THE SOUND OF FLEXIBILITY

C Diaz Brito Brito Acoustics, Tenerife, Canary Islands, Spain
A Muciaccia Desmus Design, Barcelona, Cataluña, Spain
L Isorna Desmus Design, Barcelona, Cataluña, Spain

1 INTRODUCTION

This paper describes the acoustic design process followed for the Flexible Auditorium within the National Theatre building of the Oman Cultural Complex (Muscat, Oman) designed by Tabanlioglu Architects and currently under construction by SAH-SML JV Co. for the Ministry of Culture Sports and Youth of the Sultanate of Oman.

The venue is envisaged to be a versatile space that can accommodate a breadth of uses. The design has been developed to maximise adaptability, incorporating features such as retractable seating and variable acoustic systems. This paper discusses the design goals, the adoption of suitable acoustic criteria, and the definition of shapes and materials to provide operational flexibility and comfortable acoustic environments for each use. Enabling suitable conditions for the use of sound reinforcement systems is also a key consideration. The design approach derives from well-established theory and literature and utilises advanced room acoustics simulations to validate the proposed solutions, pending on-site measurements for further refinements.

2 HOW SHOULD A FLEXIBLE VENUE SOUND?

The conventional shoebox shape is highly regarded in acoustics for several reasons. The long side walls lead to strong lateral reflections, enhancing the spatial impression [(1)] [(2)]. The narrow width contributes to intimacy via the support of early reflections [(3)]. The symmetrical geometry helps to develop a uniform sound field, contributing to a smooth decay of sound energy [(4)]. Reflection paths and modal behaviour can be predicted with existing modelling tools to a relatively accurate degree. But how does this hall shape perform for contemporary needs?

At the core of any successful auditorium design lies a simple yet deceptively complex question: *how should it sound?* Understanding the design brief is a key step in defining how a space should be shaped to sound. Words like “flexibility” and “multi-purpose” are commonly used in project briefs nowadays, seeking to maximise the commercial viability of performing art spaces. These terms reflect a growing demand for halls to serve a variety of functions, from intimate musical performances to all sorts of events making use of sound reinforcement systems. Acoustics is therefore crucial to help create the right environment for each of the modes of operation.

Nonetheless, whilst acoustics plays a critical role in auditoria, it is only one of the multiple puzzle pieces that completes the bigger picture. The design of modern auditoria must balance a broad set of requirements such as accessibility, stage adaptability, lighting and AV systems integration, back-of-house logistics, etc. All these needs, including acoustics, must be reconciled through an integrated design process.

2.1 Acoustic Design Principles

The design brief required optimal conditions for chamber music performances and events making use of sound reinforcement systems, such as lectures and amplified music concerts. These uses require notably different acoustic environments.

For unamplified events, the space should sound intimate, enveloping, rich, and warm. The “natural acoustics” of the space should hence provide a good degree of reverberance to support the projection of unamplified instruments. Reflective surfaces near the performers and audience are necessary to provide early reflections that enable musicians to hear themselves and that relay sound clearly to the audience. Late reflections should complement the early ones, giving warmth and richness to sound [1] [2]. In contrast, for amplified events, the hall should sound more neutral, clear, and responsive to fast, transient sounds. This is particularly relevant at mid-frequencies, where sound reflections should be limited to improve speech intelligibility. A tight control of the room response at low frequency is also crucial to avoid the reproduced sound from being perceived as too "boomy" [5].

To address the differing acoustic requirements of each use, specific criteria have been defined based on the typically optimal values of reverberation times (RT) as a function of the room volume and type of performance. For the reflective mode, the target RT was based on the recommendations by Barron for chamber music and recital halls [1]. The recommended values for the different frequencies derive from the factors suggested by Kinsler et al [6] shown in Figure 1.

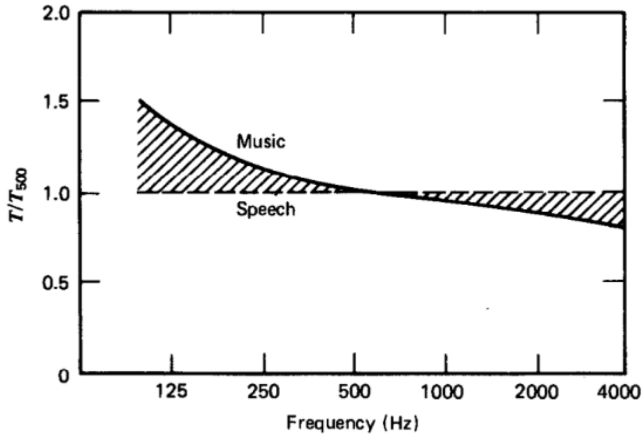

Figure 1 Relative reverberation-time limits for music and speech (Kinsler et al [6]).

On the other hand, the absorptive mode should allow an efficient use of sound reinforcement systems. Research work in the recent years has established that the reverberant sound field should be controlled to minimise the superimposition of the room response across the frequency spectrum (hence low RT values), so that sound engineers can produce a clear and balanced mix [5]. This is particularly important at low frequencies, namely at the 125 Hz octave band, which largely drives the perception of beat from percussive instruments as reproduced by the sound system. The adopted target and, more importantly, associated relative values in the frequency range are derived from the WHO Global Standard for Safe Listening Venues and Events [7], shown in Figure 2.

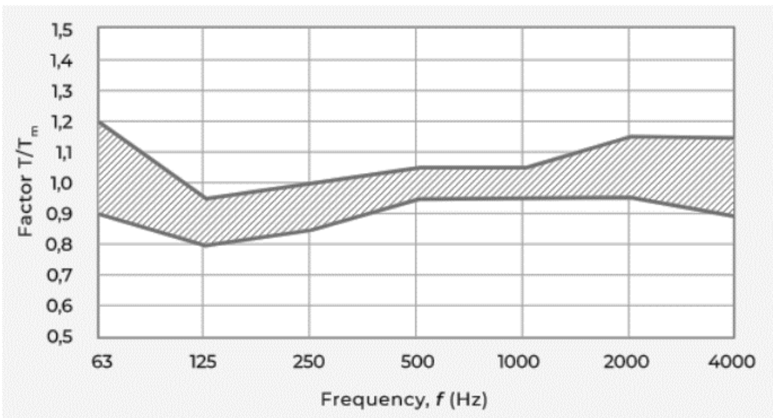

Figure 2 Recommended tolerances for reverberation time (WHO [7]).

3 HOW CAN THE VENUE ADAPT?

The Flexible Auditorium is a shoebox space with an approximate room volume of 3,000 m^3 and a maximum capacity of approximately 230 seats, including the balcony seating.

Adaptability is the core design principle that informed the geometry, materials, and systems for the hall. The retractable seating is a key element that enables the space to operate in different configurations, moving away from the traditional stage-centred layout. The flat floor configuration provides the opportunity to implement contemporary performance arrangements, such as radial audience layouts surrounding the performers, or to host diverse activities beyond the principal uses.

Additionally, a bespoke variable acoustics system was developed by passive means, rather than through active electroacoustics technology [(8)] [(9)]. The developed strategy consists of reflective wooden panels located on the side walls and stage wall, which can slide behind adjacent fixed panels via mechanical linear rails. When these sliding panels are stowed away, the sound absorptive treatment applied to the backing structure becomes exposed (see Figure 3). Both fixed and sliding panels extend up to a metal mesh ceiling at 7.8 m, above which stage engineering equipment is concealed in a false ceiling up to 10.4 m.

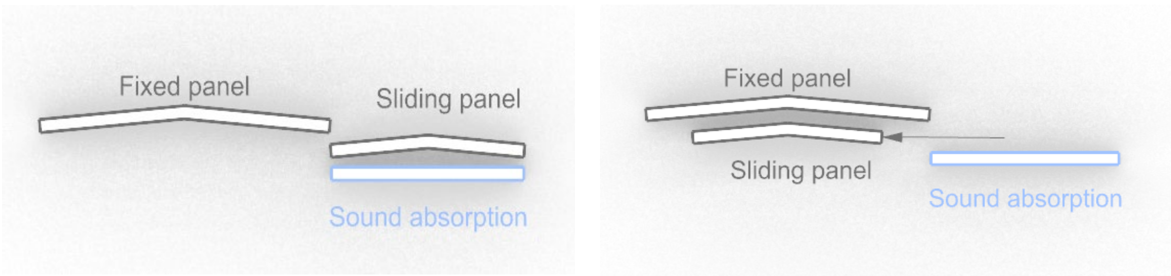

Figure 3 Bespoke variable acoustics system diagram.

3.1 Reflective mode

The reflective mode is the room configuration where the sliding panels are exposed, rendering the absorptive material behind inactive for sound reflections at mid-to-high frequencies. The acoustic environment for the reflective configuration is characterised by diffusive reflections provided by the wall panels, which contribute to an enveloping, rich sound arriving at the audience, and supportive early reflections for musicians on stage.

In this scenario, the primary sound absorption is provided by the audience seating and the acoustic treatment above the metal mesh ceiling. Nonetheless, the sound absorbing treatment behind the sliding panels is expected to provide a degree of sound absorption in the low frequency range, where the panels dimensions are negligible compared to the incident wavelengths.

3.2 Absorptive mode

When sound reflections and overall reverberance need more rigorous control, the absorptive mode is enabled by sliding the panels, thereby exposing the sound absorbing treatment. The system offers a high degree of flexibility as the panels can be operated individually, allowing all, some, or none to be retracted depending on the specific acoustic requirements of each use. The 3D acoustic models illustrating the two configurations are given in Figure 4; reflective mode on the left, absorbing mode on the right.

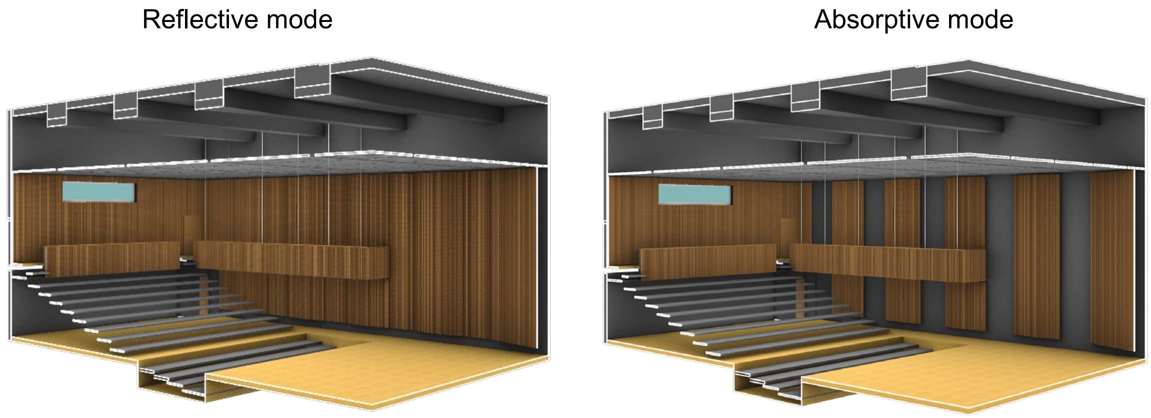

Figure 4 Acoustic models for the reflective (left) and absorptive (right) venue configurations.

Figure 5 displays the various types of acoustic treatment in the space, which include a porous lining to the underside of the suspended ceiling (highlighted in yellow) and two types of perforated panels. One of the types of perforated panel is a low-frequency sound absorber tuned to the 125-250 Hz octave bands placed along the upper walls above the metal mesh ceiling and on the rear corners of the room (highlighted in green). The other type of perforated panel is a broadband sound absorber located along the vertical stripes of walls left exposed when the sliding panels are stowed away (highlighted in magenta).

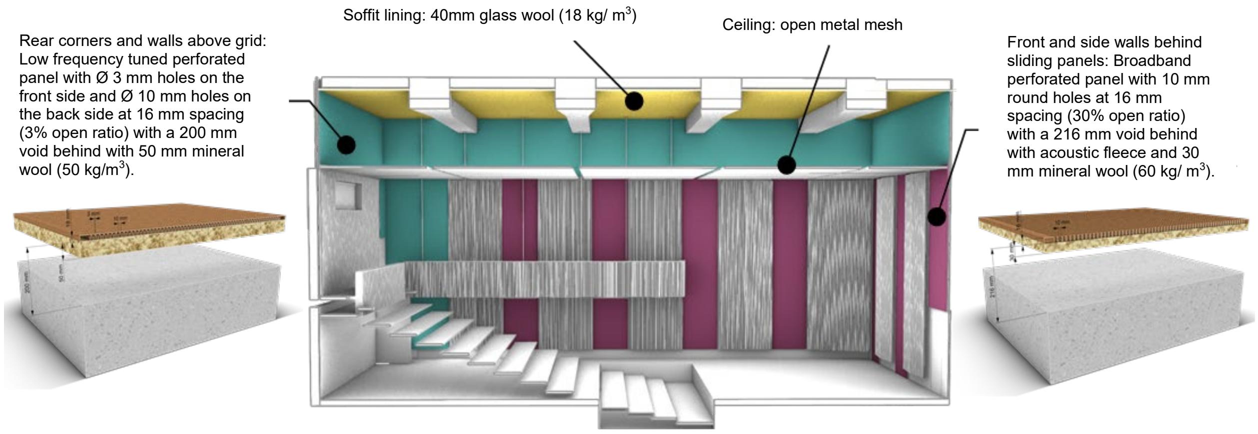

Figure 5 Acoustic treatment in the Flexible Auditorium.

4 THE ROLE OF MULTI-SCALE SHAPING

Acoustic defects such as flutter echoes, focusing, or tone colouration can become apparent due to the parallel walls and undermine the well-known benefits of the shoebox shape [(10)]. To address this, the design strategy for the auditorium focused on maximising sound diffusion through careful shaping of surfaces both at large and small scales. This approach aims to provide a uniform sound field across the frequency spectrum, with increased sound envelopment and balance across all room configurations.

4.1 Macro-shaping

A macro-shaping strategy was developed to provide diffusion at low-to-mid frequencies in line with the architectural concept for the space. The intent was to maximise the potential of the shoebox shape whilst limiting the possibility of flutter echoes and reflection focusing at specific audience positions.

To break the parallelism between walls, the panels are shaped as full-height flat surfaces folded along their centreline (i.e. like open books facing out towards the walls). Two types of panels have been developed as follows:

- Fixed 2.4 m-wide panels offset by 0.4 m from the walls.
- Movable 2.0 m-wide panels offset by 0.2 m with the walls.

Whilst the fold in the panels removes the parallelism between the walls, opposite panel faces have the potential to create repetitive reflection paths (see Figure 6). As such, variations in the panel angles were introduced.

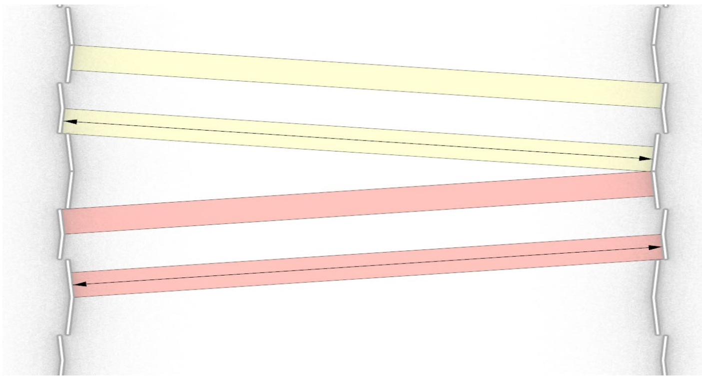

Figure 6 Possible parallelism between folded panels.

A custom Grasshopper algorithm was developed within the Rhino environment to randomise the orientation of wall panels in plan. Keeping the panels' centreline as the rotation axis (i.e. the point where the panels fold), the script provided randomised angles and iteratively adjusted them until no opposite faces were parallel to each other. Effective scattering is thus achieved across the mid-frequency range (500 - 2000 Hz), which is where the human ear is most sensitive to directional reflections [(11)] . Additionally, the layout of the panels was developed not to be "stage-centered" such that sound reflections can be controlled regardless of where the sound source is placed.

4.2 Micro-shaping

High-frequency sound waves are sensitive to small scale surface features due to their short wavelength. To address this, micro-shaping was added to the wall panels through a textured surface finish designed to scatter high-frequency energy effectively.

The preferred texture from an aesthetics perspective was the use of irregular triangular wedges with rounded edges. To avoid the possible acoustic artefacts associated with repetitive geometry, the texture was designed to incorporate surface variations in depth, width and pitch. The depths and widths range from 10 to 50 mm, as shown in Figure 7. These dimensions were selected balancing the acoustic needs with practical limitations and visual integration. Although the dimension range is smaller than the λ/4–λ/2 ideal depth for scattering frequencies above 2 kHz [(12)(13)], it remains effective for angular diffusion in the 1–4 kHz range, particularly when combined with non-periodic geometry. This resulted in a randomised and non-repetitive finish which reduces the risk of tonal reflections or whistle-like effects [(14)].

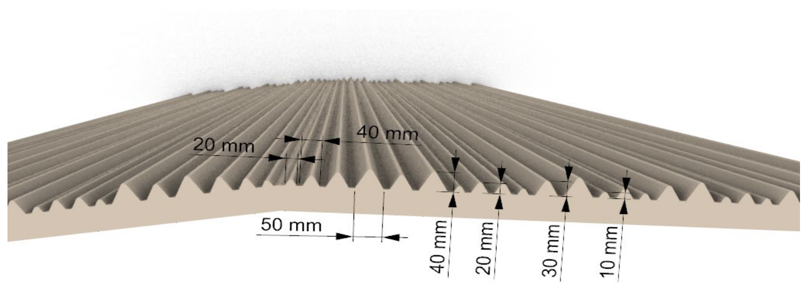

Figure 7 Wall panels texture dimensions.

A similar architectural language was used for the balcony front, which also incorporates textured, folded shapes so that reflections from the closest surfaces to the audience are adequately treated.

5 THE ROLE OF COMPUTATIONAL TOOLS

During the design process, computational tools played a key role in assessing the suitability of architectural proposals and the effectiveness of treatment proposals for both venue configurations. They also enabled the iterative implementation of changes in order to achieve the most appropriate combination of materials and acoustic systems, whilst adhering to the aesthetics and overall technical aspirations for the space.

5.1 Acoustic modelling

Acoustic simulations were carried out using Treble software (© Treble Technologies) for both scenarios. An omnidirectional sound source at the centre of the stage area and surface receivers across the audience (1 m x 1 m resolution) were used to assess the various acoustic parameters, and primarily reverberation time. A transition frequency of 355 Hz (upper frequency of the 250 Hz octave band) was used to separate the frequency domain of the wave-based solver (below the transition frequency) from that of the geometrical solver (above the transition frequency).

The RT results across the frequency range are presented in Figure 8 in terms of mean T20 ± standard deviation for both reflective and absorbing modes, against their respective targets.

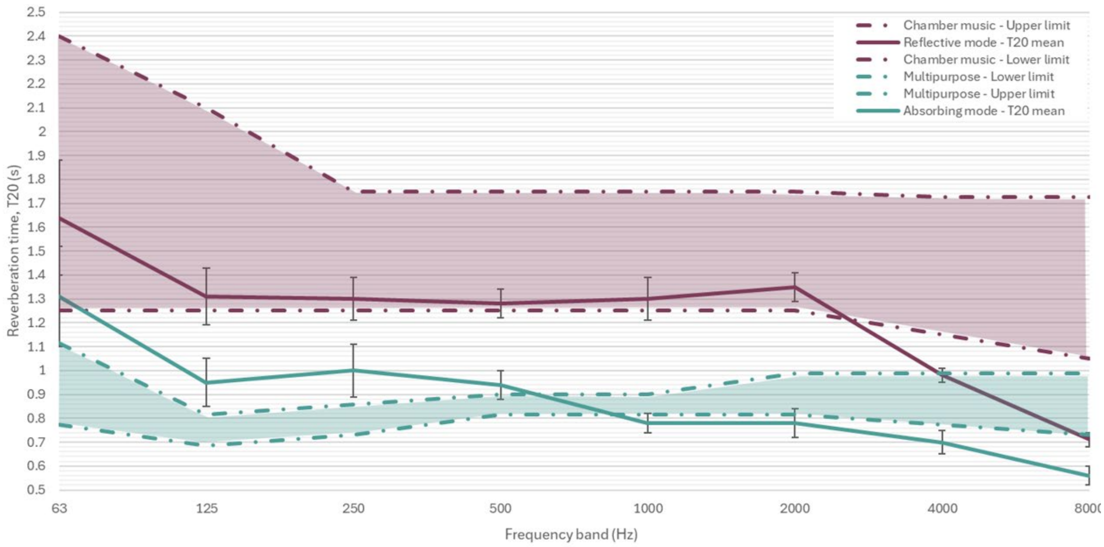

Figure 8 Acoustic modelling T20 results - reflective mode in red and absorbing mode in green.

The average reverberation time at mid-frequencies, T_{mf}, varies up to 0.5 s between reflective mode (1.3 s) and absorbing mode (0.8 s). This difference reduces to 0.3 seconds at low frequencies between 63 Hz and 250 Hz. The spatial variation is typically within 0.1 s at mid frequencies and up to 0.2 s at low frequencies.

The spatial distribution of T20 across the venue is illustrated by the surface receivers' plots (1.2 m high for the audience, 1.5 m high for the stage) for the 125 Hz, 500 Hz and 2000 Hz octave bands given in Figure 9 for the reflective mode (left) and absorbing mode (right). The surface receivers' plots indicate an even distribution of the RT across both audience and stage areas, except for some hot spots at low frequencies in the reflective mode.

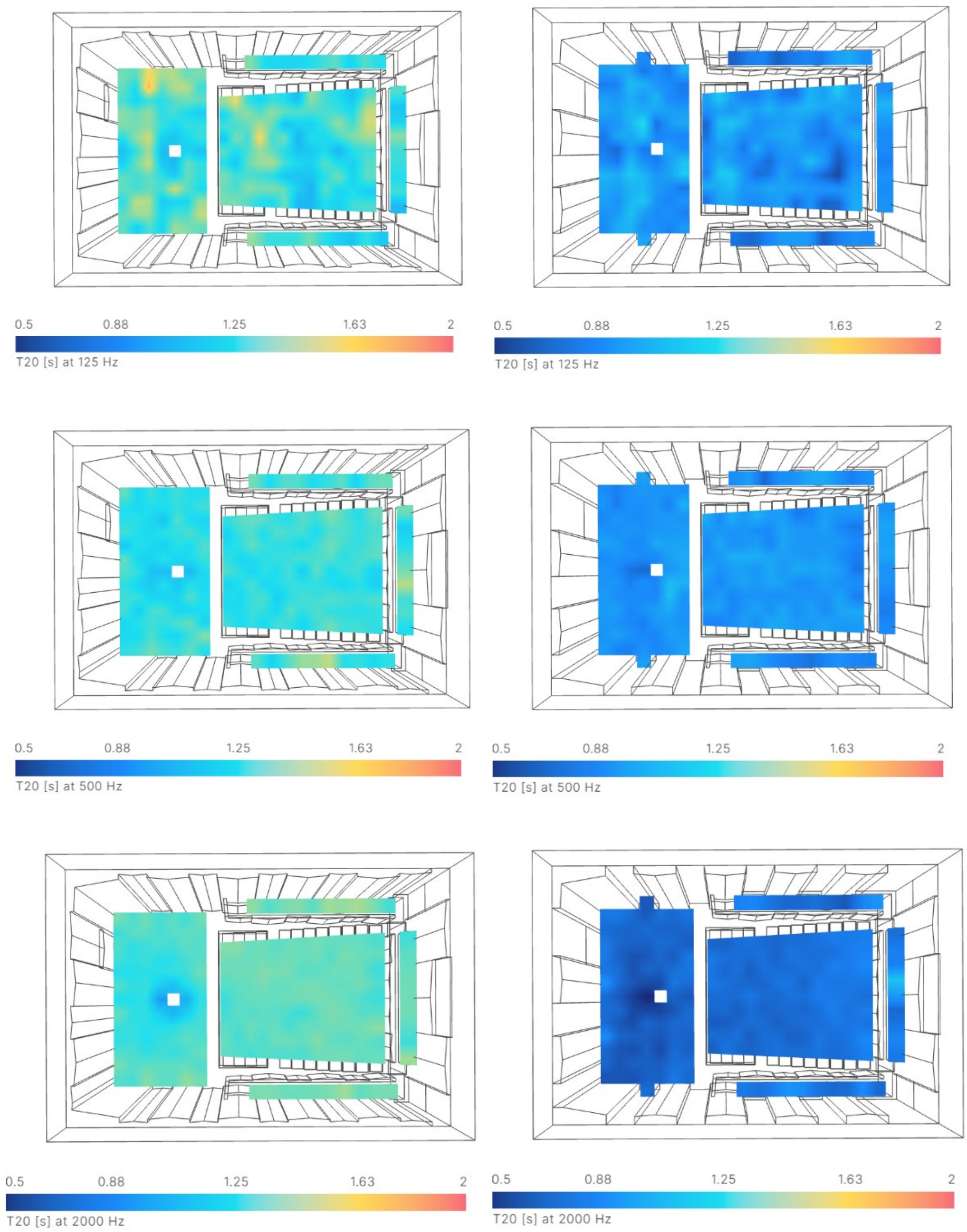

Figure 9 Acoustic modelling T20 results - surface receivers plots.

With regards to the absorbing mode, the low RT facilitates the use of the installed sound reinforcement system. The sound system design should therefore provide high values of intelligibility along with an even coverage of sound pressure levels across the audience and stage areas. The sound system has been optimised in the EASE software (© AFMG) and comprises three arrays of three medium-throw loudspeaker in a Left-Centre-Right configuration, complemented by two flown subwoofers and four point-source loudspeakers used as front fills. The predicted speech transmission index (STI) values shown in Figure 10 are largely greater than 0.8 which, according to established standards [15], corresponds to excellent intelligibility.

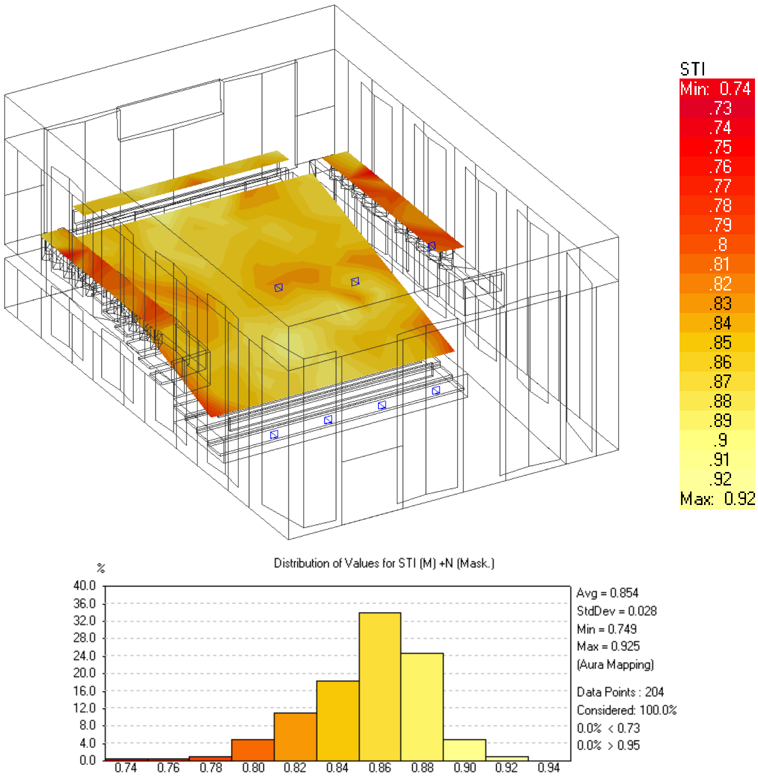

Figure 10 Acoustic modelling results - STI results for sound system design.

6 CONCLUSIONS

The project example presented herein offered the opportunity to explore the meaning of acoustic flexibility for an auditorium designed for multipurpose activities. The design was optimised for two main uses of the space: unamplified chamber music performances and amplified speech and music events. These uses require different acoustic environments: for chamber music, the space should become another instrument that helps bring the performance to life; for amplified events, the space should be a much more neutral framework that enables reproduced sound to be perceived accurately.

A bespoke passive variable acoustics system was developed to cater for the two primary, distinct uses. The system consists of a series of operable reflective wall panels that can be retracted to expose sound absorptive treatment behind. This system provides effective changes in the acoustic environment without reliance on electroacoustic processing and preserving the natural characteristics of the sound field. Macro-scale shaping through angled panels and micro-scale surface texturing were designed to promote diffusion, prevent unwanted acoustic effects, and provide an even spread of early reflections.

Parametric modelling and simulation tools played a key role in informing the geometry and finishes to provide a balanced sound field across the frequency spectrum. The current design is predicted to enable the space to comfortably meet the criterion for natural acoustics (reflective mode) and allows for sufficient reduction of reverberation times at key frequencies to adapt to a broader range of uses, particularly for the implementation of sound reinforcement systems. Whilst the results in terms of reverberation times may partially exceed some of the recommended values, the overall degree of variation is considered to align well with the project goals. Additionally, the optimised sound field with a balance of diffusive, early reflections and controlled late reflections for the main two uses is considered to provide good listening conditions for audience and performers alike. Finally, it is worth highlighting that the resulting space is not intended to be fixed in its acoustic identity but is instead proposed to be an adaptable medium to suit the user and operator needs.

Further work is expected to be carried out as the project progresses during the construction stage. In-situ acoustic measurements will enable the calibration of the acoustic models developed during the design stage and inform any necessary corrections to the predictive modelling and, where appropriate, further refinement of the acoustic treatment strategy.

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