ACOUSTIC DESIGN OF A STADIUM BOWL: LIMITATIONS AND OPPORTUNITIES OF ROOM ACOUSTICS SIMULATIONS

A Rovigatti Experience Studios, London, United Kingdom
E Dirim Experience Studios, London, United Kingdom
T Hulland Experience Studios, London, United Kingdom

1 INTRODUCTION

Modern sports stadia are designed to enhance crowd atmosphere through hard, reflective surfaces that redirect sound energy across spectator areas and the field of play[1]. At the same time, however, the stadium bowl's sound system must provide high speech intelligibility across the audience for life safety purposes[2, 3]. Consequently, achieving the right balance between reflective and absorbent surfaces is crucial to optimise the sporting atmosphere while maintaining speech intelligibility.
Modern sports stadia typically feature an enclosed bowl-shaped construction surrounding the pitch. The geometry of the stands, façade and roof varies significantly depending on the architectural design and spectator areas[4]. The optimization of roof and bowl geometry and materiality, in conjunction with the sound system design, plays a key role in retaining crowd-generated acoustic energy while mitigating strong reflections that could degrade the intelligibility of the stadium sound system[1,5,6].
The importance of integrating 3D room acoustics modelling in early design stages has been widely acknowledged in recent years[2,3,4,6,7,8]. Such modelling has a crucial role in the optimisation of stadium acoustics by allowing critical acoustic challenges to be addressed, including reverberation control, echo, and strategic placement of sound-absorptive materials[7]. Incorporating room acoustics modelling tools into the design process enables engineers to design the bowl sound system efficiently while retaining enough sound energy in the bowl to create a sporting atmosphere.
While the application of Geometrical Acoustics (GA) modelling tools (such as ODEON, EASE and Treble) is well documented and studied for concert halls, worship spaces, classrooms and offices[9,10,11], there exists a gap in the literature for their use in large semi-open volumes and highly reverberant scenarios, such as stadia. This study examines the tools and modelling methodology used for sports stadium design via case studies of new stadia. Three specialist acoustic modelling software have been compared to model the stadium acoustics. Limitations, challenges and opportunities of modelling large semi-open volume spaces are discussed and the need for further work is outlined.

2 ACOUSTIC METRICS

When designing stadia, key considerations for room acoustics include reverberation control, speech intelligibility and the sound pressure level coverage from the stadium sound system. While no stadium acoustics assessment should ever be limited to only these three metrics, they provide a useful window to understand the high-level acoustic properties of a stadium and a platform in which to compare designs. For stadia that also host live music, additional metrics typically associated with concert halls (clarity, EDT, G, Bass ratio, etc.) would also provide a useful point of comparison. This initial study will only investigate the predicted reverberation time in stadia.
The reverberation time of a stadium bowl is linked to both the intelligibility of the sound system and the perceived sporting atmosphere, making it a good starting point for acoustic investigations. A long reverberation time may make it difficult for a given sound system design to meet the intelligibility criteria, requiring a more onerous sound system design. However, a long reverberation time is an indication that sound energy is retained in the stadium bowl, which is typically desirable in a sports stadium where high levels of crowd noise (singing, chanting and cheering) are seen as a positive contribution to the stadium's atmosphere. Reverberation Time (RT) averaged in the mid frequency range (500 Hz - 2,000 Hz) in unoccupied stadium bowls can range from 2 to 7 seconds, depending

on the stadium's size and intended use. It is recognised that in venues where RT values exceed 2.5 to 3 seconds, a specialist sound system design is required to maintain speech intelligibility throughout the venue[12]. Following this research, further work is planned to carry out comparative studies that investigate the predicted Speech Transmission Index (STI) and sound pressure level (SPL) of sound systems designed for stadia.

The acoustic design of a new sports stadium begins with an analysis of the bowl room acoustics and a prediction of its reverberation characteristics, aiming to satisfy emergency communication requirements without compromising the immersive sporting atmosphere. This process typically involves applying standard room acoustics prediction methodologies — using omnidirectional sound sources — followed by detailed electroacoustic modelling of loudspeaker line arrays. The objective is to evaluate the effectiveness of the proposed sound system in meeting the speech intelligibility and sound pressure level design criteria, as well as its interaction with the venue's architectural acoustics. This initial study will focus on the reverberation time and will not consider the design of a stadium's sound system.

3 METHOD

The primary objective of this study is a comparative analysis of predicted reverberation times in stadia using three modelling tools. This begins the investigation of how each tool can effectively be used to support the design of both the architectural acoustics of stadium bowls and their highly specialist sound systems.

Two new stadia have been selected as case studies for this comparison. Due to client confidentiality agreements, the names and locations of the two future stadia cannot be disclosed; however, these details are not essential to the scope of this analysis. The venues differ significantly in terms of bowl geometry, internal volume, spectator capacity, and material characteristics (see Table 1). Simplified three-dimensional acoustic models of the stadia were developed in SketchUp Pro 2022, in accordance with state-of-the-art acoustic modelling tecnhiques[13].

Table 1 – Description of the stadium case studies

Stadium ID	Seat capacity	Volume in m^3	Acoustic feature	Typical use
1	63,000	1,122,539	Sound absorption mainly on bowl soffit	Football
2	46,000	1,588,703	Even distribution of sound absorption to bowl walls and soffit	Football, Concert

Three acoustic simulation software with different algorithms have been considered in this study. Two of them are based on Geometrical Acoustics (GA) approaches: EASE – AFMG's electro and room acoustic simulator, and ODEON Auditorium – a proprietary room acoustics software. Treble*,* the third software used, is a hybrid room acoustic simulation tool developed by Treble Technologies that combines wave-based (WB) algorithms at low frequencies and GA methodologies at high frequencies.

3.1 Geometrical acoustics software

GA modelling techniques simulate sound propagation by representing sound waves as rays or particles within a given space. These techniques are also referred to as energy-based models, where sound emitted from a source is represented by rays traced through the room; each time a ray encounters a surface, it loses energy according to the surface's acoustic characteristics, such as sound absorption coefficients.

In this study, two GA modelling software tools were employed: EASE v5.74.1.1 and ODEON Auditorium v17.04. EASE applies a pure ray-tracing technique across all reflection orders, whereas ODEON integrates an image source method and ray-tracing for early reflections, and utilises a ray-radiosity method for late reflections, resulting in shorter computation times compared to EASE.

ODEON's algorithms are further optimised to estimate diffraction paths around surfaces by adjusting scattering parameters based on the angle of incidence and the size of the reflective surfaces. They also allow for angle-dependent absorption modelling derived from random incidence absorption coefficients.
On the other hand, EASE's algorithms are highly specialised for simulating loudspeaker line arrays, accounting for elements such as phase, polarity, and delay. The software also supports manufacturer-specific data formats, allowing detailed loudspeaker specifications for accurate system design.

3.2 Hybrid wave-based and geometrical acoustics software

WB acoustic modelling techniques are considered a comprehensive solution to the limitations of GA methods, particularly with respect to low frequency accuracy and the precise modelling of diffraction phenomena. WB models numerically solve the wave equation to simulate wave behaviours such as reflection and diffraction.
In this study, Treble v2.3, which offers the flexibility to operate using either WB and GA methods or as a pure GA simulator, was tested to assess the feasibility of applying WB algorithms to large-scale environments such as sports stadia.
Treble's WB solver is based on the Discontinuous Galerkin (DG) method and, to overcome the computational cost of WB methods, its GA solver is used for the high frequencies of the acoustic response. This GA method is similar to ODEON's, using a combination of image source methods for the early reflections and ray-radiosity for the late reflections.
Treble was initially used in pure GA mode due to the high computational cost of the wave-based solver. Subsequently, reverberation time predictions generated through Treble's hybrid WB–GA approach have been introduced.

3.3 Acoustic modelling

The 3D simplified models of the two stadia were imported into each software and frequency dependent values of absorption coefficients were assigned to each surface according to its material. The absorption coefficients (see Table 2) were taken from standard material libraries in scientific literature[9,10,14], manufacturers' data and designers experiences.
While in EASE and ODEON the boundary conditions are determined by energy-based input data, such as the sound absorption coefficients; Treble requires pressure-based input quantities such as the acoustic impedance of the surface. In most cases, acoustic impedance data is not available and, therefore, WB software typically convert the sound absorption coefficients to pressure-base quantities using surface impedance models to match the input absorption coefficients[13]. When imputing absorption data as coefficients in Treble this introduces a level of uncertainty, as there are infinite surface impedance values that correspond to a certain value of absorption coefficients[15].
To input material data into Treble, the absorption coefficients used in EASE and ODEON for specific materials were inputted as targets. Treble's conversion engine was then used to convert this data to impedance values and then back to absorption coefficients for comparison with the original targets. Where these predicted sound absorption coefficients varied significantly from the target values, the conversion engine was re-run until the closest fit possible was achieved.

Table 2 – Sound absorption coefficients used for the modelling comparison

Material	Sound absorption coefficient (α) at octave band centre frequency (Hz)							Reference
	125	250	500	1,000	2,000	4,000	8,000	
Concrete	0.01	0.01	0.01	0.02	0.02	0.02	0.02	Cox and D'antonio, 2008
Standard double glazing	0.01	0.04	0.04	0.01	0.01	0.01	0.01	ODEON's material library
Standard stadium seat (plastic, unoccupied)	0.07	0.14	0.14	0.14	0.14	0.14	0.14	Vorländer, 2007 + designers' experience
VIP stadium seat (leather upholstered, unoccupied)	0.07	0.27	0.40	0.60	0.67	0.67	0.67	Beranek, 1972
Pitch - grass	0.11	0.26	0.60	0.69	0.92	0.90	0.60	Beranek, 1972
LED screen	0.08	0.11	0.05	0.03	0.02	0.02	0.02	M.D. Egan, 1988
Metal deck roof - Steel	0.06	0.06	0.09	0.10	0.10	0.07	0.04	M.D. Egan, 1988
Vomitories – 70% open area	0.70	0.70	0.70	0.70	0.70	0.70	0.70	ODEON's material library
Roof Oculus – 100% open area	1.00	1.00	1.00	1.00	1.00	1.00	1.00	ODEON's material library
Wall & Roof Panels – Low frequency absorption	0.87	0.55	0.32	0.24	0.14	0.05	0.04	Manufacturer's datasheet + ODEON's material calculator
Wall & Roof Panels – broadband absorption type 1	0.97	0.99	0.99	0.99	0.99	0.97	0.95	Manufacturer's datasheet + ODEON's material calculator
Wall & Roof Panels – broadband absorption type 2	0.97	0.99	0.99	0.99	0.99	0.99	0.99	Manufacturer's datasheet
Roof Panels – Acoustic Class A	0.50	0.70	0.90	0.90	0.90	0.80	0.80	ISO 11654:1997

Scattering coefficients have been assigned to surfaces to consider the non-specular reflections given by each surface and to compensate for the simplification of the geometry. The way the scattering properties have been defined are based on each software's guideline[16,17,18]. Table 3 shows the different scattering coefficients used for each material and software.

Single scattering coefficients have been assigned to each surface in ODEON and Treble. These values correspond to the scattering value at 707Hz, and from this single value a scattering coefficient for each octave band has been extrapolated. In Treble, the single values have been determined following the procedures outlined in the Treble documentation and advised to the authors by the developers. Consequently, the material scattering in Treble is generally higher than in ODEON and EASE with no surfaces having a scattering coefficient lower than 0.3. For EASE, scattering coefficients for each octave band have been assigned directly following the software recommended settings.

Table 3 – Input scattering coefficients assigned to the surfaces in each software

Surface	Scattering coefficient, *s*								
	Treble	ODEON	EASE						
			125	250	500	1,000	2,000	4,000	8,000
Concrete	0.30	0.02	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Glazing	0.30	0.02	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Standard Stadium Seat (plastic, unoccupied)	0.65	0.65	0.3	0.3	0.3	0.3	0.3	0.3	0.3
VIP Stadium Seat (leather upholstered, unoccupied)	0.65	0.65	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Grass pitch	0.30	0.02	0.1	0.1	0.1	0.1	0.1	0.1	0.1
LED screens	0.30	0.10	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Metal deck roof system	0.30	0.40	0.1	0.1	0.2	0.7	0.7	0.7	0.7
Vomitories	0.30	0.10	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Roof Oculus	0.30	0.02	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wall & Roof Panels – Low frequency absorption	0.30	0.10	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Wall & Roof Panels – Broadband absorption type 1	0.30	0.10	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Wall & Roof Panels – Broadband absorption type 2	0.30	0.10	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Roof Panels – Acoustic Class A	0.30	0.40	0.1	0.1	0.2	0.7	0.7	0.7	0.7

3.4 Modelling scenarios

The methodology employed in this study for the prediction of the RT in each of the case studies is based on a series of modelling scenarios. In each scenario, an omnidirectional source was placed at a height of 18 meters in the centre of the pitch. The T_{30} was then predicted at set receiver locations distributed across half of the stadium bowl. Sound absorption coefficients were identical across all modelling scenarios and software except for Treble where some variation was introduced during the material impedance fit. A summary of the first and last modelling scenario is provided in Table 4.

It must be noted that this modelling has been designed as a comparative study for these software tools only and does not constitute a complete methodology to be used for actual stadium design.

A brief outline of each changeable parameter and its implementation in each software is given below:

- **Number of receivers:** Naturally room acoustic metrics vary at different receiver locations. For a large space with many receiver locations (such as a stadium bowl) it is important to ensure that enough receivers are modelled to build a representative picture of the bowl acoustics. While ideally every seat in a stadium bowl could be modelled, the increased calculation time in large stadia can make this prohibitive. Additionally, it is useful to model receiver locations that will provide points of comparison during commissioning measurements. In each scenario, receivers have been distributed across half of the audience area in the symmetrical stadium bowl at a height of 1.2m above local floor level.
  Initially, 15-point receivers were placed to be representative of specific audience areas (lower, mid and upper tier across the entire spectator's area). This was compared to a more 'detailed' grid response in ODEON and EASE. Given the scale of the stadia, a grid response could not be generated in Treble as the software can only accommodate up to 100 receiver points. Grids were defined with a minimum of 2m x 2m spacing resulting in up to 2972 individual receivers per stadium.
- **Scattering:** The study has determined scattering coefficients by following the guidelines for each software and as advised by the software developers.
- **Transition order**: ODEON and Treble implement two different geometrical solvers (image source and ray radiosity). Both tools allow the user to determine after how many reflections a ray would transition from an image source to a ray radiosity calculation methodology. In ODEON the recommended transition order for most spaces is 2. While in Treble the default transition order is 3. Both developers stipulate that altering this transition order should rarely influence the results of the room acoustic parameters. In EASE, the transition order – referred to as the reflection order – is fixed and automatically determined within the AURA mapping function. To understand the

influence of the transition order parameter, ODEON settings have been investigated, while Treble's transition order settings were set based on developers' instructions.

- **Number of rays:** ODEON, EASE and Treble all allow the user to change the number of rays used in the later part of the calculation. In all three software, these can be defined by default presets or entered manually. In spaces with long reverberation times, the number of rays used in the late part of the calculation may greatly influence the results. To investigate the influence of this, the default settings for each software were used, followed by a custom number of rays determined by applying the procedure outlined by each software (and as advised by the developers) to determine if sufficient rays have been used.
- **Impulse response (IR) length:** The impulse response length in each modelling software was selected to be long enough that the reverberation of the space was accurately captured. Sabine calculations of the space were used to obtain a rough estimate of the reverberation time. This was compared to the estimated reverberation times in each software and then the impulse response length was inputted to be at least a third longer than the predicted RT.

Table 4 – First and last modelling scenarios

Stadium - Scenario ID	**Software**	**Sound source**	**Materials**	**Scattering**	**IR length, *ms***	**Receivers**	**Ray-tracing transition order**	**Late rays (ODEON & Treble) Total rays (EASE)**
1 – A	ODEON	1 x Omni at 18m	As per Table 2	As per Table *3*	12000	15 across ½ seating area	3	9,954
	EASE	1 x Omni at 18m	As per Table 2	As per Table *3*	12000	15 across ½ seating area	3	15,120,000
	TREBLE	1 x Omni at 18m	As per Table 2	As per Table *3*	12000	15 across ½ seating area	3	150,000
2 - A	ODEON	1 x Omni at 18m	As per Table 2	As per Table *3*	6000	15 across ½ seating area	3	6,430
	EASE	1 x Omni at 18m	As per Table 2	As per Table *3*	6000	15 across ½ seating area	3	104,651,000
	TREBLE	1 x Omni at 18m	As per Table 2	As per Table *3*	6000	15 across ½ seating area	3	150,000
1 – B	ODEON	1 x Omni at 18m	As per Table 2	As per Table *3*	12000	15 across ½ seating area	3	2, 500,000
	EASE	1 x Omni at 18m	As per Table 2	As per Table *3*	12000	15 across ½ seating area	3	1,000,000,000
	TREBLE	1 x Omni at 18m	As per Table 2	As per Table *3*	12000	15 across ½ seating area	10	1,500,000
2 – B	ODEON	1 x Omni at 18m	As per Table 2	As per Table *3*	6000	15 across ½ seating area	3	15,500,000
	EASE	1 x Omni at 18m	As per Table 2	As per Table *3*	6000	15 across ½ seating area	3	1,000,000,000
	TREBLE	1 x Omni at 18m	As per Table 2	As per Table *3*	6000	15 across ½ seating area	10	1,500,000

4 DISCUSSION

This section outlines the initial findings by comparing the T_{30} predicted in each software averaged across all receiver locations. The comparisons have assessed differences in relation to the 5% subjective difference limen threshold (Just Noticeable Difference, JND)[19]. A macro-level analysis was also conducted to identify any consistent patterns in prediction results across the two case studies throughout the different modelling tools.

4.1 Effects of parameters setting

As discussed above, the parameters investigated for their impact on the overall prediction results include the number of receivers, the transition order between early and late reflections, and the calculation accuracy in terms of the number of rays used. These analyses focused on ODEON and EASE. In Treble these parameters were determined mostly based on feedback from the developers. Regarding the number of receivers, the maximum variation in predicted reverberation time (T_{30}) between an average of 15 discrete receiver points and a full grid of up to 2,972 receivers was 5%. As this fits within the JND range it was determined that the 15-point receivers provide a sufficient representation for the overall acoustic character of these two stadia for this comparative modelling exercise. It should be stressed that similarly placed receivers in different stadia may not provide the same indication. Stadium geometry, materiality, symmetry and source location will all influence the spread and variance in acoustic parameters across an audience area. When designing stadia, it must be highlighted again that the proposed stadium sound system should be used in the modelling and the acoustic parameters across the entire audience area should be understood to enable a design that can provide a consistent acoustic experience for all attendees.

To assess the impact of different transition orders (TO), two significantly different settings were tested in ODEON and compared with EASE predictions. In Stadium 1, the impact of the increase in transition order ranged from 0.01 to 0.10 seconds, with the most pronounced differences occurring at the higher frequency bands (4 kHz and 8 kHz). For Stadium 2, increasing the transition order in ODEON from 0 to 3 resulted in a significantly closer alignment with EASE predictions. The differences between ODEON and EASE ranged from 0.07 to 0.19 seconds, depending on the frequency band, with the largest discrepancies observed at 4 kHz and 8 kHz.

Lastly the number of late rays was investigated. The default settings for each software were used followed by a custom number of rays determined by applying the procedure advised by the developers of each software to determine if sufficient rays have been used. The changes in the predicted T_{30} with increased number of rays (High) were all well within the ± 5% range of the intermediate number of rays (Medium).

Table 5 - Predicted T_{30} comparison between ODEON and EASE with different calculation settings. Results are presented as averaged values for LF (Low frequencies average between 125Hz and 250Hz), MF (Mid frequency average between 500Hz, 1,000Hz and 2,000Hz) and HF (High frequency average between 4,000Hz and 8,000Hz).

Parameters	**Stadium ID**	**Metrics**	**Comparison of predicted T_{30} (seconds) with different calculation settings**					
			ODEON			**EASE**		
			LF	**MF**	**HF**	**LF**	**MF**	**HF**
Number of Receivers	1	$T_{30,15\ rec.}$	7.74	5.44	2.21	8.88	5.72	2.57
		$T_{30,15\ rec.}$ JND (5%)	±0.39	±0.27	±0.11	±0.44	±0.29	±0.13
		*$T_{30,15\ recs}$ - $T_{30,grid}$	0.00	0.00	-0.10	0.01	-0.01	0.02
	2	$T_{30,15\ rec.}$	3.19	3.37	1.95	3.50	3.52	2.17
		$T_{30,15\ rec.}$ JND (5%)	±0.16	±0.17	±0.10	±0.18	±0.18	±0.11
		*$T_{30,15\ recs}$ - $T_{30,grid}$	-0.03	0.05	0.00	0.00	-0.03	0.00
Transition Order	1	$T_{30,TO=3}$	7.74	5.40	2.30	8.87	5.73	2.56
		$T_{30,TO=3}$ JND (5%)	±0.39	±0.27	±0.11	±0.44	±0.29	±0.13
		**$T_{30,TO=3}$ - $T_{30,TO=0}$	0.01	0.02	0.10	N/A	N/A	N/A
	2	$T_{30,TO=3}$	3.22	3.32	1.95	3.51	3.55	2.17
		$T_{30,TO=3}$ JND (5%)	±0.16	±0.17	±0.10	±0.18	±0.18	±0.11
		**$T_{30,TO=3}$ - $T_{30,TO=0}$	0.09	0.11	**0.19**	N/A	N/A	N/A
Number of late rays	1	$T_{30,Medium}$	7.74	5.38	2.20	8.87	5.72	2.56
		$T_{30,Medium}$ JND (5%)	±0.39	±0.27	±0.11	±0.44	±0.29	±0.13
		***$T_{30,Medium}$ - $T_{30,High}$	-0.01	-0.02	-0.03	0.00	0.01	0.00
	2	$T_{30,Medium}$	3.22	3.32	1.95	3.51	3.55	2.17
		$T_{30,Medium}$ JND (5%)	±0.16	±0.17	±0.10	±0.18	±0.18	±0.11
		***$T_{30,Medium}$ - $T_{30,High}$	0.09	-0.09	-0.01	0.02	0.01	0.00

*Difference between predicted averaged T_{30} across15 receiver points and predicted averaged T_{30} across receivers' grid

**Difference between predicted averaged T_{30} with ODEON's TO=3 and predicted averaged T_{30} with ODEON's TO=0

*** Difference between predicted averaged T_{30} with medium number of late rays and predicted averaged T_{30} with very high number of late rays

4.2 GA modelling comparison

Given that variations in parameter settings had minimal impact on the predicted reverberation times, Scenario A (see Table 4) was analysed to determine whether consistent patterns in reverberation time predictions could be observed across the two case studies.
Stadium 1 represents a conventional football stadium, where sound absorption treatment is primarily applied to the bowl's soffit surfaces. The geometry includes a large opening at the roof oculus, while the remaining surfaces are predominantly reflective. This configuration results in a highly reverberant environment, with significant absorption concentrated on the roof and minimal absorption elsewhere.
In contrast, Stadium 2 was designed to achieve more controlled reverberation, enabling the venue to function effectively as an indoor arena for concerts. In this case, sound absorption treatment is more evenly distributed across the walls, seating areas, and soffit.
An overall comparison of the reverberation time predictions from the different GA tools, particularly between ODEON and EASE, suggests that similar spectral trends can be observed. In general, EASE tends to predict higher reverberation times than ODEON. At lower frequencies, the differences become more pronounced, with the largest difference occurring at 125 Hz and being up to 1.5 seconds.

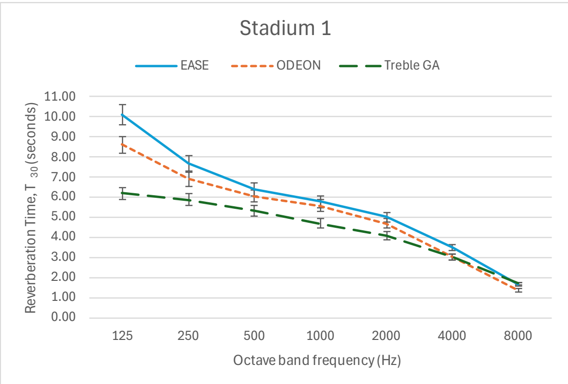

Figure 1 - T_{30} comparison for Stadium 1 with GA solvers only

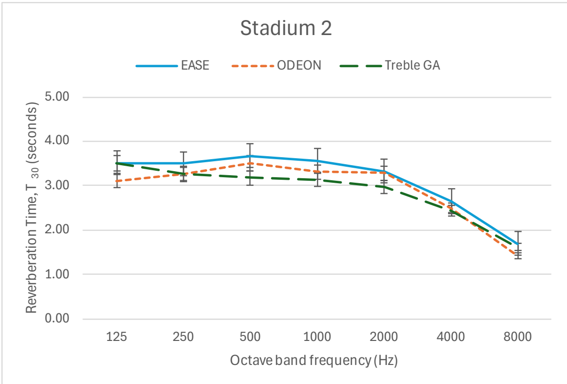

Figure 2 - T_{30} comparison for Stadium 2 with GA solvers only

In general, the reverberation time predicted with Treble (GA) was shorter than that of ODEON and EASE. This difference became more pronounced at low frequencies and when the reverberation time overall was longer (Stadium 1, T_{30} at 125Hz difference up to 3.91 seconds). The predicted reverberation time spectrum shapes were generally similar to ODEON and EASE for both case studies. In less reverberant spaces, Treble's (GA) predictions are closer to those of the other tools, although they generally remain outside the JND ranges at mid frequencies (Stadium 2, T_{30} at 500Hz difference up to 0.49 seconds) and align more closely with EASE at the spectral extremes. In highly reverberant environments, such as in Stadium 1, Treble's (GA) predictions diverge significantly from those of the other tools. The larger discrepancies between Treble's predictions and those of the other software in highly reverberant environments can likely be attributed to differences in absorption coefficients. In Treble, most materials were defined as custom elements, with absorption coefficients determined analytically. The absorption coefficients varied following the fitting process to impedance data. While this only represented a maximum divergence from the desired absorption coefficients of up to 0.06, at worst it represents an absorption coefficient that is nearly three times higher than what is desired.
In such large spaces, even small variations in absorption properties can lead to significant differences in predicted reverberation times.
A final iteration of the Stadium 1 model was conducted under occupied conditions to assess whether Treble's predicted levels would align more closely with those from the other software. Under less reverberant conditions, Treble's reverberation time predictions showed improved agreement with ODEON's results, falling within the ODEON T_{30} JND range between 500 Hz and 8 kHz.

Finally, calculation times between the software varied with EASE generally taking the longest followed by ODEON and Treble taking the shortest. The number rays used in the calculations greatly affected their run times. For the GA solvers, EASE took up to 6-7 hours to complete, ODEON took 20 minutes to complete, and Treble took 4 minutes (see Table 6).

4.3 WB modelling

Finally, Treble's wave-based solver was used to predict the reverberation time in the 63Hz and 125Hz octave bands. Results that combine WB modelling (at 63 and 125Hz) and GA (250Hz to 8kHz) are presented in Figure 3 and Figure 4.

For Stadium 1, where the overall reverberation time was longer and the absorption distributed mostly on the soffit of the bowl, the predicted reverberation time in these octave bands were extremely close to what was predicted in ODEON (0.06 seconds difference at 63Hz and 0.07 seconds difference at 125Hz).

For Stadium 2 the predicted T_{30} at 125Hz from Treble WB solver and ODEON were also extremely closed (0.05 seconds difference), while at 63Hz T_{30} predictions were significant different (up to 0.8 seconds).

EASE cannot provide estimates in the 63Hz octave band and in general the predicted reverberation time at 125Hz is significantly higher than both ODEON and Treble.

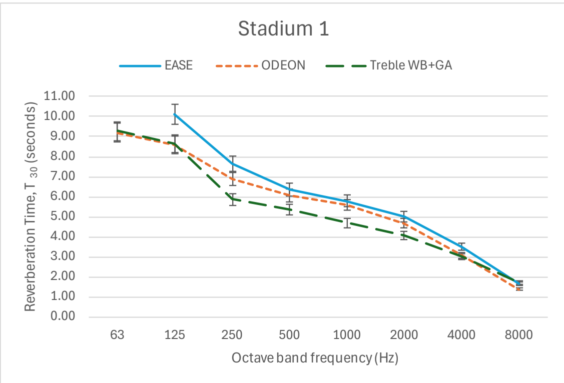

Figure 3 - T_{30} comparison for Stadium 1 with GA and WB solvers

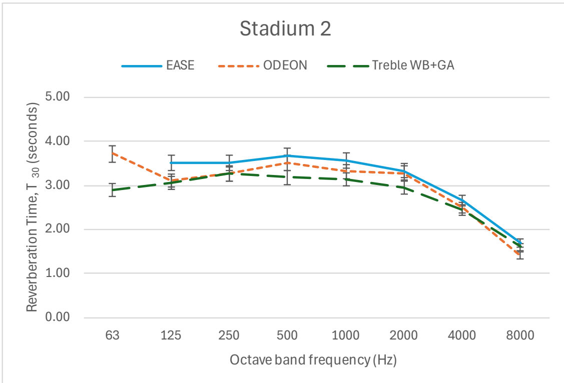

Figure 4 - T_{30} comparison for Stadium 2 with GA and WB solvers

It should be noted that long computational time and significant computational resource requirements for WB solvers still represent a limitation compared to the GA solvers (see Table 6).

Table 6 - Calculation times for each software

Stadium (Scenario B)	ODEON	Ease	Treble (GA)	Treble (WB)
1	27 minutes	6-7 hours	4 minutes	10 Hours
2	6 minutes	2-3 hours	3 minutes	11 Hours

5 CONCLUSIONS AND FUTURE STEPS

For modern stadia, it is essential that the acoustic design can retain crowd noise to provide an exciting atmosphere while preserving the intelligibility of emergency announcements. These acoustic principles are often at odds with each other and provide a unique challenge in stadium design. 3D acoustic modelling programmes are useful tools in assessing stadia and allowing a balance between these two to be achieved, especially for new stadia when no existing measurement data is available. While the application of these tools is well documented for concert halls, worship spaces, classrooms etc., there exists a gap in the literature for their application in stadia. Stadia are often orders of magnitude larger than these spaces with long reverberation times and limited absorption placement. This study examines the tools and modelling methodology used for sports stadium design via case studies of two new stadia.

A comparative study of three software tools, ODEON, EASE and Treble was carried out. To compare these, a single omnidirectional source was placed at a height of 18 meters in the centre of the pitch. The predicted T_{30} in octave bands was then compared at set receiver locations in the two stadium bowls. In each software the calculation parameters were adjusted in line with the recommendations of the developer to achieve a converging result. Material absorption coefficients were identical in ODEON and EASE. However, in Treble the absorption coefficients varied following the fitting process to impedance data. While this only represented a maximum divergence from the desired absorption coefficients of 0.06, at worst it represents an absorption coefficient that is nearly three times higher than what is desired.

The predicted T_{30} across all three software tools was broadly similar. Differences between the predicted results was more noticeable in lower frequencies and longer reverberation times. Generally, the predicted T_{30} were longest in EASE and lowest in Treble with ODEON in-between.

This study offers the following recommendations for further work:

- The modelling parameters of each acoustic software have been explored. While there is no "one size fits all" approach to modelling stadia, the influence these parameters have when applied to stadium modelling is better understood. There now exists an opportunity to develop this knowledge further to create an optimised methodology for modelling stadia.
- Characterising the T_{30} of a stadium may be possible using carefully distributed and a statistically relevant number of receiver locations. This would be influenced by the stadium geometry, material distribution and source locations. Once the receiver locations are determined, this also provides an opportunity to verify the study via measurements upon commissioning.
- Each software suite provides a set of strengths and weaknesses when it comes to modelling stadia. These are now better understood and the application of each software when assessing different acoustic elements can now be developed further.
- Further work is required to ensure accurate input data is used in Treble. This research has shown that it is challenging to fit impedance values to specialist materials used in stadia. This has limited the ability to directly compare the software. Future research should explore additional options to determine the equivalent impedance data for a material with given absorption coefficients and look to use measured impedance data if possible.
- Without measured data of these stadia it is difficult to conclusively comment on the accuracy of each software and has limited this to being a comparative study only.
- This study has been limited to a single omnidirectional sound source. Future research should aim to include real world sound sources and compare the implementation and accuracy of how each software can model a stadium sound system design, in comparison with real life measurement data.

6 ACKNOWLEDGEMENTS

The authors would like to acknowledge the help and assistance provided from the developers of Treble, ODEON and EASE. Their input and expert knowledge, especially from Treble's team, has played a key role in enabling the delivery of this research. Additionally, the authors would like to acknowledge Daniela Filipe and Kevin Luckhurst for their support and technical input.

7 REFERENCES

1. O. Creedy, 'Acoustic design for sport stadia and arenas', Proc. of IOA, Vol. 41, Pt.3 (2019)
2. R. Hammond, P. Mapp and A.J. Hill, 'Modelling the effects of spectator distribution and capacity on speech intelligibility in a typical soccer stadium', J.Acoust.Soc.Am. 145(3) (March 2019)
3. A. Peretokin, A. Livshits, A. Orlov, N. Shirgina, 'Acoustic features of sports facilities on the example of FIFA 2018 football stadiums in Russia', Proc. 23rd ICA, Aachen (September 2019)

4. R.Patel, A.Popplewell, City of Manchester stadium: maximising acoustic excitement for performer and spectator, Proc.of IOA, Vol.25, Pt.7 (2003)
5. H.W. Choi. N.G.Gi, H.Song, S.W. Kim, ‘Acoustical characteristics of semi-open stadiums’, Proc. 32nd Inter Noise, pp. 569-576, Seogwipo (August 2003)
6. J.L.A. Sanchez, J.R. Garcia, ‘Acoustic problems in the new Atletico de Madrid Club Stadium: a change for the worse’, Proc. 48th Inter Noise, pp.7581-7591, Madrid (June 2019)
7. I. Prasetiyo, J. Sarwono, H. Natanael, I. Tanjung, ‘Study on acoustic performance of football stadium’, Proc. 23rd ICSV, Athens (July 2016)
8. Y. Lee, Y. Tsay, ‘Acoustical and electrocaoustical process for improving a multi-purpose sports stadium, Proc. 48th Inter Noise, pp.5732-5739, Madrid (June 2019)
9. Odeon A/S, ODEON Auditorium (Version 17.04) https://odeon.dk
10. AFMG Technologies GmbH, EASE (Version 5.73) https://www.afmg.eu/en/ease
11. Treble Technologies. Treble (Version 2.3) https://www.treble.tech
12. M. Eşmebaşı, Z. B. Özyurt, Z. S. Gül, ‘Contemporary sports arena room acoustics design’, Proc. 28th ICSV, Singapore (July 2022)
13. S. Siltanen, T. Lokki, L. Savioja, C. L. Christensen, ‘Geometry reduction in room acoustics modeling’, Acta Acustica, 94(3) (2008)
14. T.J. Cox, P. D’antonio, ‘Acoustic absorbers and diffusers: theory, design and application’, Crc. Press, (2009)
15. G. Fratoni, D. D’Orazio, M. Garai, ‘Uncertainty of input data for wave-based room acoustic simulations in large non-trivial environments’, Proc. Forum Acusticum, (2023)
16. Odeon A/S, ‘ODEON Room Acoustics Software: User’s Manual’, version 17 (2021)
17. AFMG Technologies GmbH, ‘EASE 5 Third Edition: User’s Guide’, version 74 (2025)
18. Treble Technologies, ‘Treble User Guide’, https://docs.treble.tech/user-guide (2025)
19. International Organization for Standardization, ‘ISO 3382-1:2009 Acoustics. Measurement of room acoustic parameters. Part 1: Performance spaces’, Geneva, Switzerland (2009)