. It was desirable that sound from the various loudspeakers could reach the various seat locations in the stadium with uniform loudness.

Uniformity of sound coverage was tested through the reproduction of broad-band noise and was intended to simulate crowd noise. In addition to these measurements, overall sound level readings were made at various seat locations, at various levels. The sound coverage of the arena was remarkably uniform for its size.

Articulation tests of speech intelligibility were also conducted at various ambient noise levels. Two problems arose when making these tests. Firstly, the author considered impractical to carry out articulation tests in the presence of actual crowd noise (which fluctuates on its own terms). Alternatively, crowd noise would be simulated through the reproduction of broad-band noise. Word articulation tests would be conducted whilst said noise would be transmitted through the speakers. Secondly, the usual articulation tests would require trained speakers and trained listeners. These were considered impractical for the investigation. Rather, word lists would be pre-recorded and played when testing speech intelligibility. An inexperienced group of listeners would be scattered around the seating tiers at different locations and levels and would write the word they thought they heard on a test sheet. This way of testing intelligibility proved to be suitable for routine use by inexperienced personnel in the performance evaluation of speech communication systems. Concerns also arose concerning the possibility of excessive noise from mechanical and ventilating equipment which were mitigated and brought to a suitably low level.

A high degree of intelligibility from the loudspeakers was achieved and the sound system was regarded as a successful one. Both the room acoustics and sound reinforcement system satisfactorily met the proposed design goals and the results achieved contributed significantly to the understanding of acoustics problems in large spectator spaces.

> "(…) in view of the potential acoustical disasters inherent in the 'big room' that were not only averted but triumphantly overcome, we think that not only have we had good advice, but that 'Somebody up there likes us.'"
>
> (Talbot, 1966)

5.2. Singapore National Stadium, Singapore - 1977

The former National Stadium of Singapore opened on 1973 and seated 60,000 people. It was intended for sports, entertainment events and national rallies. Being an open-air Olympic-sized arena, a high-quality sound system was necessary and relied on the use of line arrays of horn-loaded loudspeakers with highly efficient compression drivers. Since then, the stadium was demolished in 2011 and gave way to a new National Stadium in 2014. Still, this case study presents a frame of reference for stadium acoustics considerations in the 1970s.

Comprising of a single seating tier ring with only one roof for control booths and broadcast and television booths, the public stands were equipped with wooden benches rather than seats. This meant the capacity of the stadium was flexible. A full stadium could seat approximately 60,000 people.

Figure 5. 1.: The former National Stadium of Singapore (The Straits Times, 2016).

Given the general layout of the stadium, various viable locations for speeches and music concerts were considered. The best ones were found to be across the length of the pitch which while not uncommon, were not the most frequent locations. For speeches, the speaker would normally be in the grandstand either on the sound control room or in the front portion of stand. For mass rallies and national celebrations, the speaker could also address the audience on pitch level, in front of the grandstand. When larger audiences were expected, stage productions could be arranged on the centre of the field or even across the field from the grandstand.

The sound system had to consider the prevailing weather conditions in Singapore which comprised of high humidity. The system had to be straightforward to install and relocate between modes of operation. Two basic sound system configurations were considered. One involved using a large number of loudspeakers or distributed arrays installed on poles within the audience area. The other, involved using central loudspeaker systems located in the vicinity of the speaker or performance. The first approach would evidently interfere with sightlines and was consequently judged as unacceptable by the owners. A distributed loudspeaker approach would be ideal but would have required careful zoning of the loudspeakers as well as a system of time delays to prevent artificial echoes. A large number of loudspeakers could also implicate a large rate of failures and therefore be costly and difficult to maintain.

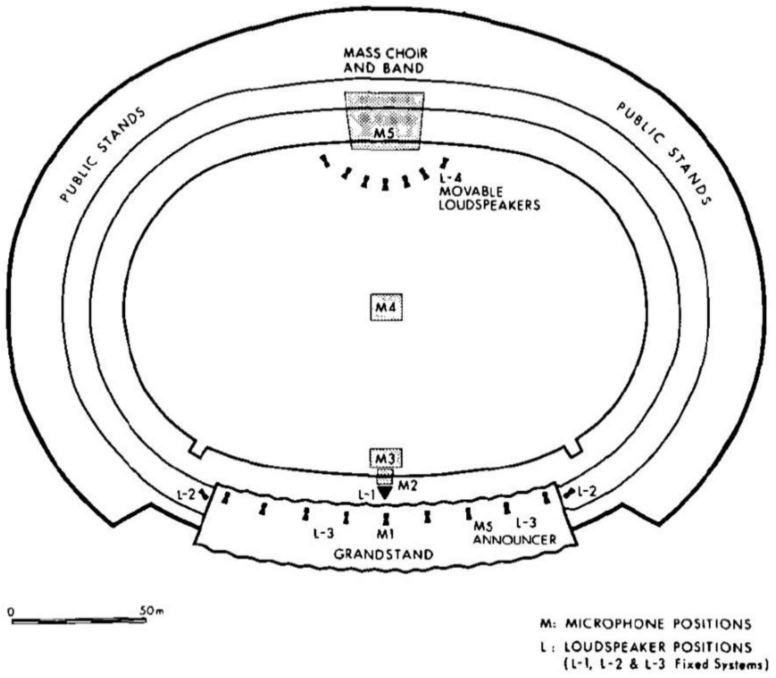

Figure 5. 2.: Layout of the stadium with microphone and loudspeaker positions (Figwer & Philbrick Jr., 1977).

The solution relied on a central loudspeaker cluster in the front edge of the ceiling of the grandstand. It contained horn-type high-frequency loudspeakers with compression drivers and horn-loaded low-frequency loudspeakers in bass reflex enclosures. The cluster covered the field, the seats in the stands across the field and most seats on the sides of the stadium. In terms of sound pressure levels, the objective was to provide no less than 95 dBA at the most distant seats in the speech frequency range. These were at approximately 175 m. The seats located underneath the grandstands' ceiling, with no decent coverage from the central cluster, would receive sound from nine separate loudspeakers systems.

The seats located immediately adjacent to the sides of the grandstand would also have no direct line of sight to the central loudspeaker cluster. Hence, two side loudspeaker clusters would complement the existing sound system. These were to be located at the apexes of the grandstand ceiling, directed to the sides of the arena. Electronically delayed signals were employed to prevent the occurrence of artificial echoes.

5.3. Athens Olympic Stadium, Greece - 1983

The Olympic stadium in Athens is the largest and most complete sports facility in Greece. It was completed in 1982 and was designed for football matches, light athletic events and national celebrations. It holds a total seating capacity of 85.000 divided into two decks whereas the upper deck is above a great portion of the lower one.

The sound system for the Olympic stadium had to provide high-quality, full-range reinforcement of live speech and music playback. Its specifications were set by the technical committee involved in the project and the loudspeaker were to operate at about 97 dBA with a maximum potential of 103 dBA. A signal-to-noise ratio of 70 dBA was also a requirement.

Figure 5. 3.: The former Athens Olympic Stadium in Greece (Papanikolaou, Pergantis, & Trochidis, 1983).

Two sound system design configurations were debated. One using a central loudspeaker system and the other distributing loudspeakers installed on poles in the field area. The latter would become the chosen design since the two level distribution of the seating area in conjunction with the large distances made it impossible to cover the desired specifications with a central system (Papanikolaou, Pergantis, & Trochidis, 1983). Loudspeakers mounted on poles could obstruct sightlines and create aesthetical problems but this was the preferred design.

It consisted of two 32 loudspeaker rings, one in the field area, the other covering the upper deck. The objective was to provide 97 dB from the first row to the most distant one with a specific frequency range to ensure high intelligibility. The zoning of these loudspeakers also made it simple to provide the necessary time between the loudspeaker rings, preventing possible echoes. Reverberation times were measured and found to be 0.6 sec at 500 Hz.

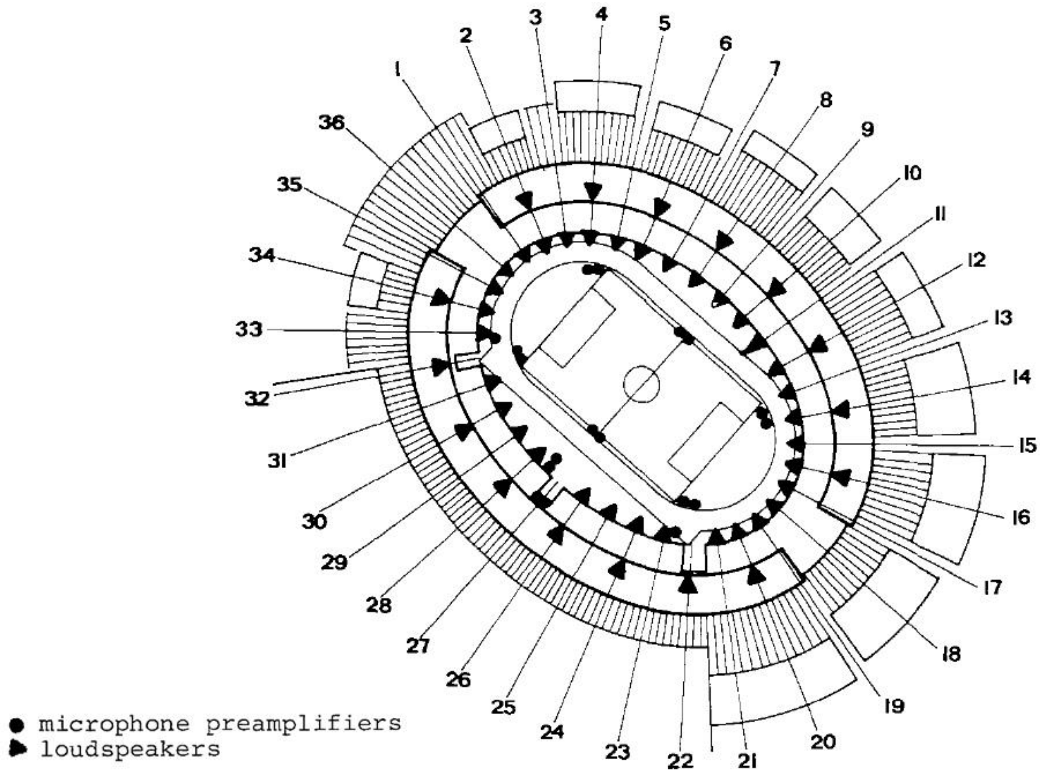

Figure 5. 4.: Layout of the stadium with microphone and loudspeaker positions (Papanikolaou, Pergantis, & Trochidis, 1983).

For achieving acceptable sound pressure level coverage, the loudspeakers of the lower ring were mounted with their axis pointing to the most distant listener in the lower deck, and thus also contributing to the first rows of the upper deck area. The upper deck loudspeaker ring also has its top loudspeakers' axis pointing at the most distant listener. The intention was to smoothen the sound pressure level uniformity threshold between seating areas. Overall sound pressure was also measured, accounting for air sound absorption.

Performance measurements were made under typical summer conditions. The sound system was fed with pink noise and its sound pressure level was measured at various positions of the seating tiers. The sound level meters used would stand at a height of 1,20m (average height of a seating person). Maximum SPL measurements were also conducted under the same conditions as were background noise levels.

The frequency response of the system was determined under similar conditions at various positions in the seating area. The measurement also included limited pink-noise being fed to the system whilst being analysed with tuneable 1/3-octave band filters, such as the reverberation time measurements.

> “A system of distributed constant directivity horn loudspeakers can be used in a large outdoor stadium. Measured values of sound pressure as a function of position throughout the entire stadium are uniform to within ±3 dB. The main advantage of the use of constant directivity horns, is that the very tight distribution pattern achieved, permits the coverage of the first rows of the audience with sufficient sound level, avoiding excess levels that plague these seats normally in similar setups, using conventional horns or sound columns. The frequency response of the system equalized, is also quite wide, resulting in a high voice clarity without intelligibility degradation.”
>
> (Papanikolaou, Pergantis, & Trochidis, 1983)

5.4. Wembley Stadium, England - 1991

> “A distributed loudspeaker system fed by localised amplifier racks, with fibre optic signal distribution from a centralised digital processing system, accessed by orbital computer-based input controls for Wembley Stadium is described. The use of state-of-the-art control and distribution techniques is compared with the traditional

alternatives in terms of effectiveness and quality. The electro acoustic-results are also compared against design targets."

(Jones & Griffiths, 1991)

Since then, the Wembley Stadium has already been redesigned. Thus, it is likely that the sound system may also have been updated. Nevertheless, key concepts of signal distribution and loudspeaker placement may well be still implemented.

Figure 5. 5.: The former Wembley Stadium in England (Football Tripper, 2019).

All types of inputs for this design can be divided into three categories: announcement only, line level sources to pre-determined areas, and microphone and line sources via analogue mixers. All these sources would then be routed to the central racks room where they would be fed to processing units. A different input section was also implemented via an analogue signal so that eventual emergency announcements could be made without the influence of digital signal systems.

The shape of the stadium bowl was deemed remarkably consistent which enabled a simplified electro-acoustic design divided into three main areas: the area occupied by the executive suites, the scoreboard sections and the remaining 70% of the bowl. Being that the roof is supported by a steel frame structure with 56 radial trusses neatly organized around the arena, these would be perfect locations for loudspeaker placement.

The electroacoustic component of the system also needed careful attention due to the multi-use feature of the stadium. One ideal loudspeaker placement for football matches may not be the most suitable for eventual music concerts. In the case of Wembley, the location, type and direction of loudspeaker were selected by taking into account:

- The intelligibility for announcements/sound coverage during concerts
- The sound pressure level and frequency response for varied events
- The varied nature of each acoustic space
- Reducing the risk of noise pollution to the community
- Loading on the existing structure
- Effects of climatic conditions on performance and durability
- Zoning as applicable to exists/evacuation policy
- Devices acceptable within the concert industry
- Effects on sight lines

Satisfying these requirements was declared one of the hardest areas to address by those involved. Maximizing intelligibility for announcements would be critical and the loudspeakers needed to be in front of the audience so that sound travelled towards the heads of the attendees. This would be in conflict with the normal stage position for music concerts, located on the western side of the pitch. Setting appropriate delay times for the rest of the loudspeakers would be crucial.

Four types of speaker systems were employed to match each acoustic space. For the lower decks, 60 x 40 constant coverage horns were located at the front of the roof trusses at approximately 20 metres from the audience. Low frequency cabinets were mounted adjacent to each horn in order to provide more low frequency coverage. The first half of the upper decks would be served by full range 90 x 90 cabinets and the rear of these upper decks would be covered by 90 x 40 horns. No low frequency reinforcement would be necessary since the lightweight roof already provided a potential bass trap. The 90 x 90 cabinets already contributed with a sufficient degree of low frequency energy. Careful positioning of these speakers was required to provide an even coverage of sound. The last type of loudspeaker system refers to the single speaker cluster located just below the roof on the North stand. It was designed to cover the pitch area.

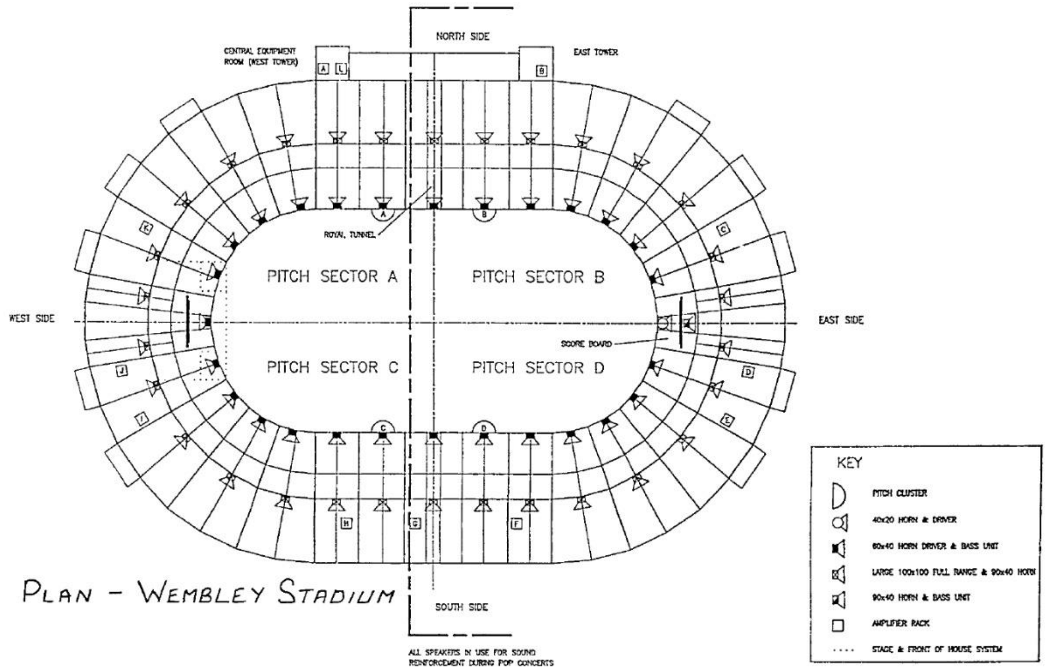

Figure 5. 6.: Layout of the stadium with microphone and loudspeaker positions (Jones & Griffiths, 1991).

As for sound pressure levels, both sporting events and music concerts were considered. Measurements were made throughout several events in Wembley whilst attracting capacity crowds. In the case of sporting events, results showed that 95 dBA at the heads of the audience would be at or above the level generated by the audience for some 90% of the event. On a parallel investigation, Jim Griffiths found that pop concert events become an ineffective form of entertainment to the public below said 95 dBA margins. Therefore, this was the sound pressure level pursued for both sporting events and music concerts.

Wembley presented the first stadium sound system controlled with graphical touch screen controls and its fibre optic transmission systems presented a few advantages such as faster installation times and better audio quality when converted. The system designed for the stadium also had the advantage of being able to be linked in with other similar systems for other events.

5.5. Gelora Bung Karno, Indonesia - 2016

The Gelora Bung Karno stadium was built in 1960 and is one of the biggest in the country, holding 88,093 people sitting and 100,800 people standing. In 2016, studies were made to improve the acoustics of the arena. These studies showed there were problems related to echoes which are undesirable and can impair intelligibility. These echoes appeared as an impulse sound was generated within the building, urging for a redesign supporting a good acoustical experience while understanding the behaviour of sound in a fully occupied stadium.

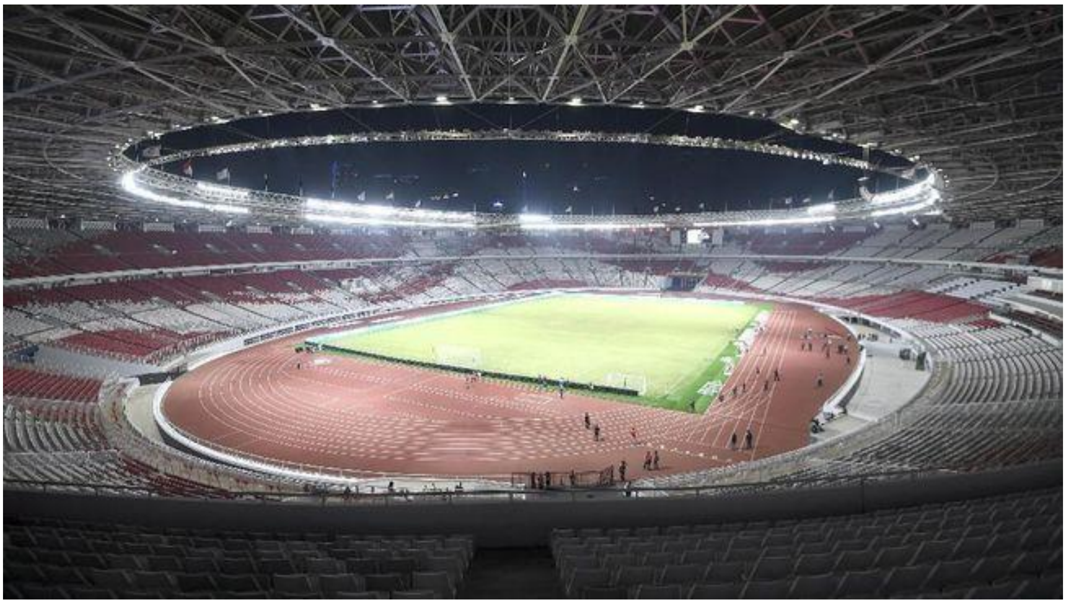

Figure 5.6.: The *Gelora Bung Karno* in Indonesia (CNN Indonesia, 2018).

Reverberation-time measurements were conducted with an impulse response using the main sound system. This way, some of the acoustical parameters could not be compared with the one resulted from simulations. CATT-Acoustic software was used for the computer simulations with some simplifications made on the geometry model design such as the flattening of steps in the seating tiers. The intent of this simplification was to provide similar diffusion results of an uneven surface in the existing conditions. The type and position of the sound sources was varied in order to provide overall results. White noise and the human voice were the sources used. The difference between simulation and measurements data was then calculated and revealed the simulation had an overall average error of approximately 5%.

The scenario used for simulation included a vacant and fully occupied stadium. The echoes appeared mostly on the lower decks, further away from the pitch and under the upper deck. These were the anticipated results and are due to a combination of surfaces which may create both specular and diffuse reflections. A combination of seating area, rear walls and ceilings would provide the most notorious echoes. The results of the simulation are then used as a base for determining the optimum area for acoustic improvement.

The disturbances coming from ceilings and walls will always occur in the stadium, but analysis shows that improvements made on these surfaces would be fruitful. In order to degrade the level of disturbances on a receiver, absorptive materials can be employed. Absorbers with a great absorption coefficient between 500 and 1,000 Hz were placed on the ceiling and trench wall of the lower decks. This resulted in less echo-disturbance and better diffusion of sound.

Computer simulation studies provided a quicker investigation of the acoustic properties of the stadium. Researchers learned that adding absorption materials could decrease the level of troublesome echoes but could raise the difference between the troublesome echoes and the rest of them. This was the base for this research. The aid of technology in acoustic investigation of buildings with this magnitude helped improve and quicken acoustic evaluation methodology as it will in the future.

With a careful analysis of all the referred case studies, the impact of technological advances are noticeable. Since the days of tape-machines and vital significance of architectural acoustics, improvements in the ever-progressive quality of sound systems and the increase in financing of stadia construction have brought challenging futuristic designs which depend more on the quantity and placement of speakers. Since the measurements done in the Astrodome, in Houston, that speech intelligibility is carefully considered as is today. Something that can be achieved with proper acoustic design. As the years gone by, stadiums started to become multifunctional, hosting a variety of events which required different acoustic approaches. The computer age brought us the possibilities of ray-tracing models and digital sound processing which facilitate the work of the acousticians and allow for quicker, more inexpensive solutions.

Even today some stadia may lack of a sophisticated acoustic approach. Such is the case with the Old Trafford Stadium, in Manchester, which is reported to have acoustic inefficiencies

(White, 2013). Proper acoustics will create a better overall atmosphere for fans and performers, have an impact on financial income and on the desire of the spectator to return.

6. Chapter Six: Interviews

With the intention of gathering knowledge towards the acoustics of sports stadia, I made a collection of several possible contacts with firms, engineers and acousticians involved in the design and building of major stadiums in Europe. Reducing the scope of work to a single continent would also reduce the list of available contacts, permitting a focused research.

42 european stadiums were considered from Portugal to Russia, from Norway to Turkey. This way, we could assume these stadiums had to fulfil different expectations in relations to construction design and expenditure, but also prevailing factors like the climate and proposed functionalities for the arena. More than half of these were built from the year 2000 onward which would, in theory, enable more possible connections. However, the other half would be built from 1900 onward, granting a line of acoustical thought throughout the century. Not surprisingly, reaching the people involved with these designs came to a stalemate.

Stadium capacity was also varied in my recollection of stadium data since this would be a major producer of sound pressure. The capacity of these varied between 10,000 and 90,000 people. Stadium renovations are also considered since these commonly refer to stadium amplifications, bringing more people and structural re-modernizations. Most of the stadiums in the list were renovated recently.

When the collection of available connections concluded, an enquiry was devised consisting of thirteen questions. These were all focussed on the acoustics of the stadium. How acoustical awareness has evolved, current and future trends, the lack of specific literature and a personal assessment of the specific building. Different approaches would be negotiated in terms of interviewing methods. Phone and video calls would grant a practical and quick interview. However, from all answers I received, the preferred method was to respond via email.

1.	What can you tell me about the latest acoustical trends in football stadiums in these past few years? (evolution, considered materials, concepts,...)
2.	What are your main concerns during construction, sound-wise? (sound absorption/reflection, sound pressure,...)
3.	What do you think will be the next "big thing" in stadium acoustics and, hence, design?
4.	Exciting news have been surfacing about the use of acoustic meta-materials. Are these being already put to practice? What are your thoughts?
5.	There is very little literature related to sound acoustics in football stadiums. What are your thoughts? Should there be an effort to better grasp an understanding of these components?
6.	What were your bigger challenges to date in stadium design?
7.	Do your projects always live up to their expectations?
8.	Glass-fibre membrane ceilings have been a constant in football stadium design in these past few years and are being put to use in different climate contexts. From cold countries like Poland and the Ukraine, to hot countries like Turkey and Spain. Does it mean this is a successful approach to stadium insulation? Is it merely an aesthetical approach or is it the future?
9.	How does the production phase work? (Scheduling, contacts, experts involved, priorities,...)
10.	Do the architects/designers involved think about the acoustical capabilities of the stadium since day one?
11.	Typically, what's the financial investment dedicated towards these edifications? Does it tend to be enough? Is it normal to go a bit overboard and include unforeseen expenses?
12.	Do you only think about the acoustical performance of the space for football matches? Do you consider eventual music concerts and other sorts of events?

Table 6.1.: List of questions sent to the interviewees.

Ultimately, five contacts reached out and sent me their input on the various topics I selected. These were Andy Simons, Damon Lavelle, Dennis Paoletti, Javier Eusebio and Olly Creedy. Andy Simons is a founder director from British architecture firm KSS which is responsible for several stadium constructions and redevelopments throughout the United Kingdom and beyond. Among these are the construction of the Amex Community Stadium in Brighton and main stand developments in Liverpool's Anfield Stadium. Damon Lavelle is an architect representing global design firm Populous and is best known for his notable work in the Estádio da Luz from

Lisbon, Cardiff's Principality Stadium and recent 2018 Russia World Cup stadiums. Dennis Paoletti is the founder of the Paoletti Consulting firm, recognized in the areas of acoustics and audiovisual/multimedia system design, and is an avid writer and lecturer in the field of stadium and arena acoustics. Javier Dávila de Eusebio represented a team of professionals from Spanish architecture firm IDOM responsible for the new *San Mamés* Stadium in Bilbao. Finally, Olly Creedy is an associate director from British architectural acoustics firm Vanguardia, involved in the Olympic Stadium in London and the new Tottenham Hotspur Stadium.

When asked about the latest acoustical trends in football stadia, the answers were quite varied. Simmons outlined the importance of the environmental noise impact. In KSS projects such as the Amex Stadium in Brighton, the stadium is completely enclosed to protect nearby buildings. Stade Oceane at Le Havre has a deliberate roof soffit sounding board to focus crowd noise onto the pitch to avoid breakout to residential areas. The IDOM team recognised the importance of the natural acoustic pressure in a football stadium as a growing trend, catering again for more fan involvement. These natural acoustics are commonly translated into non-absorptive materials, which will compose the stands, walls and ceilings, reflecting sound onto the pitch. The geometry of the roofing solution also takes more importance than the material itself. Creedy delineates progressively multi-use venues hosting sports, motorsports, concerts, and other events, which requires the stadium to present satisfactory overall acoustics. All interviewees agreed on one particular topic, however. Higher-quality full-range sound systems are always on demand and stadiums pay due attention to high speech intelligibility and music quality.

Sound-wise concerns amid the construction revolve around possible noise breakout during construction as pointed out by Paoletti. Local requirements and ordinances must be followed for a controlled noise environment. Depending on whether it is an open-air or enclosed stadium, approaches to sound control will vary. In the case of an open-air stadium, reflective surfaces and high sound pressure will be critical whereas in the case of an enclosed stadium, absorption is considered allowing for sound performance and comfort for the spectators. High sound pressure from the stands cannot exceed the sound pressure capabilities of the sound system however, ensuring emergency announcements may be heard. Concrete is the most commonly used material given its affordable cost and fire-insulating properties. Hence, it will be the geometry of the design that will dictate how sound is to behave in the bowl. Careful planning of raked and compact stands, continuity of the upper walls of the bowl and low profiling of the roofing solution are some of the steps taken along the way. A careful balance between sound absorption for intelligibility and minimising absorption for maximising the atmosphere is mandatory.

As for the future of the football stadium as we know it, the world is aware of the possibility of a self-sufficient sustainable stadium in the upcoming years. However, how will acoustics accompany this evolution? It is hard to predict since it is unlikely that this field will have enough force to drive an actual structural evolution. Nonetheless, multi-functionality will continue to assert itself, demanding powerful and adaptable active noise sources which can overcome stadia geometry and materials and implementing delay systems, permitting multiple zoning of active systems. With e-sports and other interactive events gaining popularity, the idea of the interactive stadium, like in all walks of life due to advances in A.I., will be a key driver. Variable acoustic systems may come to mind in the future. The IDOM team likes to believe that the next evolutionary step would be transferring the natural acoustics elements of large stadiums into other types of stadia, but according to them, there has been a relative low interest for that. That and the creation of an increasingly fan engaging main stand seem interesting. Some studies have been made to better understand the geometries, incline and preferred materials of the stands to maximize their sound pressure capabilities. These sound levels may be transferred onto other stands whilst providing adequate diffusion.

Acoustical metamaterials and their potential insertion in stadia were discussed and originated similar responses. The interviewees agreed that such materials are very futuristic and expensive. These materials are supposed to achieve effects not found in nature and address long-standing engineering challenges in acoustics such as the creation of ultrathin barriers whose performance surpasses current technologies (Haberman & Norris, 2016). In fact, these metamaterials are very recent, but in the last decade they have developed into a well-established and expanding field encompassing ideas like negative refraction, enhanced absorption and material tunability. Hence, their eventual need towards improved stadia acoustics with multipurpose features. Further studies and laboratory tests would grant more confidence towards the use of these materials in future stadia designs. For now, and as supported by the interviewees, it appears as a farfetched idea.

When discussing the usual challenges acousticians come across when dealing with the acoustic atmosphere of the stadium, Creedy referred that providing the optimum performance for atmosphere while maintaining intelligibility of the sound system is a persisting challenge.

Multipurpose stadiums will obviously require special attention when addressing this topic. Paoletti outlines the PA system coverage as another typical challenge in the area having in mind the shape of the space and the size of the exposed perimeter enclosing walls. Lavelle tells us that the biggest challenge is leading change.

It is in the interest of all those involved that the stadium design lives up to its expectations. Responses regarding this topic were optimistic and Paoletti extended on the idea that a properly managed project is important and that the team must involve every possible engineer and consultant. The IDOM team favours a holistic approach on all their projects, favouring functionality over the design disciplines. Sometimes the best performance is not possible due to time constraints or the allowed budget. Regardless, a holistic approach is key when aiming for a successful design. As confirmed by Simons, projects almost always exceed the initial budget which can typically be around 3,500 to 20,000£ per seat. Choices cannot be made lightly and functionality must be, indeed, prioritised.

The use of lightweight materials for roof construction such as acrylic and PTFE materials has been employed for several years. In recent decades, these roofs have resulted in elegant designs throughout Europe in different climates. This is because the membrane structures are light and allow sufficient penetration of light to enable the stadium of the gymnasium to be operated without electrical lighting during daytime. In the acoustical sense, some problems are encountered when using these PTFE membrane materials. Most membrane materials are sound-reflective; therefore, the sound generated inside the stadium can reverberate, resulting in difficulty in understanding announcements (Kim, Jeong, & Sohn, 2009). All interviewees agreed on the idea that these lightweight materials are inexpensive and easily constructed and installed, hence their success. Sound-absorption could be considered, but since these roofs are designed to reflect the sound onto the pitch, it is often disregarded.

Concluding this chapter, the acoustical capabilities of stadia are considered since the early concept stages. As Simmons said, they define the choices available for the envelope. The IDOM team tells us that the design will be frequently driven by aesthetics rather than functionality. Something expected from designers, not from stadia. Functionality performance will always be prioritised which implies dealing with acoustics since day one. Given the multifunctionality pattern of modern stadia and likelihood to host a varied selection of events, careful acoustic design cannot be overlooked. Lavelle highlighted good acoustics for speech intelligibility and music concerts and protecting the neighbours from the generated noise as key acoustical considerations for stadia acoustics. Roofs can be extremely helpful in these matters. Modern sound systems have also allowed for improved acoustics control through careful placement and equalization. The future promises better fan engagement and variable acoustic systems which should further enhance stadia atmosphere and cater for other types of events.

7. Chapter Seven: Conclusion

> "The rise of television, technology and communications has brought with it an exponential interest in professional sports and the viewing of such events that captivate so many around the world, and this has brought stadia design to the forefront of engineering and architectural innovation."
>
> (Jenaway, 2013)

This paper reflects the constantly highlighted factors of speech intelligibility and sound system design as the predominant features of a successful stadia acoustical design. As we have seen, there is great importance in isolating the stadium bowl from the external environment as does containing it within. Stadia are commonly and almost entirely made of concrete which helps in those objectives. Roofs are typically constructed with lightweight and transparent materials so they allow some light inside and reflect sound from the stands onto the pitch. From this point on, it would be vital to calculate reverberation times, study the diffusion of sound and carefully place a specific sound system design with due sound equalization.

The future of stadia design and construction seem to focus on their sustainability and environmentally sustainable design. Events such as the FIFA World Cup are sometimes hosted in peripheral countries with more difficulties in guaranteeing a sustainable design. Some of the stadiums built for these types of events often aim for portable or modular seating, meaning these could increase seating capacity when needed and disassembled when not in frequent use. In such a way, we get to a certain topic addressed by Creedy when asked about the future of stadia acoustics. Variable acoustic systems. When it comes to the future of stadia acoustics, said variable systems could be a versatile approach to multifunctional spaces and be easily adaptable to any given event. Football matches, music concerts, motorsports, among others, require different performance areas in different locations. A system that could be as easily as adaptable, could be beneficial.

The examination of every material and design aspects from a sustainable point of view is also a current and future trend. From site location to material specifications, the view that everything should be lightweight, recyclable or locally sourced whenever possible is definitely a path to follow. From an acoustic standpoint, stadiums need to fit in with its surroundings regarding noise. Stadia embedded in city centres or near suburban areas tend to create traffic and noise propagation, something to keep in mind when dealing with such stadiums. While the concrete structure will be the most effective in containing and isolating sound, the insertion of lightweight and recyclable roofs is a modern trend and is proved to be effective when it comes to further contain the sound within the bowl. A stadium that can effectively isolate its noise propagation from its surrounding community is a sustainable and environmentally friendly one, sound-wise.

The creation of amazing Home Ends, as known as Kop in the UK, have been schemed to include continuous geometries, large-scale sizes and steeper inclines, creating intense sound pressure that any team would want as home advantage. The most recent example of such feat is the new Tottenham Hotspurs Stadium with a 17,500 single tier stand. It was designed like a concert hall in a way that reverberation times last longer. Keeping the atmosphere and personality of stadium in mind, discussion of materials, localized absorption treatment, seat padding, and other acoustical discussions, were taken to a unique level. Stadium atmosphere is still a driving factor towards evolutive acoustics and will continue to be so. Its geometries need to be carefully studied so that a sense of sound clarity can be achieved.

Transferring good natural acoustics from a stadium to other types of stadia could also be beneficial. However, such feat has not received much attention from experts in the industry. Understanding success cases in acoustical design for stadia and shift the same concepts to new buildings, which could be different in size and purpose, infers similar success cases. These concepts would be referring mostly to materials and their placement, scales, reflective and absorptive treatments, among others. In order to allow for the best natural acoustics in football stadia, the materials used on the bowl stands and upper walls are typically non-absorptive, contrary to what one would assume given the intense sound pressure levels felt in stadiums with full attendance. The same is applied to roofing solutions and the geometry of these components takes more importance than the material itself, always with the atmosphere in mind.

The future direction of stadia is shaped by those involved with stadia design, construction and operation. Only with a proper understanding of where these design and construction aspects have evolved from and why so that they can fully appreciate stadia and the direction that it is headed for in the future to meet with the expectations, requirements and aspirations of the society of today. The importance of stadia in this society cannot be understated. Sports and leisure and, by extension, the associated infrastructures such as stadia are facing a defining period in its history.

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Appendix A: Interviews

Andy Simons, KSS

Q.: What can you tell me about the latest acoustical trends in football stadiums in these past few years? (evolution, considered materials, concepts,...)

A.: Crafting the basic configuration of a stadium to enclose and reinforce sound is a common trend and client requirement. The highest level of crowd noise in stadia is desired by the clubs. Stadiums pay a lot of attention to the quality of music and voice quality and intelligibility. Music at pre-show and interludes (US trend) is now a key requirement. We often have a requirement to enclose sounding the stadium to avoid or reduce breakout to local residential areas. The Amex at Brighton is completely enclosed for this purpose to protect the University and Falmer Village nearby. Stade Oceane at Le Havre has a deliberate roof soffit sounding board to focus crowd noise onto the pitch to avoid breakout to residential areas. The stadium bowl is typically interlocking pre-cast concrete which is acoustically secure but the vomitory holes destroy this containment. The side walls of the vomitories are therefore acoustically lined to diminish breakout.

Q.: What are your main concerns during construction, sound-wise? (sound absorption/reflection, sound pressure,...)

A.: High crowd noise results in the PA systems being much higher specifications to ensure emergency announcements can be heard. When a stadium is full the crowd and pitch make good acoustic surfaces to avoid reverberation and absorb noise. The aim is typically to create a shaped and hard roof soffit to rebound and focus crowd noise primarily to the pitch to encourage players but also to the opposite stand. Anfield does this and the Amex is both curved and sloped to do this. A key concern is avoiding materials that can be used as drum surfaces by fans. The code requirements for stiffness of terraces to avoid the uncomfortable and potentially harmonic effects of acceleration due to rhythmic jumping is negated by the (almost) universal use of concrete in stadia construction). Concrete is also key to achieving the two hour fire compartmentation typically needed from the bowl to the rest of the stadium accommodation.

Q.: What do you think will be the next "big thing" in stadium acoustics and, hence, design?

A.: Hard to say. Unlikely to be acoustics that drives the requirements. The closing roof at Cardiff creates an awesome acoustic enclosure but it is not popular with visiting teams and is regularly vetoed. Active noise sources are now very powerful and adaptable and largely independent/able to overcome of stadia geometry or materials.

Q.: Exciting news have been surfacing about the use of acoustic meta-materials. Are these being already put to practice? What are your thoughts?
A.: The architectural world is not aware of AMM's yet. Given the scale of stadia it seems unlikely that this type of technology would scale up economically. What purpose did you have in mind?

Q.: There is very little literature related to sound acoustics in football stadiums. What are your thoughts? Should there be an effort to better grasp an understanding of these components?

A.: We always have acoustic consultants in our projects but I agree there is little written about it. I suggest you aim to make contact with the leading companies in the field. The main requirement is the player and fan relationship and keeping it as close as possible. The design process is quite intuitive. Obviously a high density crowd, steep terraces and proximity to the pitch and with a hard sloping roof surface is ideal but many brief factors mean this is not always possible to achieve. Smaller and more intimate stadiums are always best. However if your team is losing it can be very quiet however well designed. Acoustic crowd noise performance and outcomes is not usually mapped and analysed in detail.

Q.: What were your bigger challenges to date in stadium design?

A.: Too many and diverse to focus on in this forum really. Typically keeping budget and programme expectations realistic. This is a product of working with clients that know football but not large construction processes.

Q.: Do your projects always live up to their expectations? To date thankfully always yes.

A.: A new stadium is a wonderful thing and the initial enthusiasm and high capacities always create a great buzz. The teams crucially raise their game too in a new stadium. Winning is essential.

Q.: Fibreglass membrane ceilings have been a constant in football stadium design in these past few years and are being put to use in different climate contexts. From cold countries like Poland and the Ukraine, to hot countries like Turkey and Spain. Does it mean this is a successful approach to stadium insulation? Is it merely an aesthetical approach or is it the future?

A.: Stadium roof have no insulation requirement as the bowl is external. The roof is principally for rain and sun protection. Occasionally acoustics as noted. The current trend is for ETFE which is wonderful and light but is acoustically transparent.

Q.: How does the production phase work? (Scheduling, contacts, experts involved, priorities,...)

A.: We complete concept and a more detailed developed design, the contractor typically then comes on board with prices for staffing, overhead and profit, we work through the technical design with contractor input, final contractor price, contract award. The team is large with all design disciplines represented. Structure, MEP, architecture, fire, acoustics, landscape, cost, planning, programming, interiors, branding, hospitality, graphics, wayfinding and lawyers.

Q.: Do the architects/designers involved think about the acoustical capabilities of the stadium since day one?

A.: Yes, it’s a very early consideration because it defines the choices we have for the envelope.

Q.: Typically, what's the financial investment dedicated towards these edifications? Does it tend to be enough? Is it normal to go a bit overboard and include unforseen expenses?

A.: Typically £3,500 to £20,000 per seat. The projects almost always exceed the initial budget

Q.: Do you only think about the acoustical performance of the space for football matches? Do you consider eventual music concerts and other sorts of events?

A.: Yes, all event types are considered. Concerts are a big part of stadia ROI.

Damon Lavelle, Populous

Q.: What can you tell me about the latest acoustical trends in football stadiums in these past few years? (evolution, considered materials, concepts,...)

A.: Please look closely at the newly opened Tottenham football stadium – again with input of Vanguardia consultants. It has a very big single tier stand in the south with roof geometry that reflects the sound from end to end. This is standard formula that we have used many times.

Q.: What are your main concerns during construction, sound-wise? (sound absorption/reflection, sound pressure,...)

A.: There are many good papers on this subject. For concerts, the low frequencies and delay issues are the overriding challenges, as are noise break-in and break-out.

Q.: What do you think will be the next "big thing" in stadium acoustics and, hence, design?

A.: Personally, I think that multi-functionality is the key driver – and so delay systems for concerts including active systems for multiple zoning will be the key. That is, with e-sports and other interactive events gaining popularity, the idea of the interactive stadium, like in all walks of life due to advances in AI, will be a key driver.

Q.: What were your biggest challenges to date in stadium design?

A.: The biggest challenge is leading change

Q.: Do your projects always live up to their expectations?

A.: The latest stadium is always behind the latest idea

Q.: Fibreglass membrane ceilings have been a constant in football stadium design in these past few years and are being put to use in different climate contexts. From cold countries like Poland and the Ukraine, to hot countries like Turkey and Spain. Does it mean this is a successful approach to stadium insulation? Is it merely an aesthetical approach or is it the future?

A.: This is a cheap material and due to its lightness, easy to construct, etc. It’s about cost.

Q.: How does the production phase work? (Scheduling, contacts, experts involved, priorities,...)

A.: Procurement is usually design and build, so partners are brought in early , usually to control costs.

Q.: Do the architects/designers involved think about the acoustical capabilities of the stadium since day one?

A.: Yes

Q.: Typically, what's the financial investment dedicated towards these edifications? Does it tend to be enough? Is it normal to go a bit overboard and include unforseen expenses?

A.: The business case will rely on multi-functionality, so good acoustics for concerts is a key consideration. Also, in city stadiums, protecting the neighbours from noise is important. If the stadium has a roof, its better if it can keep out some noise in a city – from planes for example. But this all costs a great deal of money, which is hard to justify in terms of business return. Stadia are not arenas, nor are they concert halls.

Q.: What's your opinion on the final acoustical results of the Estádio da Luz? Do you feel it was a success case? Is there anything you would change now?

A.: Benfica is an economic building that needed to be built quickly with a club that was bankrupt. Hence, we had only cheap, hard surfaces to reflect sound. It is impossible to keep the traffic noise from the second circular freeway out of the stadium, particularly for the upper tier. The key thing is the design of the stadium bowl, all seats are exposed to each other so there's a good sound reflection profile – i.e. no big overhanging tiers. The geometry of the bowl also helps reflect and concentrate noise from one end to the other. The roof reflects the sound in the same way – the corner roof sections are higher, so the roof tends to focus the reflections in the opposing direction, and there are no excess reflections creating dissonance on the corners as the sound leaks out before that can happen – this applies to the corner stand as well – because the gap is larger there.

I think that the acoustics are good there overall – having the money to upgrade, the stadium would be more enclosed, and then we would look at better PA systems and perhaps a new roof. But the character of the current stadium is what it is!

Dennis Paoletti, Paoletti Consulting

Q.: What can you tell me about the latest acoustical trends in football stadiums in these past few years? (evolution, considered materials, concepts,...)

A.: See Stadia magazine (UK). Fan involvement/engagement/participation, technology/multimedia with strong back-up, good food, very high quality audio.

Q.: What are your main concerns during construction, sound-wise? (sound absorption/reflection, sound pressure,...)

A.: Construction noise impact is a concern, local noise control requirements/ordinances, environmental noise control.

Q.: What do you think will be the next "big thing" in stadium acoustics and, hence, design?

A.: Follow the industry via targeted magazines and conferences. See Convention, Sports and Entertainment Facilities Conference in San Diego. Many good presentations including ”The Sports Facility of the Future”.

Q.: Exciting news have been surfacing about the use of acoustic meta-materials. Are these being already put to practice? What are your thoughts?

A.: Meta materials are very futuristic. It will probably take many years to come to practical fruition.

Q.: There is very little literature related to sound acoustics in football stadiums. What are your thoughts? Should there be an effort to better grasp an understanding of these components?

A.: Why? What are the problems? Some aspects of acoustical consulting are very basic - e.g. HVAC noise and vibration control. Room acoustics is not an issue for outdoor venues unless there are large overhangs or a movable roof above the seating areas. Indoors, echo and reverberation control are major issues but well-known by acoustical consultants.

Q.: What were your bigger challenges to date in stadium design?

A.: Multiuse ‘’sports; concerts; rodeo; tractor pulls/motor sports, etc.”. Many young people want high sound levels in entertainment. Corporations support these Millennials with products and programs. The shape of the space, e.g. circular, and the size of the exposed perimeter enclosing walls to the sound field. PA system coverage, quality and video support; coverage under large overhangs and in concession areas.

Q.: Do your projects always live up to their expectations?

A.: Most often yes – if properly managed. Managing client expectations is important. The “team” needs to include owners/owner reps, PMs, CMs, all engineers and designers, and all key consultants.

Q.: Fibreglass membrane ceilings have been a constant in football stadium design in these past few years and are being put to use in different climate contexts. From cold countries like Poland

and the Ukraine, to hot countries like Turkey and Spain. Does it mean this is a successful approach to stadium insulation? Is it merely an aesthetical approach or is it the future?

A.: I believe there is experience with the acoustical properties of PTFE materials. In the 80's(?), the Metrodome - an inflatable air structure used this same type of material. The results: low frequency sound energy transmitted throughout the relatively thin material; high frequency sound energy reflected off the impervious material resulting in very high levels of reverberation. Double skin surfaces were tried where the interior skin was perforated to absorb high frequency sound energy, effectively. Any such material could easily be tested in an acoustical laboratory and acoustical consultants would know how to apply it in any application.

Q.: How does the production phase work? (Scheduling, contacts, experts involved, priorities,...)

A.: Difficult question to answer; intent not very clear. It's also very broad… It would take a long time to answer and there are books on this phase of work.

Q.: Do the architects/designers involved think about the acoustical capabilities of the stadium since day one?

A.: I believe the "good ones" who've got experience with this building type know to include an acoustical consultant on the team early.

Q.: Typically, what's the financial investment dedicated towards these edifications? Does it tend to be enough? Is it normal to go a bit overboard and include unforeseen expenses?

A.: Do you mean financial investment from the client's side or the consultants'?
From the owner's perspective, that's the responsibility of the owners/cities and investment people funding the project.
From the consultant's standpoint, no one plans to go overboard. If/when it happens, the team collectively goes into "value engineering" mode. They look for alternative less expensive solutions, reduce or remove less critical recommendations; potentially save them for a later time when money becomes available.

Q.: Do you only think about the acoustical performance of the space for football matches? Do you consider eventual music concerts and other sorts of events?

A.: Definitely. Non-football events bring in revenue; therefore, it’s wise to accommodate and plan for them.

Javier Eusebio, IDOM

Q.: What can you tell me about the latest acoustical trends in football stadiums in these past few years? (evolution, considered materials, concepts,...)

A.: In our opinion, there has been a recognition trend of the importance of the natural acoustic pressure in a football stadium in the latest years. But this is mostly an isolated feature for football: no such interest is really appreciated in more open layout stadia types, such as Athletics, Cricket, and the kind. We consider that natural acoustics are key in football, and appreciated by players and fans, but not really appreciated in other open-air sports. On those concepts, a different consideration must be done to amplified sound, which is also key as to make intelligibility for Public Announcements really work at all types of Stadia. But the trend has been to rely this intelligibility on to the power of the speakers and their disposition around the bowl, with no real analysis of architecture or material features. So in order to allow for the best natural acoustic performance in football stadia, the materials used on the bowl stands and upper walls must be non-absorptive, to allow for sound reflection onto the pitch. The materials for roofing solutions are reflective most of the times, and the geometry of the roofing solution takes more importance than the material itself. A low-profile roofing is always helpful to achieve the effect.

Q.: What are your main concerns during construction, sound-wise? (sound absorption/reflection, sound pressure,...)

A.: A key difference exists between Stadia (open air venues) and Arenas (Indoor venues). At Arenas, absorption is paramount to allow for sound performance and comfort for spectators.

But reflection and sound pressure are more important in open air stadia, and in our opinion, critical in Football stadia. For us, sound pressure depends more on the geometry of the Bowl (stands rake and compact layout), the continuity of the upper walls of the Bowl (create a ribbon enclosure at that high position), and a low profile of the roofing solution. As all materials for these elements are reflective, the effect is somehow easy to obtain when all components are treated in a coordinated manner. These materials are such as precast concrete for the stands, and flat hard finishes for upper ribbon solutions (blockwork, steel panels, composite panels, curtain walls).

Q.: What do you think will be the next "big thing" in stadium acoustics and, hence, design?

A.: We would like to believe that the best big thing would be to transfer those natural acoustics elements to other types of stadia. But we have seen a relative low interest for that, and more designers are recognizing the importance of this acoustic performance, but mainly for Football stadia. So the real next big thing on this could be creating Stands which are Fan Engaging and Acoustic-performing by design. Some studies and schemes have been made to create impressive Home Ends, with continuous geometries, larges scales and sizes, which can create the added pressure that every team would want to have as home advantage. The Home End, Kop as they call in the UK, is key to get the fan engagement in the Stadium. The more continuous they could be in their geometry, and the steeper the rakes could be, the better they could create an acoustic pressure effect to the entire stadium, transferring sound onto the other stands, with an even and greater diffusion of sound to the surrounding stands.

Q.: Exciting news have been surfacing about the use of acoustic meta-materials. Are these being already put to practice? What are your thoughts?

A.: We have not heard about any real application of such meta-materials in the construction of football stadia. We can imagine that some commercial construction materials could replicate the acoustic effects of these materials, but they might have counter effects with durability and ease of maintenance in such public spaces with high levels of attendance. In any case, we consider that the meta-materials impressive effects could be difficult to control in such large layout venues, although it is true that they open the way to explore how to apply them and achieve impressive effects.

Q.: There is very little literature related to sound acoustics in football stadiums. What are your thoughts? Should there be an effort to better grasp an understanding of these components?

A.: Please refer to Answer 1. We believe it is paramount, and it has been recognized by players and fans. In a similar way as compact concert halls with prism shape perform better with natural acoustics, the compactness and continuity of the bowl makes most of the effect of sound pressure in a football stadium. The effort could be more of spreading the convenience to adopt such design features to bring Fans to the Stadia and keep them engaged. We doubt that Data studies, measurements, surveys and reports and papers will bring any major change on this appreciation by Clients (Teams, developers and Contractors). They have to live it!

Q.: What were your bigger challenges to date in stadium design?

A,; In our opinion, the challenge would be to keep the key performance of football atmosphere with the necessary revenue streams that are driving the Market nowadays. The need for multifunctional spaces in the Stadia (such as multifunction lounges at relevant positions of the Stadium bowl with good pitch views), and the need for distinctive ticketing options for seating, (ranging from General Admission to VIP and VVIP seating) are a challenge against the best performance of a bowl in terms of spectator comfort and acoustic performance. And as mentioned in a previous question, the challenge to bring this acoustic performance to other types of Stadia, different from Football specific.

Q.: Do your projects always live up to their expectations?

A.: We take a holistic approach on all our projects, to tackle all the key issues that could worry our Client and the stakeholders. While this holistic approach achieves a great level of performance in all aspects of design, as they are all assessed and solved with our in-house specialists, it always comes with a balance: the best performance sometimes is not possible with the allowed budget, or the time constraints won't allow for the best detailed definition of some elements. But we believe the key for a great performance of the design is a Holistic approach, so Functionality reigns over the design disciplines, and keep the right balance among them, so all expectations are met.

Q.: Fibreglass membrane ceilings have been a constant in football stadium design in these past few years and are being put to use in different climate contexts. From cold countries like Poland and the Ukraine, to hot countries like Turkey and Spain. Does it mean this is a successful approach to stadium insulation? Is it merely an aesthetical approach or is it the future?

A.: These type of roofing solutions perform in a balanced way in many aspects of the design: aesthetics, endurance, resilience, lightweight, weather protection, sun protection, and also sound reflection. This doesn't actually mean that it is the most convenient insulation solution for all weather conditions, but you have to consider that football is an outdoor game, and the spectators are assuming the weather conditions coming with the game. This is why winter tournaments are non-existent in northern countries, nor it is assumed to have summer tournaments in hot climates (like Qatar 2022 case). But the insulation performance of the roofing solution is not that relevant in this case, while keeping the best balance of the different features is.

Q.: How does the production phase work? (Scheduling, contacts, experts involved, priorities,...)

A.: Our approach to production work is as follows: We assign a Project Manager to be the interface between the Client and Stakeholders and the Design Team, and being in charge of the allocation of the production Team. This means that if we are lacking any of the disciplines required by the Client, or we need to assess any issue with more specialized professionals, the Project Manager has the responsibility to look for an outsource support. The Project Manager will put together the Lead Architect, and Lead Engineers for each discipline.
First step is to get the Concept of the Design performed by the Architect and his/her team, assessing the main principles of the design with their previous experience. They will verify the concepts with the Lead engineers, and complete the Concept Design.
Next step is to develop the Schematic Design which will imply the input of all disciplines to complete the basic elements of a coordinated approach, following the conceptual agreement with the Client.
The following disciplines are the ones typically involved: Architecture/Mechanical Engineering, Electrical Engineering, Civil & Structural Engineering, Environmental Engineering, Geotechnical Engineering, Cost Engineering, Health & Safety Coordination in Design and Construction/Fire, Protection Engineering, Traffic Engineering, Acoustics Engineering, Telecommunications & Audio-visual/Specialist Equipment.

Once the Schematic Design is completed and approved by the Client, the design development continues to Detailed Design, which includes detailed definition, detailed specifications and bills of quantities, to allow the Client to Tender the Construction. At that stage, through workshops with key stakeholders and methodical analysis, we are capable of assimilating the diverse aspirations and the key design requirements. Our professionals develop the design through workshops, clear communication and progressive sign-off (self-assurance) to deliver the complete Detailed Design. Our role as Designers is usually continued onto the Supervision of the Works, to ensure adherence to the principles of all designed features and their execution within quality parameters. Specifically in Spain, we usually undertake the statutory roles of Architect's Works Director (Architect's Site Supervision) and Technical Architect's Works Execution Director (Technical Architect's Site Supervision), which according to Spanish codes assume responsibility for the correct execution of the works as designed and defined in terms of cost and quality. Such responsibilities imply taking the representation of the Client in front of Contractors, Subcontractors, Suppliers, and Authorities at all levels of the Public Administration.

Q.: Do the architects/designers involved think about the acoustical capabilities of the stadium since day one?

A.: As mentioned before, this is correct in our own approach, as we believe it is a key aspect. But we can see quite often in the Market that our Architect Colleagues and Competitors sometimes are more driven by aesthetics, by added revenue spaces, by fashionable constructive solutions, iconic images, etc. And they many times leave behind the functionality performance, which in Football stadia should be implying acoustics from day one, looking for the best football atmosphere based on acoustic pressure and reflection.

Q.: Typically, what's the financial investment dedicated towards these edifications? Does it tend to be enough? Is it normal to go a bit overboard and include unforeseen expenses?

A.: Stadia investments are huge economic efforts, but even managing large sums, quite often they get bigger than expected, basically by adding program requirements and subject to construction market capabilities. But the range of investment is very wide, as it depends on the program added to the Stadium functions.

For as little as 2,200 euros per seat a medium size stadium of 40,000 seats can be affordable, but we have seen investments in the early 2000s to go as high as 4,500 euros per seat. In any case, all these investments depend very much on the program, and always consider unforeseen expenses (contingencies).

Q.: Do you only think about the acoustical performance of the space for football matches? Do you consider eventual music concerts and other sorts of events?

A.: In our experience, the same features that allow for a good acoustic performance for football, as explained in the previous responses, give a very good performance in concerts and music events as well. In every football stadia design, a configuration for concerts must be considered. The usual layout goes for End Stage and Central stage, and our design approach usually include a sound performance computer simulation for the 3 situations: Football match, End Stage and Central Stage. You have to consider that the concert configurations depend on the scenic layouts, the speaker cluster configuration and their power. The reflections which work well for natural acoustics in football are usually working well for concerts, allowing for corrections and adjustments provided by the Speakers systems.

Q.: What's your opinion on the final acoustical results of the new *San Mamés* stadium? Do you feel it was a success case? Is there anything you would change now?

A.: With regards to *San Mamés* acoustic performance, we believed that the design features as commented will do the trick but could count with a sure result by only trusting the computer simulations. The performance at the previous Stadium was outstanding, and recognised all over Spain, and gave the stadium its nickname *La Catedral* (The Cathedral). We took measurements of real acoustic performance at the previous stadium and targeted those measurements with the simulations. And then measured again the real new stadium performance. We get an average of 110 dB, and comparing with any other stadium (for example, Berlin's *Olimpiastadion*), their average is on 86 dB. So it is clearly a success case, and we increased by 10 dB the Cathedral's performance.

Olly Creedy, Vanguardia

Q.: What can you tell me about the latest acoustical trends in football stadiums in these past few years? (evolution, considered materials, concepts,...)

A.: The latest trends are steering towards more multi use venues rather than just football. This requires the venue to provide good acoustics for a number of different events; sports, motorsport, concerts etc. Stadiums are also tending to provide more production content and higher quality, full-range sound systems are expected.

Q.: What are your main concerns during construction, sound-wise? (sound absorption/reflection, sound pressure,...)

A.: We must ensure the stadium envelope provides sufficient attenuation for external noise breakout and that that the appropriate absorption is provided in the stadium. This requires us to provide a careful balance between sound absorption for intelligibility and minimising absorption for maximising the atmosphere.

Q.: What do you think will be the next "big thing" in stadium acoustics and, hence, design?

A.: Variable acoustic systems?

Q.: Exciting news have been surfacing about the use of acoustic meta-materials. Are these being already put to practice? What are your thoughts?

A:: Not aware of any wide spread use of these.

Q.: There is very little literature related to sound acoustics in football stadiums. What are your thoughts? Should there be an effort to better grasp an understanding of these components?

A:: We have carried significant research on stadium acoustics (atmosphere, intelligibility, materials architecture).

Q.: What were your bigger challenges to date in stadium design?

A.: Providing the optimum performance for atmosphere but maintaining intelligibility of the sound system.

Q.: Do your projects always live up to their expectations?

A.: Mostly!

Q.: Fibreglass membrane ceilings have been a constant in football stadium design in these past few years and are being put to use in different climate contexts. From cold countries like Poland and the Ukraine, to hot countries like Turkey and Spain. Does it mean this is a successful approach to stadium insulation? Is it merely an aesthetical approach or is it the future?

A.: Not sure what you mean by this. Glass fibre insulation is often used for acoustic absorption within roof builds. Thermal requirements depends on if the stadium is open or closed.

Q.: How does the production phase work? (Scheduling, contacts, experts involved, priorities,...)

A.: Refer to RIBA stage of work.

Q.: Do the architects/designers involved think about the acoustical capabilities of the stadium since day one?

A.: Yes, important that this is discussed during the feasibility and concept stages.

Q.: Typically, what's the financial investment dedicated towards these edifications? Does it tend to be enough? Is it normal to go a bit overboard and include unforseen expenses?

A.: We must work within the project budgets.

Q.: Do you only think about the acoustical performance of the space for football matches? Do you consider eventual music concerts and other sorts of events?

A.: Yes, refer to answer 1.