SUPPLEMENTARY PACK – CABINET 15 DECEMBER

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CARDIFF COUNCIL
CYNGOR CAERDYDD

CABINET MEETING: 15 DECEMBER 2022

ST DAVID'S HALL – ADDENDUM TO REPORT

CULTURE, PARKS & EVENTS (COUNCILLOR JEN BURKE-DAVIES)

AGENDA ITEM: 5

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1. Further to the Economy & Culture Scrutiny Committee pre-decision scrutiny of the St David's Hall Cabinet report, held on 12th December 2022, the following information originally contained within the Confidential Appendices to the report is now addended in the public domain.

<u>Business Case</u>

2. The Outline Business Case attached at Confidential Appendix 4 sets out that AMG will operate the venue without subsidy whilst also investing in the building and protecting the classical programme (as set out in the report). AMG can achieve this, where the Council has been unable to, by introducing their Academy product to St David's Hall. This will transform the venue's commercial programme and significantly improve commercial revenue.

3. In addition, AMG's Academy venues are sponsored across the UK, and therefore AMG will also explore the opportunity to secure sponsorship revenue relating to naming rights for the building. As part of this, AMG has committed to retain 'St David's Hall' as a key part of the venue's name throughout the term of the lease.

<u>AMG Offer</u>

4. The AMG offer has also been extended since the Cabinet report was initially published as follows:

5. In addition to the 60 days to be allocated in the peak period (Sept-May), a commitment to allocate a minimum of 25 days within the off-peak event calendar to accommodate the continued delivery of the Welsh Proms, a National Youth Orchestra of Wales concert, and the Cardiff Singer of the World competition. These dates would be secured for the full term of the lease. The 25 days offer is not intended to limit the number of days in the off-peak period, but rather is a commitment to set aside an appropriate number of days to deliver

the classical programme that can be committed to up to 12 months in advance (or earlier as required).

Sandy Brown Report

6. The Outline Business Case attached at Confidential Appendix 4 contains an Acoustic Report by Sandy Brown, the original sound engineers involved in the construction of St David's Hall, at Appendix G. The report provides an update on the acoustic quality of the main auditorium undertaken for the Council in 2021. It also provides a review of an initial proposal from AMG to insert removable seating in the lower stalls area to allow standing for certain events. The full report is now available in the public domain attached as Appendix 1 to this addendum.

7. A brief summary of the report is provided below by a Director of Sandy Brown:

In July 2021 acoustic consultants from Sandy Brown visited the hall and carried out detailed acoustic tests over two days to quantify the hall's key acoustic properties. The hall's natural acoustic qualities were benchmarked in detail across all the seating terraces.

The Sandy Brown team also built a detailed 3D acoustic computer model of the hall using specialist acoustic software and this was used to assess the AMG proposals. The modelling indicated that changes in the hall's natural acoustic properties as a result of the proposals were expected to be minimal and generally below the thresholds of change required for it to be noticeable. Sandy Brown have given recommendations to be followed if the AMG proposals are implemented, and their benchmark test results and computer model are available to assist in reviewing any design proposals if necessary.

SENIOR RESPONSIBLE OFFICER	**Neil Hanratty** **Director of Economic Development**
	15 December 2022

Appendix A – Sandy Brown Acoustic Report

SANDY BROWN

Consultants in Acoustics, Noise & Vibration

21303-R01-A

23 August 2021

St David's Hall

Acoustic benchmarking report

London, Manchester, Edinburgh, Birmingham, Belfast

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Version	Date	Comments	Author	Reviewer
A	23 Aug 21		Darren McGaghran	Craig Simpson

Disclaimer

This report has been prepared for the sole benefit and use of our client based on their instructions and requirements. Sandy Brown Ltd extends no liability in respect of the information contained in the report to any third party.

Summary

St David's Hall is world renowned for its acoustics as a symphonic hall. It was selected in an American study by Leo Beranek (1996) to be amongst the top eight concert halls in the world and the only one to have been built in the twentieth century.

The hall is noted as having the perfect balance of reverberance and clarity.

A series of benchmark acoustic tests has been undertaken to quantify, in detail, the current acoustic conditions throughout the hall using the most up-to-date room acoustic measurement techniques.

The reverberation time and Early Decay Time (EDT) in the hall are still as reported by Beranek. The clarity of the hall is found to be higher (better) than reported by Beranek, with Beranek's lower figure only measured in the furthest tiers from the stage.

Speech intelligibility in the hall is 'fair'. This is due to the long reverberation (rather than too high a background noise) but in any event unamplified speech is not a key requirement for the space.

The in-house sound system marginally increases the speech intelligibility but it is still ranked only as 'fair'. With the large drape deployed behind the stage reverberation reduces slightly and the intelligibility of the sound system increases slightly to 'fair' to 'good', but it is not 'excellent' anywhere in the hall.

The background noise from building services is reasonably low, but with a few areas where it is slightly increased due to chiller pump noise ingress and an LED transformer fan off to stage right.

Contents

1 Introduction

St David's Hall is world renowned for its acoustics as a symphonic hall.

An option for investment is being explored to transform the hall into a space which is also suited for an Academy offer, but importantly, it must remain as a premium symphonic concert hall, maintaining the acoustics required for a perfect classical music experience.

The natural acoustics of the hall are known to be extremely favourable for concert use, and the original design was carefully aimed at achieving this.

To quantify and document the existing acoustic conditions of the hall, a series of benchmarking measurements has been undertaken. The intention is that appropriate solutions for any upgrading / modernisation of the hall should be checked to ensure they do not adversely affect the acoustic quality of the hall for classical music.

This report details the benchmarking acoustic measurements that have been undertaken, sets out the results, and provides an assessment and commentary.

2 Benchmarking testing

2.1 Measurement methodology

Adam Page, Craig Simpson and Darren McGaghran of Sandy Brown undertook measurements in St David's Hall on 22-23 July 2021.

The hall was unoccupied during the measurements. The largest stage extension which can hold a full symphony orchestra was in place and the corresponding front rows of seats in the stalls (A-E) were removed. The back row of stalls seating was also partially removed. The stage was empty with the exception of a grand piano.

Due to the large size of the hall a large number of measurement positions was chosen, 39 in total. These included at least two measurement positions in each tier, with more measurement positions in the stalls and larger tiers (eg Tier 11 and Tier 5). An image showing the layout of the tiers is shown in Figure 1. A full list of measurement locations and the corresponding tier and seat number is provided in Appendix A.

Two source positions on stage were chosen to assess the unamplified acoustic conditions within the hall. Measurements were taken at 39 measurement locations for the first stage source position, with a reduced number of measurement positions for the second stage source position.

Measurements were also taken with the in-house sound system to assess the amplified acoustic conditions within the hall, and the background noise level across the hall was measured.

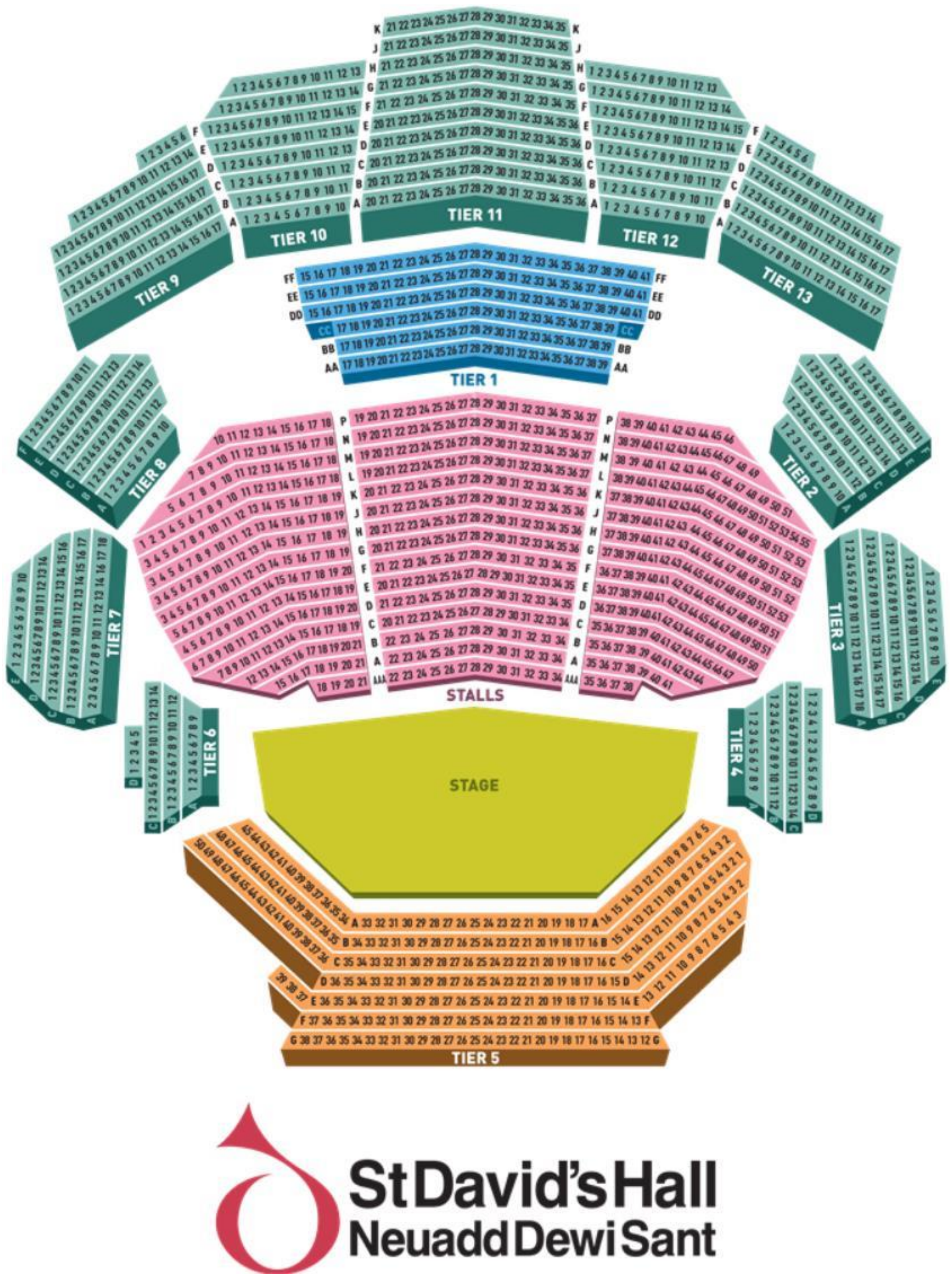

Figure 1 Seating plan of St David's Hall (courtesy of St David's Hall)

2.2 Measurement of the natural acoustic conditions

Room acoustic measurements were carried out using IRIS, a 3D acoustic measurement system that uses specialist hardware and software to analyse a range of acoustic parameters commonly used to characterise such performance spaces. The system consists of a calibrated 'Tetra mic' which gives directional information on the incoming sound, a specialist audio interface and the IRIS software. A 01dB omni directional loudspeaker was used to provide the sound source.

IRIS works by generating the impulse response of a space from a swept sine signal and then deconvoluting the impulse response. An image of the IRIS 'Tetra-mic' and omni-directional loudspeaker is shown in Figure 2.

IRIS can measure many acoustical parameters, however the main ones of interest are Early Decay Time (EDT), Reverberation Time (T_{30}), Musical Clarity (C_{80}), and sound strength (G). All of these parameters have been measured and the results included in this report.

Sound strength measurements require a calibration level that is only obtainable in an laboratory setting, however an in-situ measurement can be made in large halls such as St. David's Hall, but this is considered an approximation and may not be reflective of the true sound strength, G, in the hall.

Objective stage support parameters were also measured. The measured Early Support (ST_{Early}) and Late Support (ST_{Late}) has also been included in this report.

Figure 2 View of IRIS measurement microphone with an omni-directional loudspeaker on stage

3 Natural acoustics of the hall

The following sections provide a summary of the measurement results. The detailed results have been provided in the relevant appendices to this document.

Measurements were taken to characterise the un-amplified or 'natural' acoustic qualities of the auditorium. An omni-directional loudspeaker (see Figure 2) was used to simulate a 'natural' source on stage.

Two source positions were used on the stage. The first source position was used to carry out measurements at 39 measurement positions. At the second stage source position a more limited number of measurement positions was used.

The acoustic characteristics of an auditorium will typically vary somewhat across the space, being influenced by factors such as line of sight to the stage, the amount of localised acoustic absorption and presence of localised reflections from different surfaces. For ideal conditions the natural acoustic should not vary significantly across the hall.

The key room acoustic parameters are reported across each terrace or tier of the auditorium, eg stalls and individual tiers. The results are presented as an average of all the measurements carried out within each tier. The results shown generally relate to the first stage source position.

Detailed results of the unamplified acoustic measurements are provided in Appendix B.

3.1 Average reverberation time

The reverberation time in each octave band, averaged across all measurement positions is shown in Figure 3. The reverberation time is noted to be relatively flat across most of the frequency spectrum, with no pronounced bass rise. The reverberation time at the higher frequencies drops due to the acoustic absorption present in the hall being more efficient at higher frequencies, and the effect of absorption by the air.

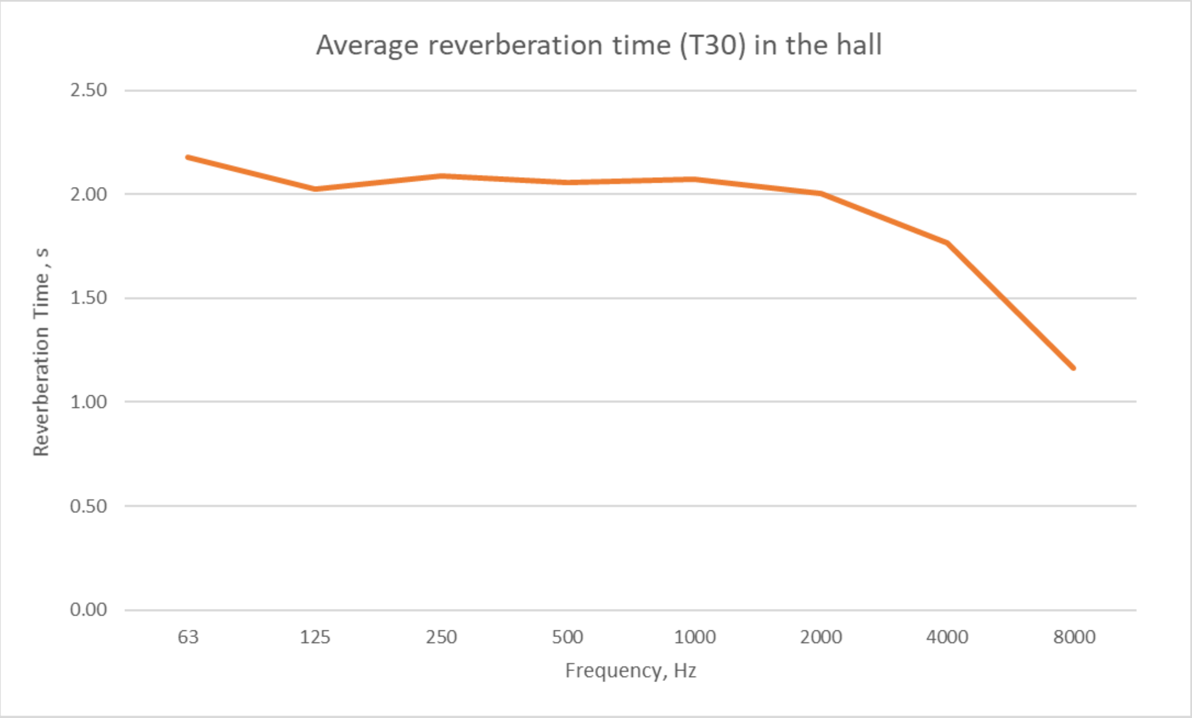

Figure 3 Average reverberation time in each octave band frequency

3.2 Reverberation time and Early Decay Time (EDT) across the hall

Figure 4 compares the Early Decay Time (EDT), which correlates to the subjective impression of reverberance within a space, and the overall reverberation time (T_{30}). It is to be expected that the overall reverberation will vary little across the auditorium but that the EDT would present some level of variance as it is more affected by localised acoustic conditions. The results in Figure 4 show this variation.

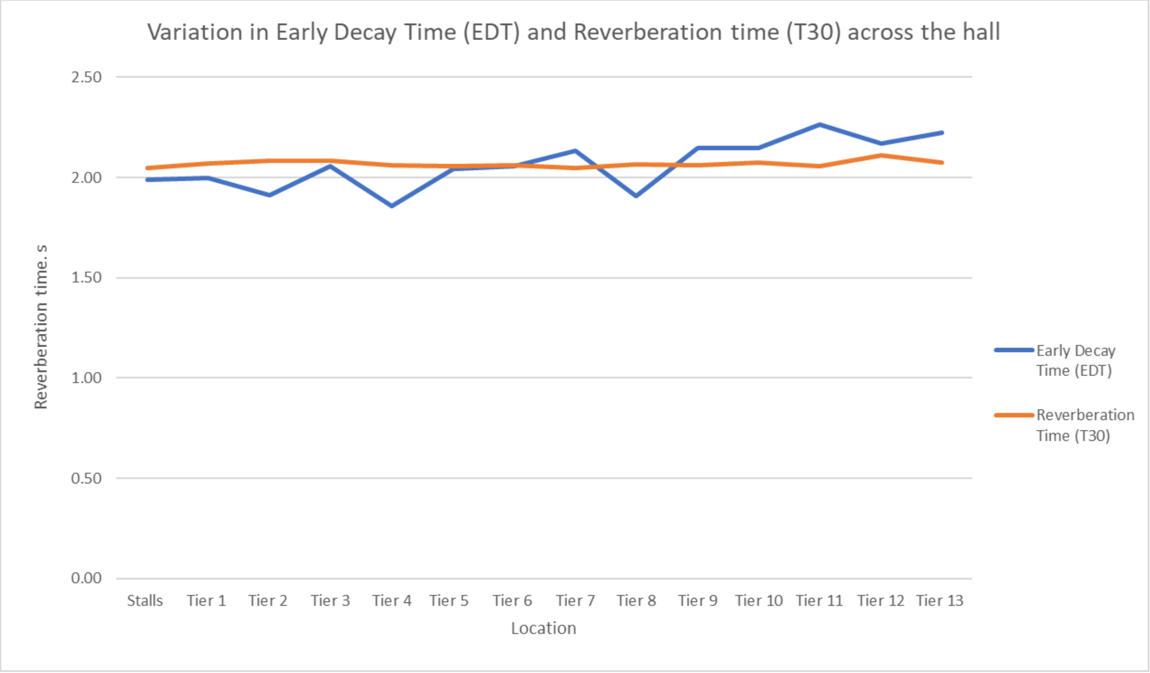

Figure 4 Variation in Early Decay time compared to reverberation time averaged in each zone – Source on stage

3.3 Clarity

Figure 5 shows the variation in musical Clarity (C_{80}), across the hall. Clarity relates to the perceived clarity of sound within a space. It is a ratio of the amount of sound arriving before 80 milliseconds, vs after 80 milliseconds.

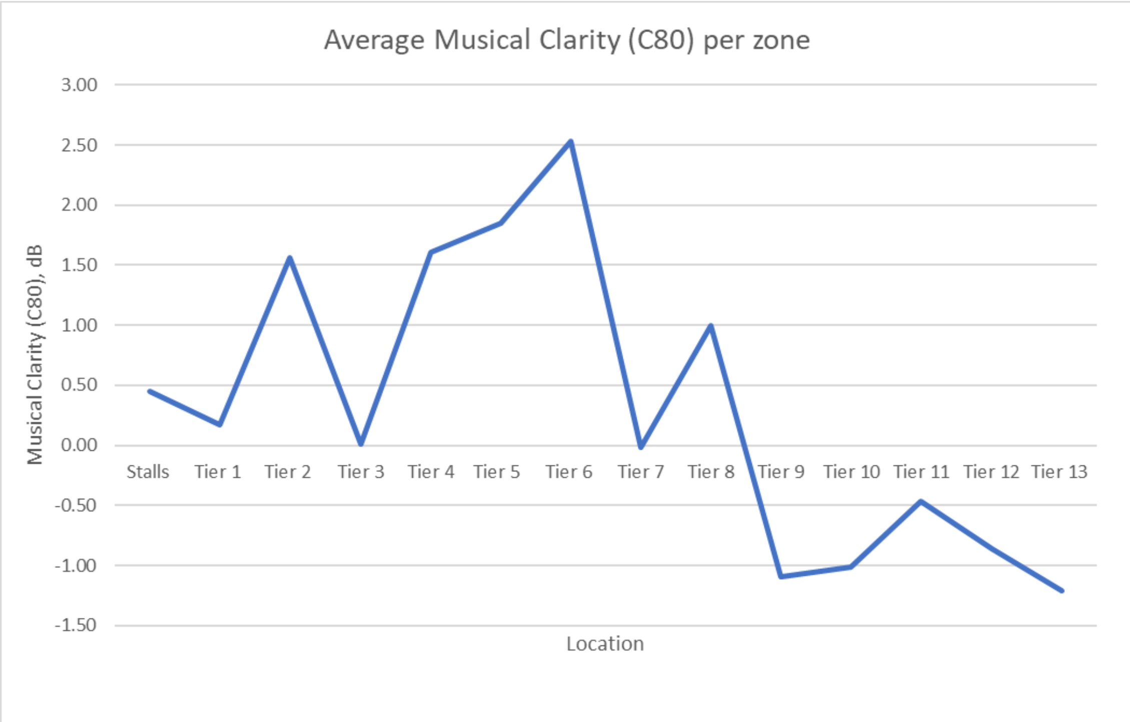

Figure 5 Musical Clarity (C80) averaged per zone – Source on stage

3.4 Speech intelligibility

Speech Transmission Index (STI) is a measure of the transmission quality of speech with respect to intelligibility, ie, how easy it is to understand speech. It varies on a scale from 0 to 1 which is shown visually in Figure 6.

When the Speech Transmission Index is measured through a public address system it is known as STIPA.

Figure 6 classification of Speech Transmission Index on a scale of 0 to 1

We measured the STI in the same locations shown in Appendix A and then averaged these values per zone in the auditorium. The results are shown in Figure 7.

The speech intelligibly throughout the hall is in the 'fair' band.

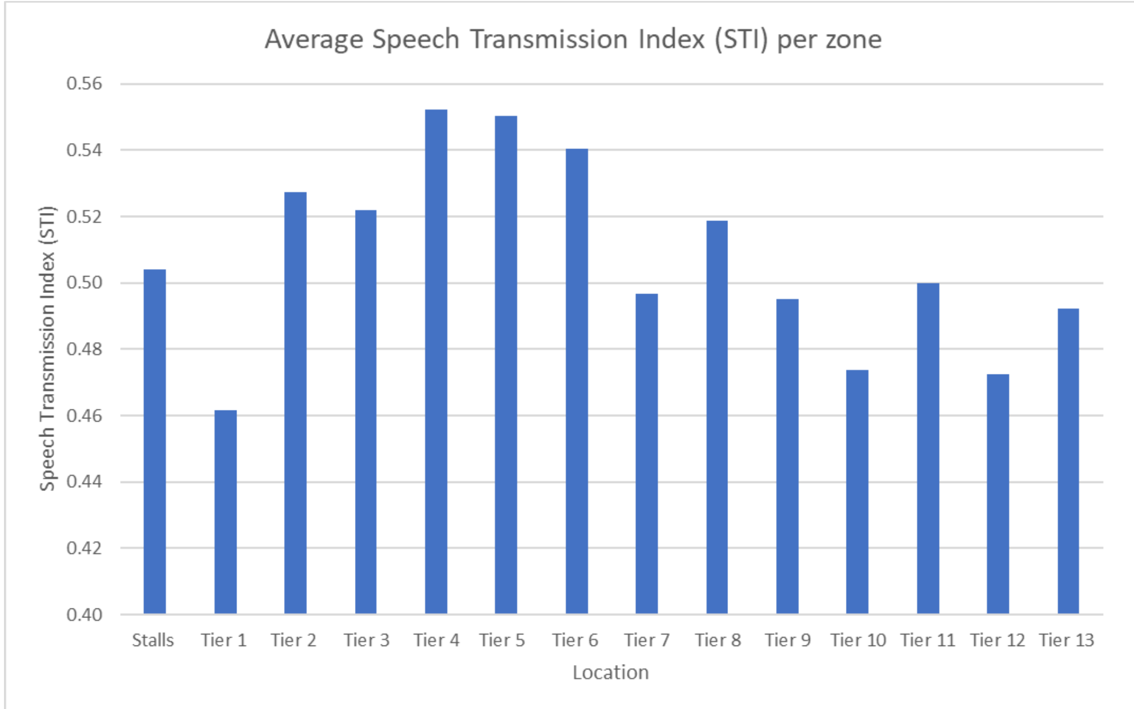

Figure 7 Average Speech Transmission Index (STI) measured in each zone of the auditorium – On stage source

3.5 Stage support measurements

We also carried out measurements of the acoustic conditions on the stage which relates to how the performers acoustically experience the auditorium.

Two parameters have been measured: the early support (ST_{Early}) and late support (ST_{Late}). The early support relates to the ensemble conditions and how easy it is for other performers to hear each other. The late support relates to the perceived reverberance of the hall.

Measurements were carried out with the loudspeakers and microphone 1 m apart, in three different locations on stage. Both the loudspeaker and microphone were 1.5 m above the stage level.

Table 1 Measured ST_{Early} parameters

	Octave Band Centre Frequency (Hz)							
ST_{Early} (dB)	63	125	250	500	1000	2000	4000	8000
Stage Position 1	-12.2	-16.2	-15.3	-16.4	-13.2	-12.2	-15.1	-16.9
Stage Position 2	-14.9	-22.6	-18.2	-18.0	-19.4	-18.9	-20.8	-24.6
Stage Position 3	-12.8	-23.6	-21.3	-20.7	-18.4	-15.3	-16.2	-22.9
Average ST_{Early} (dB)	-17 (250 Hz – 2 kHz octave band and position average)							

Table 2 Measured ST_{Late} parameters

	Octave Band Centre Frequency (Hz)							
ST_{Late} (dB)	63	125	250	500	1000	2000	4000	8000
Stage Position 1	-14.3	-18.2	-16.7	-16.6	-16.5	-14.0	-17.3	-23.2
Stage Position 2	-16.7	-19.8	-16.2	-15.9	-15.0	-16.3	-16.9	-22.4
Stage Position 3	-15.1	-19.3	-16.4	-15.9	-15.7	-13.5	-14.3	-25.3
Average ST_{Late} (dB)	-16 (250 – 2 kHz octave band and position average)							

4 In-house sound system

Measurements were taken to characterise the acoustic conditions within the hall for amplified sound. The existing d&b audiotechnik in-house sound system was used for these measurements. The system was configured for a typical amplified show.

A summary of the key results are shown in Figure 8 to Figure 10.

Detailed results of the unamplified acoustic measurements are provided in Appendix C

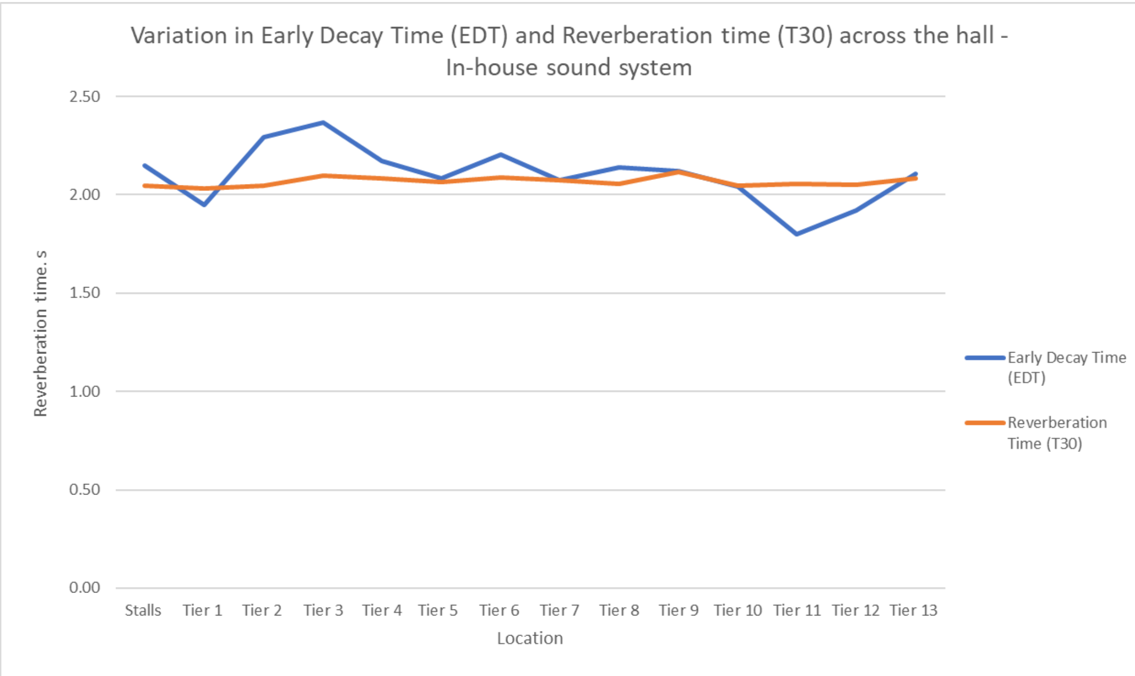

Figure 8 Variation in Early Decay Time compared to reverberation time averaged in each zone – In-house sound system

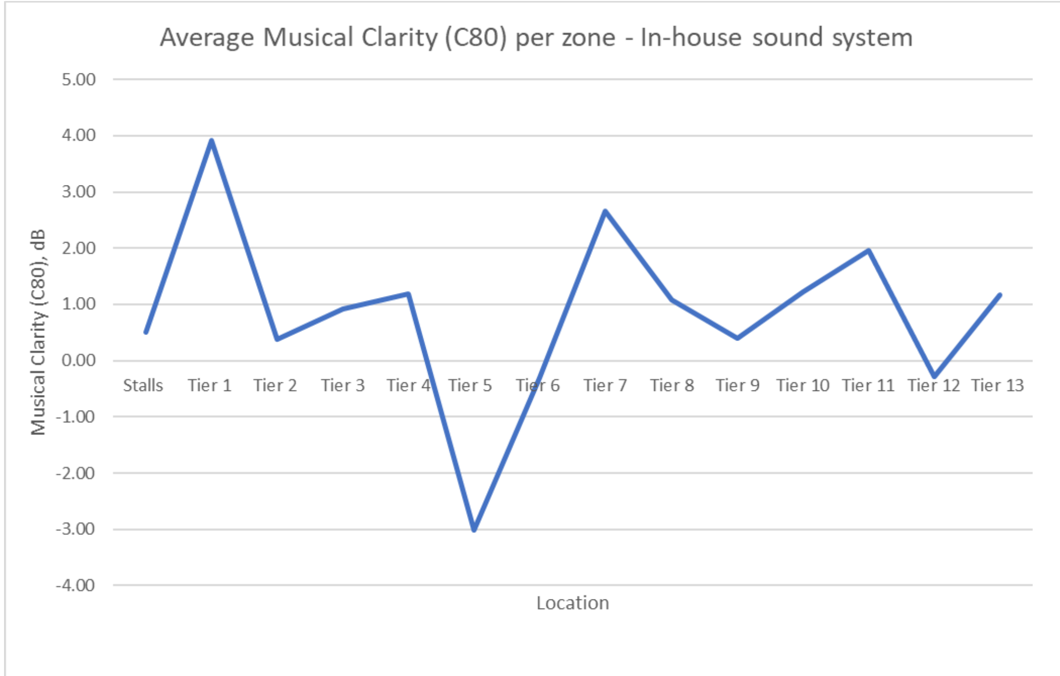

Figure 9 Variation in Musical Clarity (C_{80}) averaged in each zone – In-house sound system

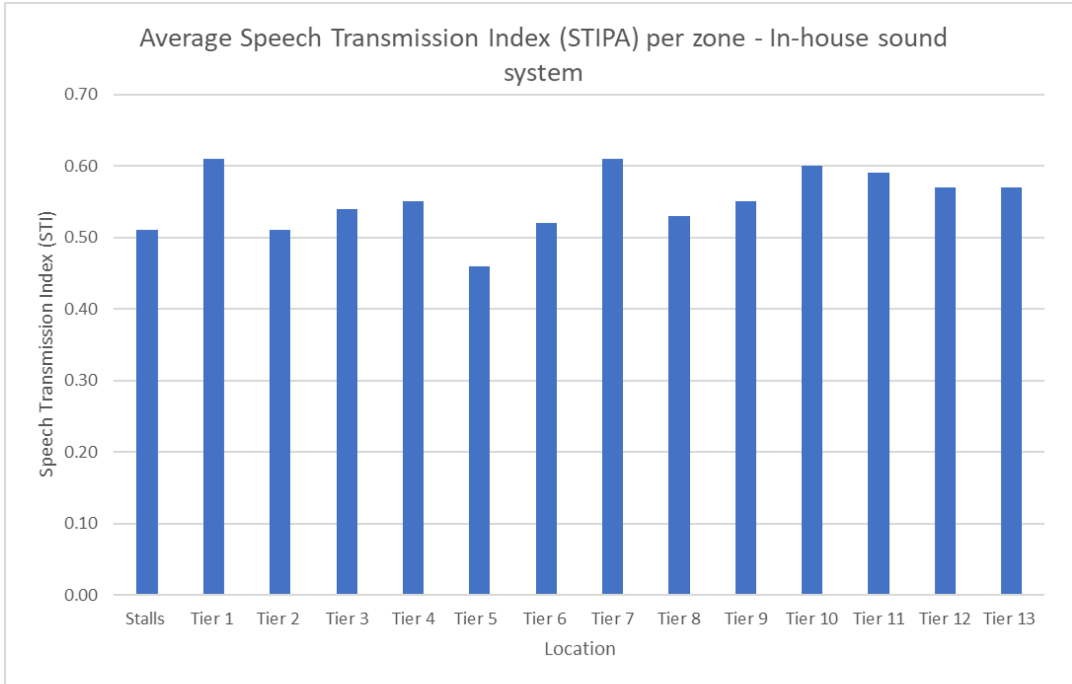

Figure 10 Average Speech Transmission Index (STIPA) measured in each zone of the auditorium – In-house sound system

4.1 Effect of adding the stage drape

It was discussed on site that there is a large stage drape that is deployed during certain amplified shows where the back tier behind the stage (Tier 5) is not sold eg comedy shows (see Figure 11).

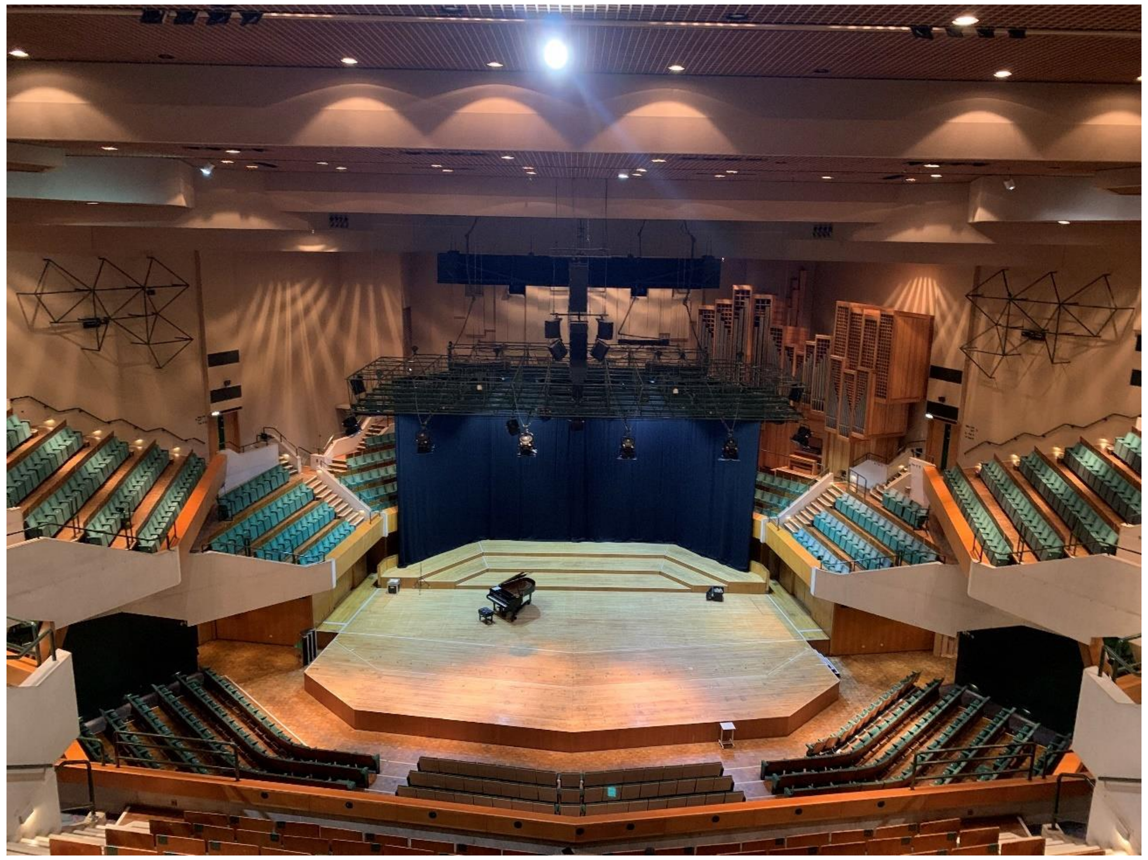

Figure 11 The stage drape deployed

We carried out measurements in the stalls area with the drape deployed and compared these to the measurements taken in the same locations without the drape.

Figure 12 shows a comparison between the measured reverberation time in the stalls, with and without the stage drape deployed. The reverberation time has been averaged across all measurement positions in the stalls.

It can be seen that the drape reduces the reverberation time at most frequencies with the most pronounced effect seen at mid-frequencies (500 Hz, 1kHz and 2 kHz).

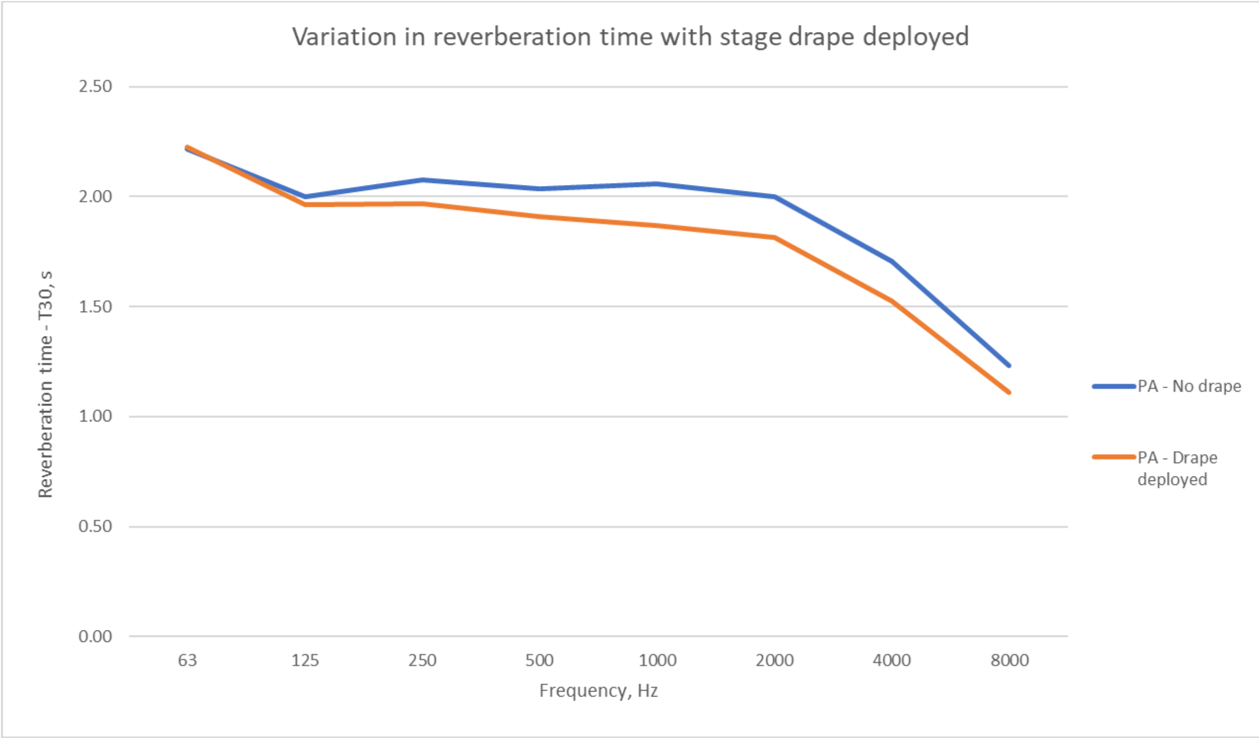

Figure 12 Comparison in reverberation time with and without the stage drape deployed

Due to operational limitations on the day, it was not possible to take full impulse response measurements at all the other tiers in the hall, however speech intelligibility measurements (STIPA) were taken using a handheld NTi XL2 sound level meter.

Figure 13 shows the comparison in speech intelligibility (STIPA) across the hall, with and without the stage drape deployed. Small improvements in speech intelligibility are noted across the hall with the stage drape deployed.

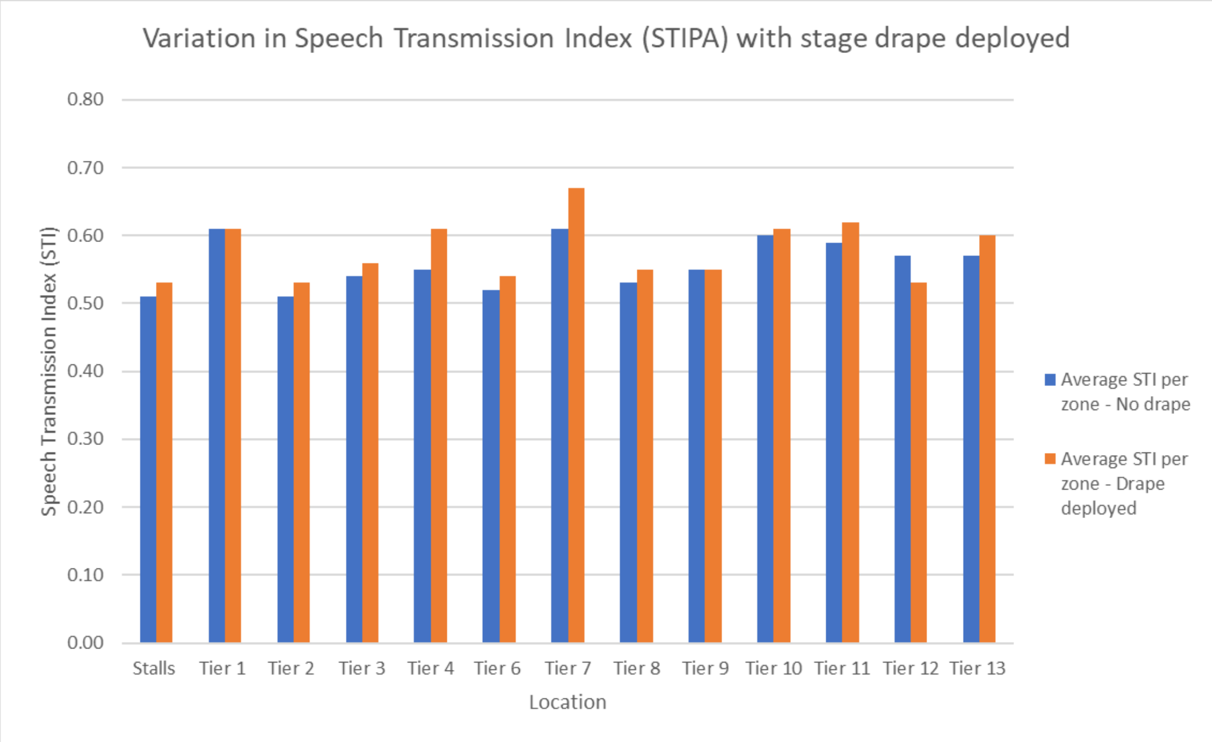

Figure 13 Comparison in STIPA per zone with and without stage drape deployed

5 Background noise levels

Background noise levels due to building services were measured using a B&K type 2250 sound level meter. The building services were understood to be running at the duty required for a concert, although air was not being recirculated by the air handling units in the usual way due to the Covid-19 pandemic. One of the pumps associated with the chillers was not running correctly at the time of the tests.

The measured background noise level was in the range NR 21 – 28, with an average level of NR 23. Full results are provided in Appendix D.

The noise from the main ventilation supply and extract air grilles serving the space was very low. The background noise was influenced by a small fan on an electrical transducer located off to stage right which we were told is a controller for LED lighting. At some positions the noise from the chiller plantroom was noticeable off to the stage left side and close to the organ. There was also a very low level electrical hum, possibly from high level lighting. It was thought that this may have been due to strip lights in the attic space but these were switched off to check and it did not appear to make any difference.

6 Comparison to historic data

Acoustic information on the hall at the time of construction has been sourced from Leo Beranek's book 'Concert and Opera Halls, How they sound', 1996 (Beranek). Various sources of information on St. David's Hall are presented within the main body and appendices of this book, including information from Barron, Gade and Sandy Brown. Sandy Brown Associates were the acoustic consultants for the design of the hall.

We have summarised the key available historical acoustic information on the hall in Table 3. There are some limitations on this information and it is not clear from the source where the measurements were taken or if they have been averaged across multiple positions within the hall.

We have provided a comparison between the historical information and our acoustic measurements, and this is shown in Figure 14 to Figure 16. We have averaged our measurement results across all measurement positions.

Generally the measurement results correlate well with the historical data, suggesting that the notably excellent acoustic conditions within the auditorium have remained relatively unchanged since St. David's Hall opened in 1982.

Table 3 Historical acoustic performance of St. David's Hall (Concert and Opera Halls, How they sound, Leo Beranek, 1996)

	Octave-band centre frequency (Hz)					
Acoustic parameter	125	250	500	1000	2000	4000
Reverberation time, T_{30} (s)	1.89	1.99	2.09	2.2	2.13	1.75
Early Decay Time, EDT (s)	1.91	2.12	2.06	2.08	2.06	1.68
Musical Clarity, C_{80} (dB)	-3.26	-1.84	-0.87	-0.62	-0.89	-0.08
Sound Strength, *G* (dB) – Gade, 1986	2.34	1.92	3.92	3.26	2.37	-

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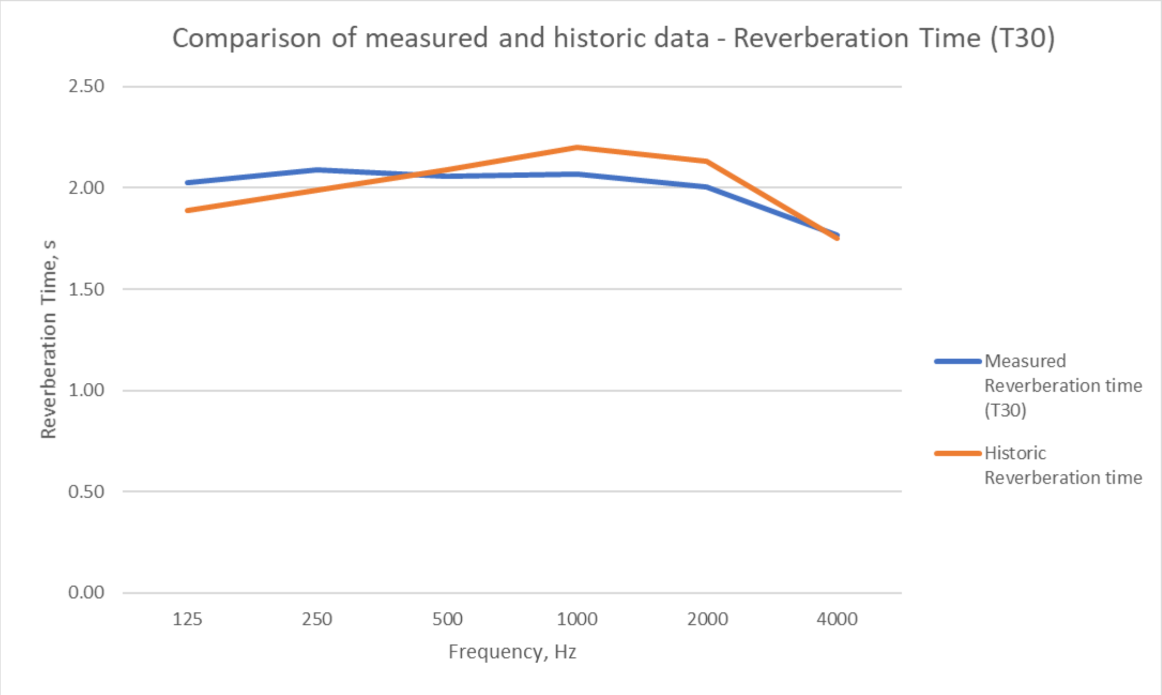

Figure 14 Comparison between measured reverberation time (T_{30}) and historcal information

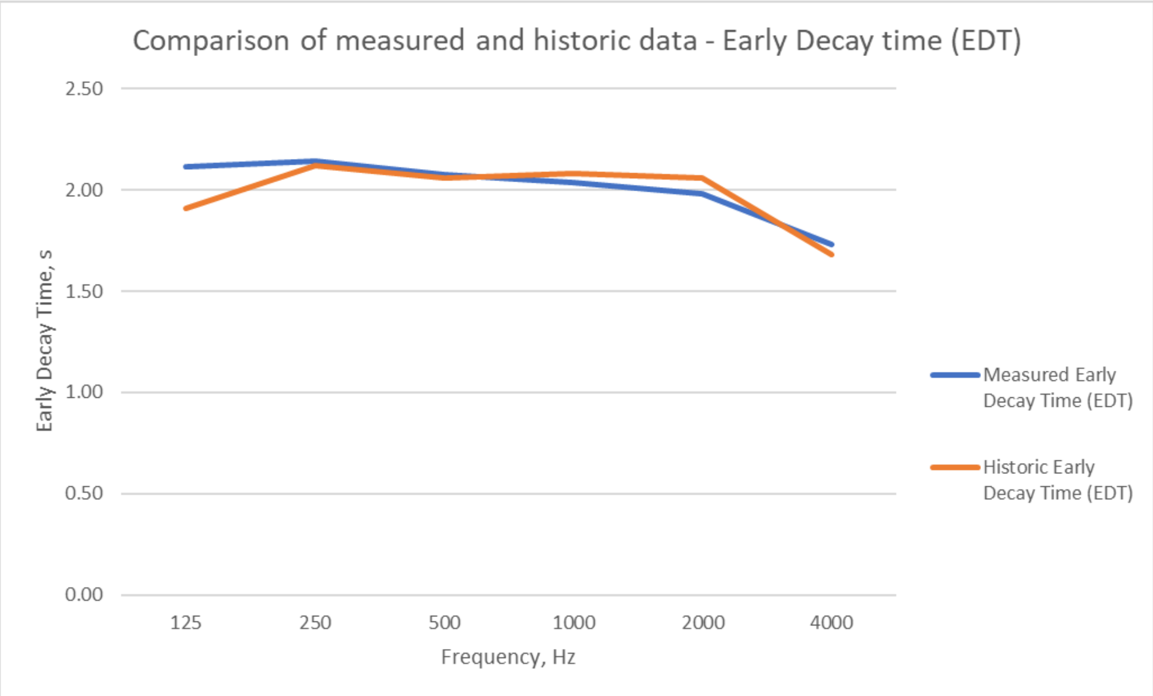

Figure 15 Comparison between measured Early Decay Time (EDT) and historical informaiton

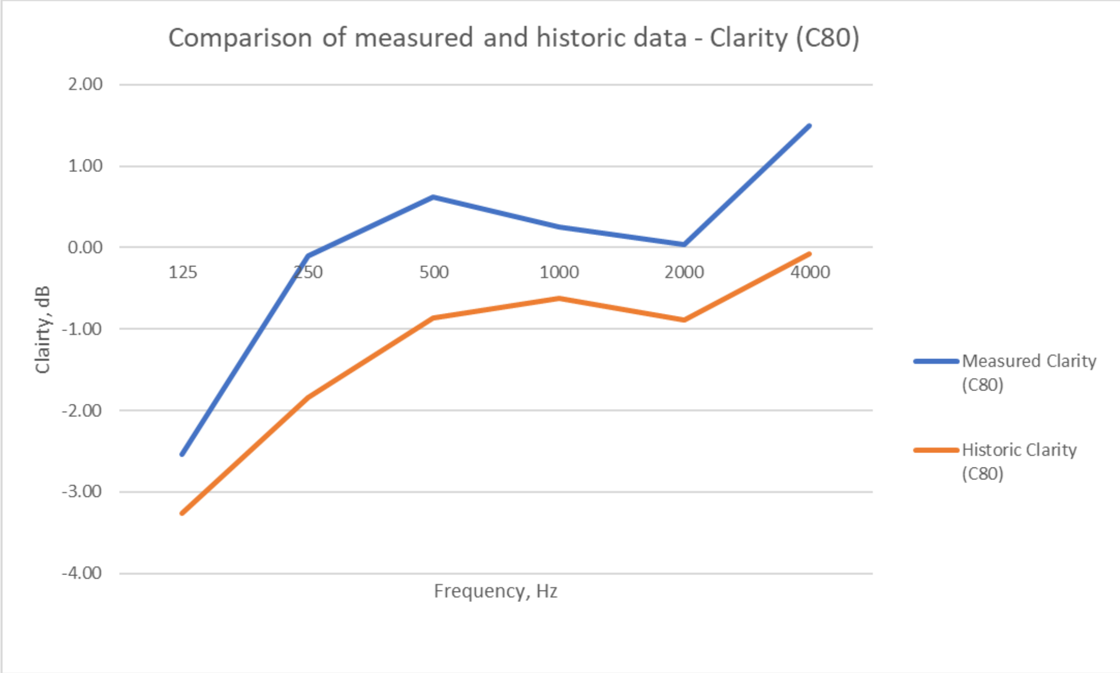

Figure 16 Comparison between measured Clarity (C80) and historical information

7 Discussion

There are no specific criteria for what makes an excellent concert hall. Beranek groups 66 halls into categories and looks at the key parameters of reverberance and clarity. The halls are classified as follows:

A+ “superior”
A “Excellent”
B+ “Good to excellent”
B “Good”
C+ “Fair to good”
C “Fair”

Cardiff is in the A “Excellent” category. There are three halls in the A+ category and six in the A category.

7.1 Reverberation time

The nine halls in categories A+ and A have a mid-frequency reverberation time in the range 1.8 – 2.05 seconds when occupied. Beranek states that the 8 ‘best liked’ halls have an average occupied reverberation time of 1.9 seconds. Cardiff, with a mid-frequency reverberation time of 1.96 seconds, is in the middle of the range. Comparing our measurements with Beranek’s records of the unoccupied reverberation time indicates that the hall remains in the middle of the optimum range.

Group B+ halls have an average reverberation time of 1.7 seconds, and group B and C+ halls an average reverberation time of 1.5 seconds.

7.2 Early decay time

The Early Decay Time (EDT) at St David's Hall is in the range 2.0 – 2.1 seconds at mid frequencies. This is at the low end of Beranek's range for A+ and A halls (average EDT 2.45 s), and is more in line with Beranek's B rated halls (average EDT 2.0 s).

7.3 Clarity

The clarity (C80) we have measured at St David's Hall ranges from -1.0 to +2.5 dB across the various tiers. This is slightly higher than reported by Beranek, who only notes a single value of -0.9 dB.

Beranek notes that, when conductors are asked about their preference for clarity during rehearsals, they express satisfaction with values of +1 to +5 dB, but for a concert would usually prefer a more reverberant space (ie lower clarity) of -1 to +4 dB. St David's Hall is firmly within this ideal range across all tiers. With reference to Figure 5 the clarity at St David's is at the upper end of the range, and is only at the lower end of this range in the furthest tiers (9-13) from the stage.

7.4 In-house PA system

The speech intelligibility in the hall is only measured as 'fair'. This is due to its reverberant nature and agrees with our subjective impression of the speech intelligibility in the space.

Deploying the large stage drape behind the stage reduces reverberation and improves the speech intelligibility of the PA system, but only from 'fair' to marginally 'good' in a few tiers.

7.5 Background noise level

The background noise level in the space is quite low. While a new hall may have a design target of NR15, it would be desirable for the background noise to be around NR 20 or lower. This is likely to be achievable if the offending chiller pump and LED light transformer fan were addressed.

Appendix A

Measurement locations

Table 4 Measurement positions

Measurement ID	Seating location	Measurement ID	Seating location
M1	Stalls F27	M21	Tier 12 A4
M2	Stalls K23	M22	Tier 12 F10
M3	Stalls N25	M23	Tier 13 B15
M4	Stalls N15	M24	Tier 13 D5
M5	Stalls J13	M25	Tier 3 D3
M6	Stalls F8	M26	Tier 3 A15
M7	Stalls J43	M27	Tier 4 C12
M8	Stalls F48	M28	Tier 4 A3
M9	Tier 1 BB20	M29	Tier 5 A10
M10	Tier 1 DD35	M30	Tier 5 E10
M11	Tier 1 EE26	M31	Tier 5 G27
M12	Tier 7 A5	M32	Tier 5 C32
M13	Tier 7 D12	M33	Tier 5 B43
M14	Tier 9 A7	M34	Tier 6 A7
M15	Tier 9 D13	M35	Tier 6 D1
M16	Tier 10 A9	M36	Tier 8 D4
M17	Tier 10 F6	M37	Tier 8 E13
M18	Tier 11 A22	M38	Tier 2 A1
M19	Tier 11 E27	M39	Tier 2 E11
M21	Tier 11 H34	-	-

Appendix B

Unamplified acoustic measurements

Source position one

Table 5 Early Decay Time (seconds)

Position	Octave-band centre frequency (Hz) 63	125	250	500	1000	2000	4000	8000
M1	1.40	2.09	1.98	2.11	1.99	1.91	1.59	1.39
M2	1.80	2.31	2.45	2.21	1.85	1.74	1.49	1.03
M3	1.24	2.21	2.18	1.88	1.78	1.63	1.48	0.95
M4	1.38	2.00	2.20	2.13	1.77	1.76	1.49	0.99
M5	1.15	2.02	2.26	2.23	1.97	1.92	1.59	1.11
M6	1.40	1.57	2.05	2.05	1.94	1.76	1.69	1.47
M7	1.31	2.19	2.06	1.93	2.02	1.78	1.61	0.99
M8	1.50	2.14	2.00	2.12	1.83	1.83	1.62	1.26
M9	2.48	2.02	2.17	1.97	1.90	1.93	1.65	1.15
M10	1.62	2.28	1.97	2.10	1.97	1.89	1.62	1.17
M11	2.10	2.01	2.18	2.11	1.95	1.95	1.74	1.14
M12	2.02	1.90	1.94	1.91	2.15	1.95	1.68	1.00
M13	2.29	2.08	1.99	2.18	2.30	2.12	1.90	1.21
M14	2.73	1.59	1.90	1.92	2.21	2.14	1.95	0.99
M15	2.00	2.27	2.49	2.26	2.20	2.10	1.99	1.05
M16	2.27	2.23	2.32	2.15	2.25	2.17	1.82	1.10
M17	1.57	1.66	2.06	2.00	2.19	2.37	1.90	1.02
M18	2.41	1.92	1.89	2.29	2.16	2.08	1.94	1.39
M19	2.12	2.39	2.59	2.37	2.29	2.37	1.95	1.33
M20	2.31	2.49	2.28	2.26	2.21	2.25	1.93	1.23
M21	2.37	2.62	2.39	2.27	2.23	2.12	1.96	1.22
M22	1.77	1.49	1.78	2.11	2.07	2.20	2.03	1.15
M23	2.54	2.36	2.53	2.20	2.28	2.30	2.08	0.91
M24	2.17	2.11	2.29	2.09	2.32	2.10	1.88	1.03
M25	2.69	2.22	2.38	2.10	2.17	2.17	1.89	0.83
M26	2.46	2.00	1.89	2.01	1.95	1.90	1.55	0.97
M27	1.72	1.97	2.07	1.84	1.93	1.98	1.57	1.19
M28	1.87	2.67	1.98	1.89	1.76	1.91	1.58	1.06
M29	2.32	1.73	1.98	1.95	2.01	1.96	1.75	1.34
M30	1.62	2.29	2.46	2.12	2.05	1.91	1.78	1.09
M31	1.87	2.14	2.20	2.01	2.15	2.09	1.84	1.45
M32	1.68	2.14	1.85	1.97	2.09	2.00	1.80	1.40
M33	1.42	2.23	2.10	1.94	2.14	1.93	1.64	1.15
M34	2.42	2.07	2.13	2.32	1.84	1.77	1.58	0.99
M35	2.02	2.33	1.99	2.11	1.95	1.84	1.50	0.94
M36	2.11	2.05	2.47	1.99	1.77	1.82	1.63	1.04
M37	2.32	1.94	1.94	1.88	1.98	1.67	1.40	0.74
M38	2.30	2.15	1.98	1.98	1.89	1.99	1.68	1.19
M39	1.94	2.51	2.24	1.94	1.84	1.93	1.72	0.96

Table 6 Reverberation time (T_{30} seconds)

Position	Octave-band centre frequency (Hz) 63	125	250	500	1000	2000	4000	8000
M1	1.98	1.84	2.00	2.10	2.07	1.98	1.73	1.09
M2	1.93	1.85	2.10	2.05	2.06	2.03	1.72	1.13
M3	2.35	2.06	2.07	2.07	2.07	2.05	1.71	1.13
M4	2.18	2.03	2.15	1.98	2.05	2.01	1.73	1.13
M5	2.14	2.04	2.07	2.01	2.03	2.00	1.78	1.12
M6	2.19	2.03	2.03	2.02	2.07	1.98	1.71	1.12
M7	2.21	1.90	2.14	2.08	2.04	1.98	1.76	1.12
M8	2.03	1.94	2.04	2.04	2.04	1.99	1.76	1.13
M9	-	1.95	2.12	2.07	2.11	1.97	1.72	1.15
M10	-	1.92	2.09	2.04	2.09	2.02	1.76	1.16
M11	-	2.01	2.18	2.06	2.05	2.00	1.77	1.16
M12	2.32	2.20	2.02	2.06	2.06	2.00	1.77	1.18
M13	-	1.97	2.14	2.02	2.04	2.01	1.78	1.19
M14	-	2.18	2.17	2.12	2.08	2.05	1.81	1.19
M15	-	2.02	2.00	2.01	2.03	2.02	1.80	1.23
M16	-	1.98	2.08	2.06	2.09	1.99	1.81	1.22
M17	-	1.89	2.11	2.06	2.09	2.03	1.83	1.23
M18	-	2.18	2.13	2.08	2.10	2.03	1.78	1.20
M19	-	2.12	2.01	1.94	2.08	2.01	1.81	1.22
M20	2.26	1.91	2.09	2.06	2.08	2.04	1.81	1.25
M21	2.65	2.11	2.08	2.07	2.09	2.03	1.78	1.22
M22	1.74	2.12	2.18	2.12	2.15	2.03	1.78	1.26
M23	2.11	2.01	2.07	2.06	2.04	2.01	1.79	1.19
M24	2.12	2.06	2.11	2.16	2.04	2.03	1.80	1.21
M25	2.34	2.14	2.04	2.07	2.08	2.01	1.80	1.17
M26	2.00	1.95	2.14	2.07	2.11	1.98	1.77	1.16
M27	2.18	1.96	2.14	2.10	2.03	2.00	1.76	1.11
M28	2.20	1.93	2.16	2.07	2.05	1.97	1.73	1.09
M29	1.94	2.09	2.07	2.04	2.05	1.97	1.75	1.13
M30	2.14	2.04	2.06	2.05	2.08	1.98	1.77	1.13
M31	2.17	2.07	2.02	2.01	2.09	2.00	1.76	1.15
M32	2.54	2.11	2.22	2.05	2.04	2.02	1.73	1.12
M33	2.08	2.02	2.09	2.08	2.06	1.98	1.74	1.13
M34	2.13	2.07	2.05	2.06	2.06	1.97	1.74	1.11
M35	2.27	1.87	2.03	2.04	2.09	1.99	1.77	1.14
M36	2.24	2.03	2.08	2.04	2.10	2.00	1.77	1.17
M37	2.33	2.15	2.08	2.06	2.05	2.00	1.77	1.15
M38	2.07	2.09	2.17	2.12	2.08	2.00	1.76	1.14
M39	2.35	2.06	1.99	2.06	2.07	2.02	1.79	1.18

Table 7 Clarity (C_{80} dB)

Position	Octave-band centre frequency (Hz)							
	63	125	250	500	1000	2000	4000	8000
M1	5.10	-3.33	4.56	2.50	1.27	2.07	2.76	6.51
M2	2.61	-4.63	-0.38	-0.66	0.24	-1.51	-0.48	3.91
M3	3.95	-5.92	-2.95	-0.90	0.82	0.24	0.27	2.86
M4	2.74	-2.86	-2.34	-1.42	1.07	-0.09	-0.94	3.30
M5	6.35	-1.54	0.36	0.73	-0.06	-0.85	0.04	2.43
M6	1.62	1.12	2.79	2.01	-1.42	-0.99	0.98	7.98
M7	1.70	-1.14	0.40	0.20	-0.04	-0.66	0.05	4.48
M8	1.88	-0.64	2.29	3.12	-0.32	0.26	0.61	2.28
M9	-0.59	-5.13	-1.84	0.04	0.53	-1.76	-0.79	2.39
M10	1.06	-4.81	-1.08	0.35	0.02	-0.84	-0.27	3.75
M11	-1.21	-3.61	-0.70	-0.05	0.16	-0.68	0.86	3.37
M12	-1.99	-1.52	0.93	1.39	0.43	0.82	1.70	5.22
M13	-2.14	-4.33	0.57	-1.06	-0.83	-0.12	0.87	3.25
M14	-1.32	-0.92	-0.44	-0.90	-0.72	-1.02	1.45	8.33
M15	-2.32	-2.45	-1.66	-1.49	-1.26	-0.85	1.22	7.46
M16	-3.66	-4.02	-0.99	-0.69	-1.62	-2.41	0.35	7.95
M17	-2.30	-1.15	-1.66	-1.28	-0.48	-1.26	0.08	7.21
M18	-0.55	-3.37	-2.18	-0.01	-0.80	-1.24	3.06	9.71
M19	-7.42	-3.55	-0.80	-1.48	-1.41	-0.26	1.58	5.17
M20	-1.11	-3.08	1.19	0.50	0.39	0.86	1.76	6.42
M21	-0.46	-0.55	-0.32	-0.78	-1.08	-1.96	-0.44	6.51
M22	-2.05	0.77	-0.61	-1.14	-0.46	-1.69	-0.78	6.78
M23	-1.63	-4.51	-0.01	-0.83	-0.65	-0.62	1.24	9.08
M24	-2.80	-2.57	-1.88	-2.04	-1.33	-0.85	-1.11	8.98
M25	-2.38	-6.37	-0.29	-1.18	-0.60	0.94	2.92	11.20
M26	-1.02	-3.30	1.33	1.14	0.68	0.40	1.89	8.57
M27	1.99	-1.49	1.28	1.28	0.06	2.79	3.83	7.53
M28	0.30	-2.23	1.55	2.36	2.72	-0.11	3.05	7.92
M29	-0.69	-0.94	1.06	2.31	1.32	0.93	1.68	6.54
M30	1.58	-3.95	1.48	2.49	0.64	1.97	5.69	7.52
M31	-0.44	-5.47	2.12	2.21	1.15	0.75	2.84	6.39
M32	1.33	-2.21	1.01	1.73	0.35	0.62	2.07	7.24
M33	1.69	0.65	-0.24	4.10	2.16	1.88	2.98	7.28
M34	2.52	-2.28	1.17	3.38	3.61	1.62	3.19	3.61
M35	-1.12	-2.84	0.36	2.57	0.55	0.29	1.86	5.58
M36	-3.08	1.76	-1.47	0.73	1.45	1.07	2.35	6.35
M37	0.71	-1.53	-2.70	0.89	0.92	2.44	3.72	7.21
M38	-4.35	-0.67	-3.22	1.01	0.93	0.59	3.31	7.52
M39	0.33	-4.14	-0.75	2.82	1.48	0.71	2.86	6.59

Table 8 Source Strength (*G*, dB) – Note these values are an approximation

Position	Octave-band centre frequency (Hz)							
	63	125	250	500	1000	2000	4000	8000
M1	0.60	8.04	10.43	6.73	6.57	9.42	9.35	5.29
M2	-2.20	3.12	4.90	4.07	5.69	6.83	6.65	1.65
M3	-3.05	2.16	4.52	4.38	5.56	6.91	6.62	0.80
M4	-1.51	2.62	3.95	4.02	5.51	6.71	6.03	0.73
M5	-0.98	2.97	5.20	4.36	5.09	6.38	5.79	0.24
M6	-2.45	4.81	7.29	5.88	4.84	6.77	6.49	4.28
M7	-0.23	3.51	5.01	4.71	4.98	7.19	6.31	1.69
M8	-2.30	4.28	7.58	6.45	5.67	7.52	6.60	0.69
M9	-5.88	2.25	3.45	3.38	4.02	5.26	4.95	-0.71
M10	-4.63	1.41	3.01	2.82	3.18	4.99	4.67	-1.24
M11	-8.45	1.82	2.45	1.99	3.05	4.72	4.43	-1.78
M12	-4.90	2.15	6.23	5.12	4.69	6.67	5.95	1.04
M13	-6.70	1.89	5.15	3.67	3.36	5.50	4.56	-1.46
M14	-7.84	1.92	3.74	3.35	2.64	4.22	4.07	0.71
M15	-6.25	-0.37	2.67	1.49	2.24	3.74	3.24	-1.21
M16	-7.85	1.73	3.84	2.72	1.89	3.81	3.47	0.05
M17	-6.63	2.52	2.43	1.44	1.47	2.23	1.80	-2.50
M18	-6.88	2.14	4.25	2.67	2.92	4.43	5.35	2.43
M19	-6.68	0.19	3.42	2.18	1.47	3.61	3.55	-2.98
M20	-7.48	-0.18	3.14	2.07	2.08	3.83	3.02	-2.90
M21	-8.02	1.42	3.10	1.99	2.38	3.71	2.95	-1.63
M22	-6.28	2.33	2.95	1.12	1.47	2.44	1.54	-3.16
M23	-7.43	0.84	2.94	2.33	2.48	4.10	3.83	1.35
M24	-6.80	0.86	2.48	1.57	1.90	3.82	2.27	0.60
M25	-6.50	1.20	4.60	3.19	3.44	5.93	5.91	5.14
M26	-5.06	4.19	6.25	5.24	4.70	6.84	6.43	3.43
M27	-2.83	3.37	6.01	5.69	5.28	8.19	8.14	4.73
M28	-3.27	4.13	6.90	6.38	7.02	7.52	8.16	5.67
M29	-4.17	4.68	6.93	6.53	5.77	7.69	7.27	2.85
M30	-2.59	1.75	4.04	4.82	4.59	7.16	8.46	2.71
M31	-2.69	1.65	5.80	5.33	4.26	6.22	6.48	1.64
M32	-3.70	2.35	5.05	5.12	4.75	6.27	6.44	2.97
M33	-2.82	2.73	5.67	5.86	5.54	7.46	7.38	3.28
M34	-3.27	3.66	6.77	6.19	6.97	8.44	8.51	3.82
M35	-4.24	4.17	6.42	5.88	5.65	7.28	7.32	2.24
M36	-6.16	2.60	3.33	4.29	4.58	6.38	5.82	0.73
M37	-6.13	2.23	2.87	3.41	3.56	6.35	6.17	0.71
M38	-6.11	2.92	3.81	3.82	4.61	6.53	6.63	2.78
M39	-6.98	0.10	4.61	4.57	4.41	5.64	5.54	0.48

Table 9 STI (male) values

Position	STI (male)
M1	0.57
M2	0.49
M3	0.48
M4	0.49
M5	0.49
M6	0.52
M7	0.50
M8	0.51
M9	0.45
M10	0.46
M11	0.47
M12	0.51
M13	0.48
M14	0.50
M15	0.49
M16	0.46
M17	0.48
M18	0.51
M19	0.48
M20	0.51
M21	0.47
M22	0.48
M23	0.50
M24	0.49
M25	0.53
M26	0.51
M27	0.56
M28	0.55
M29	0.54
M30	0.56
M31	0.55
M32	0.54
M33	0.56
M34	0.57
M35	0.52
M36	0.51
M37	0.53
M38	0.53
M39	0.53

Source position two

Table 10 Early Decay Time (seconds)

Position	Octave-band centre frequency (Hz) 63	125	250	500	1000	2000	4000	8000
M1	1.66	2.15	1.91	1.65	1.84	1.87	1.55	1.03
M2	1.63	1.96	2.38	1.92	2.04	1.85	1.50	1.09
M5	1.80	1.77	2.21	1.85	1.92	1.82	1.62	1.14
M7	1.59	1.98	1.98	1.86	1.95	1.95	1.67	0.95
M11	2.35	2.47	2.11	1.98	1.83	1.74	1.61	1.05
M12	2.24	2.02	2.37	2.34	2.33	2.05	1.64	1.36
M15	2.31	2.27	2.02	2.17	2.44	2.18	2.00	1.02
M16	1.96	1.90	2.24	2.17	2.29	2.19	1.88	1.16
M19	2.14	2.27	1.92	2.05	2.20	2.18	1.97	1.11
M22	2.12	2.22	2.44	2.04	1.93	2.16	1.82	0.89
M23	2.52	2.24	1.92	1.84	2.03	2.00	1.67	0.57
M25	2.30	2.01	1.92	1.95	2.28	2.03	1.71	0.96
M27	2.07	2.30	2.26	1.96	2.01	1.86	1.59	0.72
M30	2.05	1.91	2.20	1.83	2.03	1.90	1.87	1.16
M31	2.09	2.24	2.30	1.95	2.20	2.23	2.21	0.11
M33	1.92	2.59	2.73	2.52	2.38	2.32	2.41	0.04
M34	2.41	2.01	2.12	2.10	2.26	1.78	2.00	0.06
M36	2.09	1.76	2.06	2.18	2.14	1.96	1.59	1.07
M38	2.11	1.89	2.22	2.00	1.91	1.97	1.69	1.00

Table 11 Reverberation time (T_{30} seconds)

Position	Octave-band centre frequency (Hz) 63	125	250	500	1000	2000	4000	8000
M1	2.21	1.89	2.02	2.12	2.06	1.98	1.71	1.12
M2	2.13	2.04	2.05	2.04	2.03	2.00	1.72	1.11
M5	-	2.06	2.16	2.09	2.05	1.99	1.71	1.12
M7	2.21	1.98	2.14	2.02	2.05	1.99	1.71	1.15
M11	2.30	2.06	2.15	2.14	2.08	1.99	1.74	1.17
M12	1.97	1.87	2.11	1.97	2.05	2.01	1.77	1.16
M15	-	1.99	2.11	2.03	2.04	2.00	1.80	1.22
M16	2.08	1.93	2.08	2.05	2.07	2.01	1.82	1.23
M19	2.31	1.98	2.12	2.04	2.11	2.05	1.81	1.23
M22	2.19	2.00	2.06	2.08	2.06	1.98	1.79	1.24
M23	2.33	1.96	2.15	2.13	2.06	2.02	1.81	1.21
M25	2.11	2.03	2.09	2.04	2.08	1.99	1.75	1.18
M27	2.32	1.96	2.00	2.04	2.07	1.96	1.72	1.16
M30	2.27	1.99	2.08	2.13	2.07	1.96	1.73	1.14
M31	2.31	2.08	2.08	2.10	2.05	1.94	1.76	1.18
M33	2.25	2.05	2.09	2.01	2.07	1.98	1.78	1.15
M34	2.26	1.99	2.08	1.98	2.05	2.01	1.72	1.13
M36	2.70	2.19	2.09	2.04	2.07	2.02	1.75	1.19
M38	2.33	2.02	2.06	2.06	2.09	1.98	1.72	1.18

Table 12 Clarity (C_{80} dB)

Position	Octave-band centre frequency (Hz)							
	63	125	250	500	1000	2000	4000	8000
M1	-2.72	3.97	7.66	6.50	5.77	7.20	6.93	2.92
M2	-3.84	1.96	4.29	4.10	4.48	6.89	6.45	2.01
M5	-3.50	2.90	5.47	4.42	4.27	6.92	7.05	2.53
M7	-3.10	3.45	5.41	4.93	4.27	6.05	5.95	0.23
M11	-8.31	0.27	2.40	1.25	2.78	5.26	4.65	-1.72
M12	-6.36	4.52	3.92	3.93	4.43	6.34	6.97	1.15
M15	-7.46	0.76	2.78	1.17	1.37	3.49	3.18	-1.10
M16	-6.51	3.01	3.36	1.76	1.73	3.25	3.46	-1.96
M19	-7.68	-0.11	3.20	1.83	1.31	3.28	2.64	-2.16
M22	-7.40	-1.40	1.27	1.02	1.39	2.53	2.30	-3.00
M23	-7.35	1.55	3.96	2.97	2.82	4.61	3.95	0.17
M25	-6.41	2.09	4.55	3.53	3.78	5.52	5.19	-0.30
M27	-4.13	2.60	5.95	5.66	5.18	7.78	8.08	3.20
M30	-4.51	4.52	5.32	5.93	5.33	7.62	7.45	2.62
M31	-2.38	2.07	4.68	4.35	5.12	7.61	8.40	6.16
M33	-3.04	5.06	7.65	6.69	6.92	9.22	10.23	8.52
M34	-3.79	6.67	9.67	7.94	8.17	10.05	11.66	9.09
M36	-6.80	1.79	2.70	3.21	2.84	5.12	5.16	-2.27
M38	-6.93	3.19	4.19	3.53	3.93	5.96	5.51	-0.67

Table 13 Source Strength (*G*, dB)

Position	Octave-band centre frequency (Hz)							
	63	125	250	500	1000	2000	4000	8000
M1	3.06	-2.07	2.87	3.60	0.54	-1.20	-0.03	5.05
M2	1.02	-5.64	-0.91	-1.11	-0.63	0.50	-0.01	5.04
M5	2.23	-2.67	0.93	0.47	-1.92	0.44	2.02	5.48
M7	4.31	-0.74	1.51	2.22	0.51	0.22	1.25	5.00
M11	1.53	-1.17	-0.94	-1.32	0.72	1.52	2.02	5.52
M12	-3.84	-1.84	-0.91	-0.29	0.09	-0.54	1.62	4.90
M15	-4.77	-2.77	-0.83	-2.16	-0.84	-0.50	1.81	7.70
M16	-1.13	-0.86	-0.64	-1.75	-2.07	-2.63	0.75	6.28
M19	-5.10	-4.12	-2.84	-1.55	-1.31	-0.71	0.70	7.02
M22	-1.94	-5.93	-1.35	-0.53	0.40	-0.21	1.82	7.07
M23	-3.56	-2.69	1.40	1.37	1.19	1.77	2.77	9.35
M25	-2.95	0.76	0.56	-0.08	0.95	0.70	2.31	6.19
M27	2.08	-2.13	1.27	2.18	2.13	2.22	4.38	8.11
M30	0.24	0.22	-0.60	2.90	2.05	1.72	3.57	6.98
M31	1.39	-1.14	1.30	1.45	1.84	2.19	5.63	11.93
M33	4.07	3.42	3.90	3.64	3.84	4.19	6.88	13.01
M34	2.06	0.57	5.42	3.66	4.25	3.96	7.38	12.49
M36	0.03	-1.45	-3.45	-1.20	-0.46	-0.23	0.86	2.32
M38	-1.39	-1.20	1.22	0.90	0.73	2.07	2.46	5.47

Table 14 STI (male) values

Position	STI (male)
M1	0.50
M2	0.49
M5	0.51
M7	0.50
M11	0.49
M12	0.50
M15	0.49
M16	0.46
M19	0.48
M22	0.49
M23	0.54
M25	0.51
M27	0.56
M30	0.56
M31	0.60
M33	0.66
M34	0.66
M36	0.48
M38	0.52

Appendix C

In-house sound system acoustic measurements

Table 15 Early Decay Time (seconds)

	Octave-band centre frequency (Hz)							
Position	63	125	250	500	1000	2000	4000	8000
M1	2.46	2.08	2.18	2.05	2.27	2.10	1.63	1.30
M2	1.83	2.11	2.00	1.99	2.17	2.16	1.63	1.17
M5	1.83	2.42	2.07	2.28	2.19	2.02	1.74	1.29
M7	2.85	2.09	2.10	2.10	2.13	1.87	1.50	1.22
M11	1.36	1.47	1.75	1.73	2.16	2.15	1.59	1.10
M12	1.89	2.05	1.81	1.91	2.23	2.01	1.74	1.95
M15	1.90	1.53	1.93	2.21	2.04	1.98	1.91	1.36
M16	2.65	1.94	2.42	2.05	2.03	1.88	1.51	0.44
M19	1.61	1.65	2.09	1.85	1.74	1.93	1.64	1.13
M22	1.76	1.36	2.02	1.92	1.92	2.01	1.86	0.50
M23	2.08	2.13	2.33	2.09	2.13	2.13	2.00	1.52
M25	2.24	1.75	2.06	2.40	2.34	2.26	1.98	1.66
M27	2.90	2.09	2.16	2.08	2.26	2.04	1.93	1.90
M30	2.85	2.65	2.44	1.70	2.17	2.12	1.72	1.32
M31	2.66	2.29	2.05	1.95	2.31	2.14	1.75	1.02
M33	3.21	2.39	2.25	2.27	2.09	2.08	1.56	1.03
M34	2.53	2.37	2.04	2.14	2.27	2.14	1.86	1.47
M36	1.87	1.70	1.63	2.02	2.26	2.14	1.89	1.43
M38	2.60	2.05	1.86	2.24	2.34	2.06	1.80	1.40

Table 16 Reverberation time (T_{30} seconds)

	Octave-band centre frequency (Hz)							
Position	63	125	250	500	1000	2000	4000	8000
M1	1.95	1.92	2.07	2.03	2.03	1.99	1.70	1.23
M2	2.29	2.07	2.05	2.07	2.06	1.99	1.71	1.24
M5	2.43	2.01	2.07	2.02	2.05	2.03	1.72	1.23
M7	2.19	1.99	2.12	2.02	2.08	1.99	1.69	1.22
M11	2.33	2.12	2.19	2.02	2.05	2.03	1.74	1.26
M12	2.20	2.07	2.10	2.05	2.09	2.05	1.71	1.15
M15	2.34	1.99	2.05	2.12	2.11	2.00	1.74	1.27
M16	2.14	2.04	2.19	2.02	2.07	2.01	1.71	1.18
M19	1.70	1.89	2.17	2.04	2.07	2.02	1.70	1.19
M22	1.96	1.93	2.09	2.04	2.07	2.00	1.72	1.23
M23	2.08	2.00	2.09	2.10	2.06	1.98	1.71	1.27
M25	2.13	1.98	2.07	2.15	2.05	2.01	1.73	1.23
M27	1.76	1.88	2.10	2.07	2.09	2.05	1.72	1.21
M30	1.94	1.94	2.00	2.15	2.11	2.04	1.74	1.25
M31	1.78	1.94	2.11	1.98	2.09	2.02	1.72	1.20
M33	1.82	2.00	2.12	2.04	2.04	2.00	1.72	1.21
M34	2.24	2.05	2.11	2.09	2.09	2.01	1.70	1.25
M36	1.95	2.01	2.12	2.04	2.07	2.05	1.73	1.26
M38	2.06	2.11	2.05	2.08	2.02	2.01	1.71	1.23

Table 17 Clarity (C_{80} dB)

	Octave-band centre frequency (Hz)							
Position	63	125	250	500	1000	2000	4000	8000
M1	-0.14	1.58	-0.97	-0.44	1.78	1.14	1.50	1.92
M2	2.71	-1.09	-0.23	-0.01	1.09	-0.72	1.71	5.84
M5	-1.52	-0.13	0.25	0.94	-0.44	0.52	1.63	2.82
M7	0.44	-1.09	-0.51	0.49	0.64	0.90	3.07	4.51
M11	2.24	2.64	3.31	4.05	3.79	2.88	7.04	6.96
M12	0.09	1.23	2.94	1.16	4.15	4.38	5.05	3.90
M15	0.44	2.13	-0.66	1.24	-0.45	1.16	3.87	6.74
M16	3.62	4.33	2.97	-0.85	3.29	3.48	5.03	11.60
M19	0.18	1.76	-1.23	0.47	3.44	4.43	5.65	9.42
M22	3.31	3.91	2.08	-0.74	0.18	1.62	4.21	11.63
M23	1.55	1.06	-1.83	-0.71	3.05	2.07	3.48	6.19
M25	1.83	2.98	0.41	-0.07	1.91	1.62	1.45	2.47
M27	-1.75	1.24	0.32	1.57	0.82	1.91	3.04	3.46
M30	3.33	0.79	0.74	0.23	-4.77	-4.47	-3.07	-5.11
M31	-2.61	1.22	-0.73	-3.21	-4.33	-5.60	-7.44	-11.98
M33	-2.85	-4.54	-3.68	-3.22	-2.82	-3.76	-2.49	-4.88
M34	1.72	2.72	-0.46	-0.14	-0.46	0.72	2.41	2.67
M36	1.73	1.73	0.28	1.72	0.42	2.47	0.73	1.85
M38	1.60	2.77	3.27	-0.91	1.68	-0.44	-1.48	0.69

Table 18 STIPA values

Position	STIPA
M1	0.50
M2	0.50
M5	0.50
M7	0.53
M11	0.61
M12	0.61
M15	0.55
M16	0.60
M19	0.59
M22	0.57
M23	0.57
M25	0.54
M27	0.55
M30	0.43
M31	0.49
M33	0.46
M34	0.52
M36	0.53
M38	0.51

Appendix D

Background noise levels

Table 19 Background noise levels

Position	NR
M1	24
M2	28
M5	23
M7	23
M11	23
M12	25
M15	23
M16	22
M19	22
M22	22
M23	23
M25	22
M27	21
M30	22
M31	24
M33	22
M34	23
M36	22
M38	23

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Consultants in Acoustics, Noise & Vibration

21303-R02-B

7 October 2021

St David's Hall

Review of LiveNation proposals

London, Manchester, Edinburgh, Birmingham, Belfast

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Version	Date	Comments	Author	Reviewer
A	23 Sep 21	Initial draft	Darren McGaghran & Craig Simpson	Gordon Dolbear
B	7 Oct 21	Formatting updates and specifications added	Darren McGaghran	Craig Simpson

Summary

St David's Hall is world renowned for its acoustics as a symphonic hall. It was selected in an American study by Leo Beranek (1996) to be amongst the top ten concert halls in the world and the only one to have been built in the twentieth century.

The hall is noted as having the perfect balance of reverberance and clarity for unamplified performances.

This report provides details of acoustic computer modelling that has been carried out to assess LiveNation's proposals for redevelopment of the hall.

Details of the computer modelling process are set out.

The computer model predictions indicate that the key acoustic qualities of the hall (reverberance and clarity) are unlikely to change by any significantly noticeable amount in either the stalls or in any of the tiers. The LiveNation proposals therefore are not expected to significantly alter the unamplified conditions within the hall.

Key risk items

The acoustic modelling has been carried out on the basis that the LiveNation proposals and alterations are limited to the stalls area and that any changes to the floor or seating is on a 'like for like' basis.

One of the risks of the proposals is that the precise sound absorption being provided by the existing stalls flooring is unknown, particularly at low frequency. Changing the floor build-up significantly risks changing the absorption of this relatively large surface area. If the new floor were to absorb more low frequency sound than the existing, this could further reduce reverberation time at low frequency, which could be detrimental.

We recommend the existing build-up be checked and the final decision on the new floor build-up be based on the findings.

Contents

1 Introduction

St David's Hall is world renowned for its acoustics as a symphonic hall.

An option for investment from LiveNation is being explored to transform the hall into a space which is also suited for an Academy offer – catering for more amplified performances – but importantly, it must remain as a premium symphonic concert hall, maintaining the acoustics required for a perfect classical music experience.

To achieve this the LiveNation proposals must not fundamentally or significantly alter the existing unamplified acoustic conditions within the hall.

A detailed benchmarking set of acoustic measurements has been undertaken in the hall in July 2021, and the results are set out in the Sandy Brown report 21303-R01-A dated 23 August 2021.

The hall has the perfect balance of reverberance and clarity, and the key acoustic properties across all the seating tiers of the hall are set out in detail in the benchmarking report.

A 3D acoustic computer model has been constructed to allow a full and detailed assessment of the LiveNation proposals, and the model has been calibrated using the benchmark acoustic survey data referenced above.

The 3D model has been used to assess the potential effects of proposed alterations on the acoustics of the hall. The benefit of this is that it allows a careful check of proposed interventions and how these may affect the natural acoustic quality, and gives detail on the extent of any acoustic changes.

The LiveNation proposals have been reviewed using the model.

2 LiveNation proposals

The LiveNation proposals include the following:

- Remove existing stalls seating and flooring
- Re-tier the stalls area with 30 mm birch ply on new timber joists
- Install a new hard wearing non-slip vinyl floor finish
- Install removable seating bars to take new seating – which is to be Espace 628 full upholstered seating (colour to match existing seating in other tiers)
- Install new handrails at the tops of each tier with removeable mesh in-fill panels. These are for standing events and will be interchangeable with the seating.
- Install a new PA system.

Drawings showing the details of the proposals are given in Figure 1 to Figure 5.

2.1 Proposed alterations to the stalls

Vinyl covering to existing or replacement timber flooring.

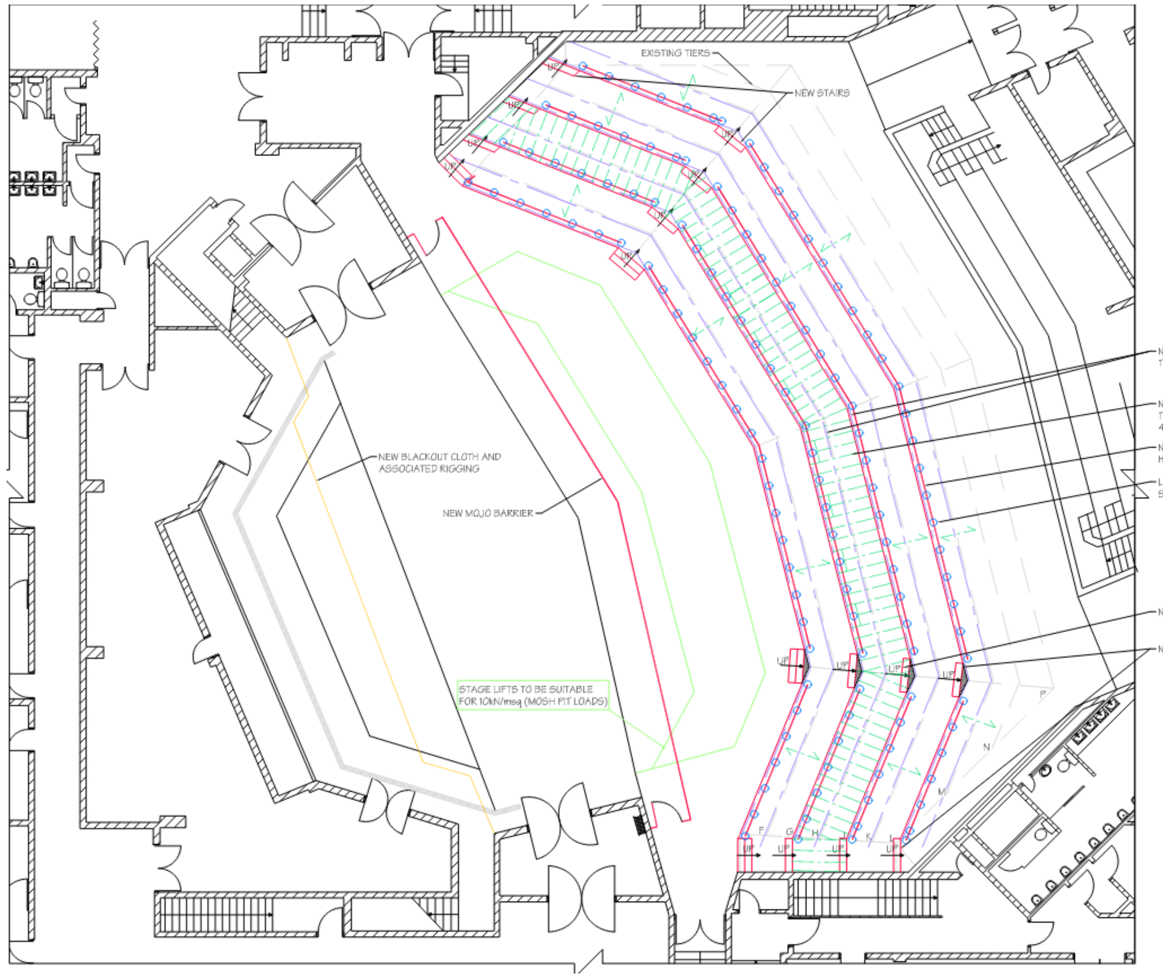

Figure 1 Plan view of the LiveNation academy proposals showing new altered stalls seating area

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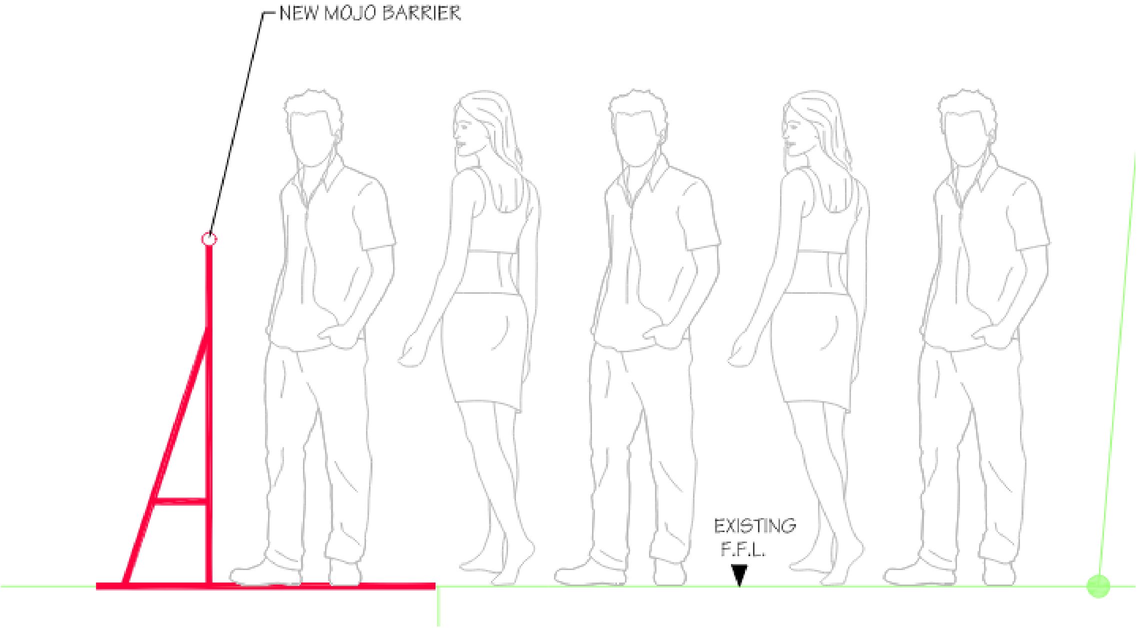

Figure 2 Proposal to use the current front of stalls area as standing space for an audience

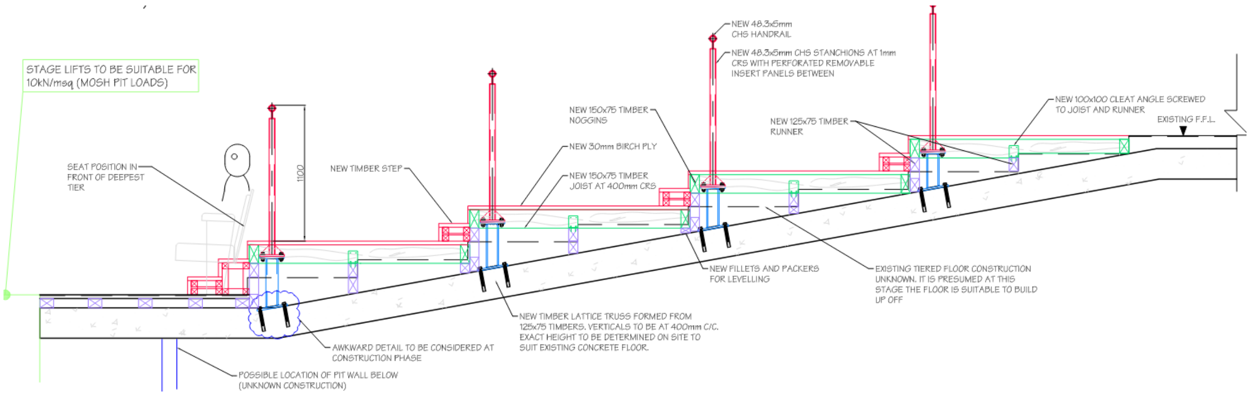

Figure 3 Proposed alterations to the raked stalls flooring

2.2 Replacement stalls seating

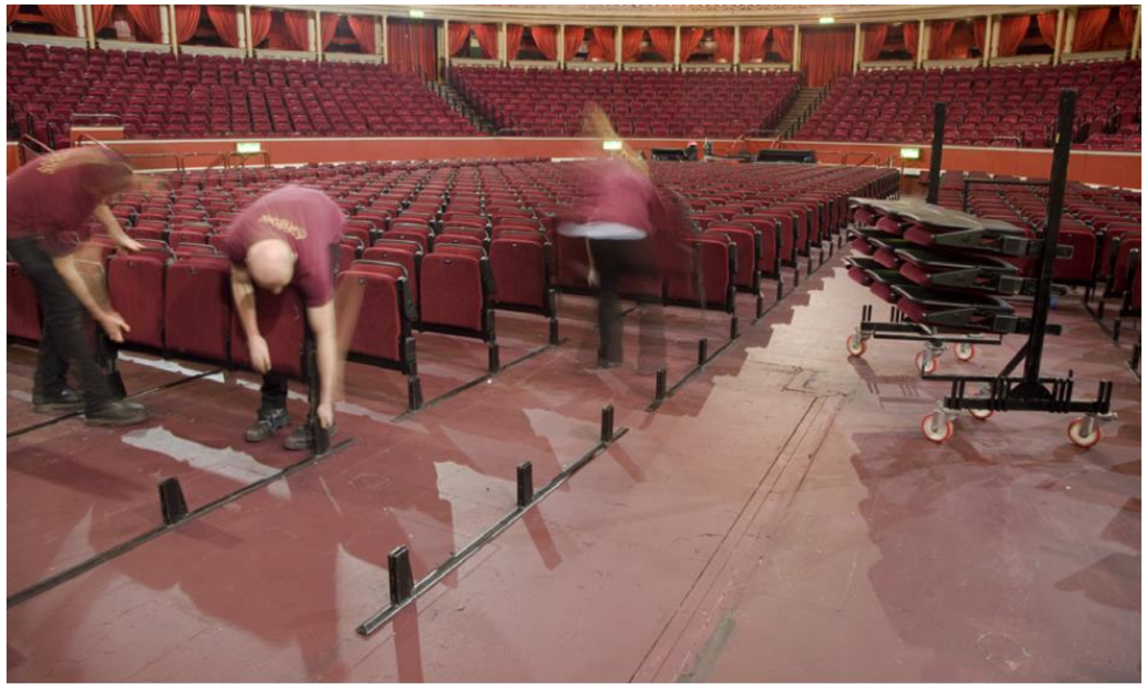

Figure 4 Proposed removable seating (shown being deployed in The Royal Albert Hall, London)

Figure 5 Espace 628 full upholstered seating

3 Computer model of the hall

This section details the process undertaken to build and test the 3D acoustic model and assess any impact that the LiveNation proposals may have on the natural acoustic conditions in the hall.

3.1 SketchUp Model

A 3D computer model was created from the provided plan and section drawings of the hall using SketchUp.

SketchUp allows for the creation of relatively simple 3D geometric models of spaces that can be easily imported into acoustic software.

Figure 6 and Figure 7 show images of the 3D model of the hall from SketchUp.

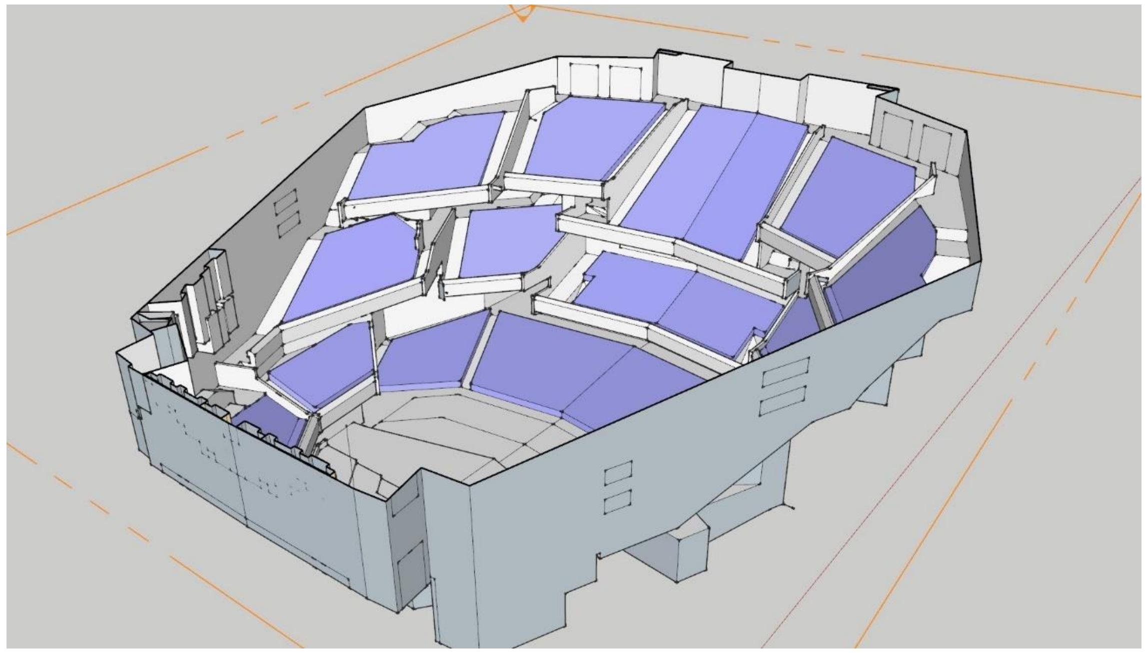

Figure 6 View of SketchUp model – Semi-Isometric

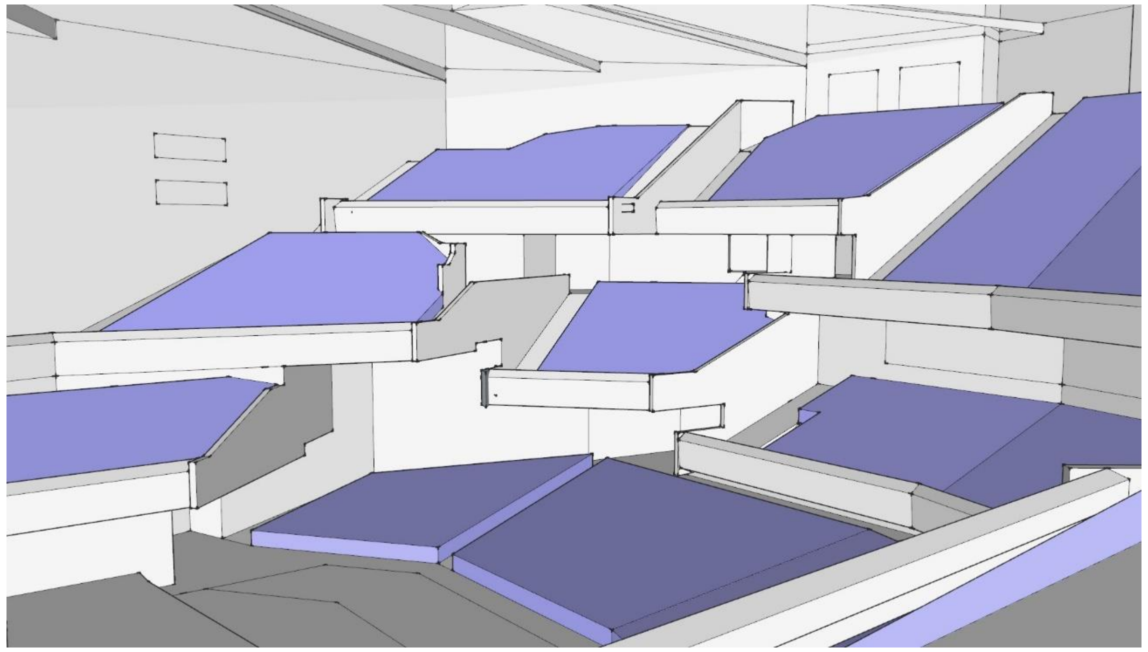

Figure 7 View of stalls and tiers within the SketchUp model

3.2 Odeon model

Odeon modelling software has been used to carry out acoustic calculations. The software has been specifically developed to analyse the complex acoustics of performance spaces. Odeon uses a hybrid ray tracing and image source technique to simulate the propagation of sound within spaces.

The 3D model from SketchUp is imported into Odeon where the acoustic analysis can be carried out. Figure 8 shows an elevation view of the acoustic model from the Odeon software.

The acoustic sources and receiver positions are then added to the model (See Figure 9) which correspond to the source and measurement positions used during our acoustic benchmark testing of the hall.

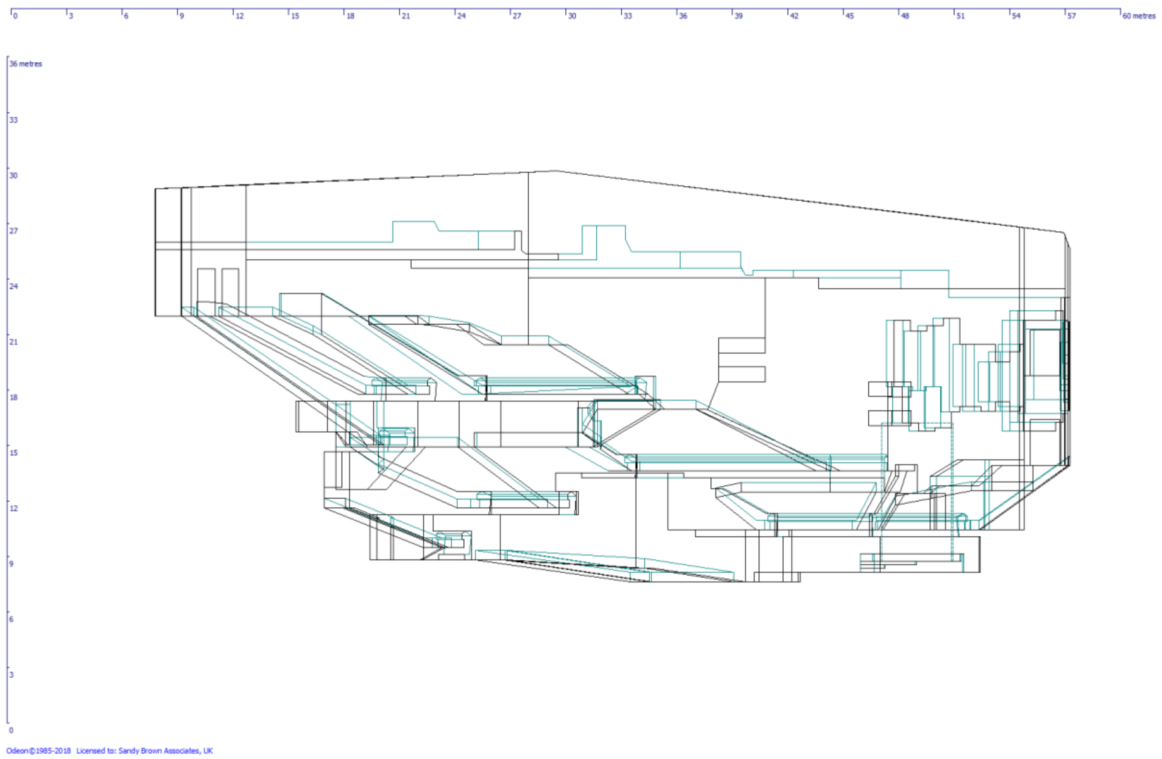

Figure 8 View from Odeon model – elevation

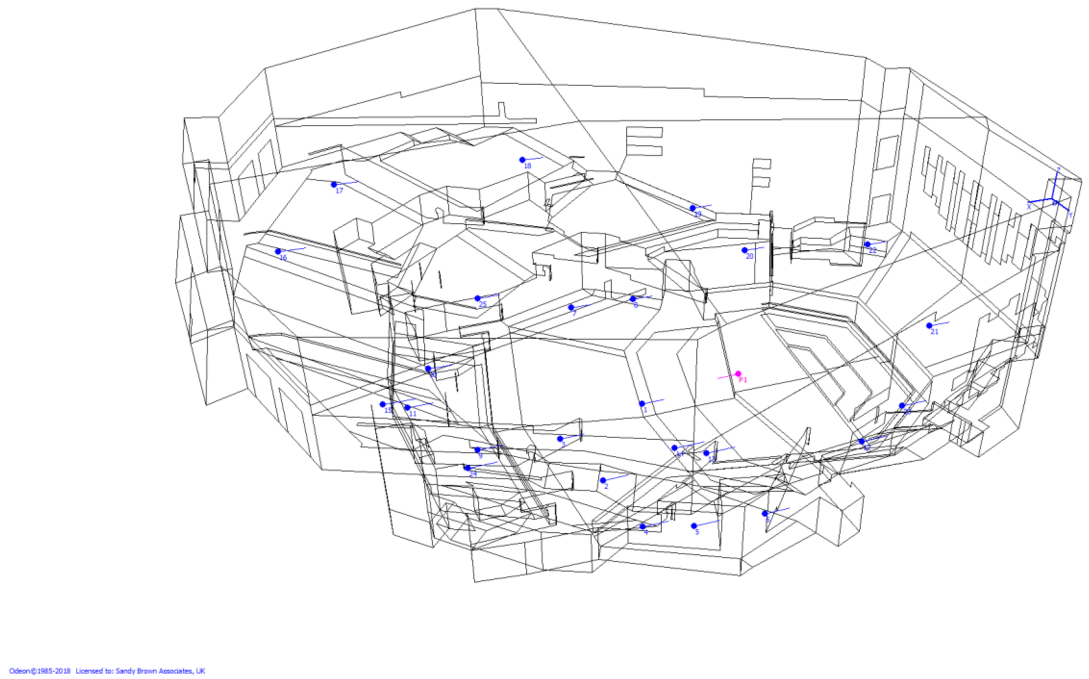

Figure 9 View from Odeon model – Measurement locations added – Semi isometric

3.3 Model calibration

Sound absorption coefficients are assigned to surfaces in the model. The properties of some surfaces can be estimated with reasonable accuracy (eg, the upholstered seating), however there is more uncertainty in the absorption being provided by some surfaces (such as the lattice ceiling and void above) which are subject to a higher degree of uncertainty.

The acoustic model was calibrated using measured results from the benchmark acoustic testing carried out in the hall. The model allows for iterative adjustment of the absorption provided by certain surfaces (up to set controllable adjustments) and the calculated reverberation times are compared with those measured for a number of measurement positions in the hall.

By this process sound absorption coefficients of materials within the model were adjusted until the calculated reverberation times matched those measured. This was useful for refining estimated sound absorption coefficients of surfaces for which no reliable acoustic data exists, eg, the lattice ceiling void.

Figure 10 shows the result of the calibration process with good correlation between measured and calculated reverberation time (T_{30}) data.

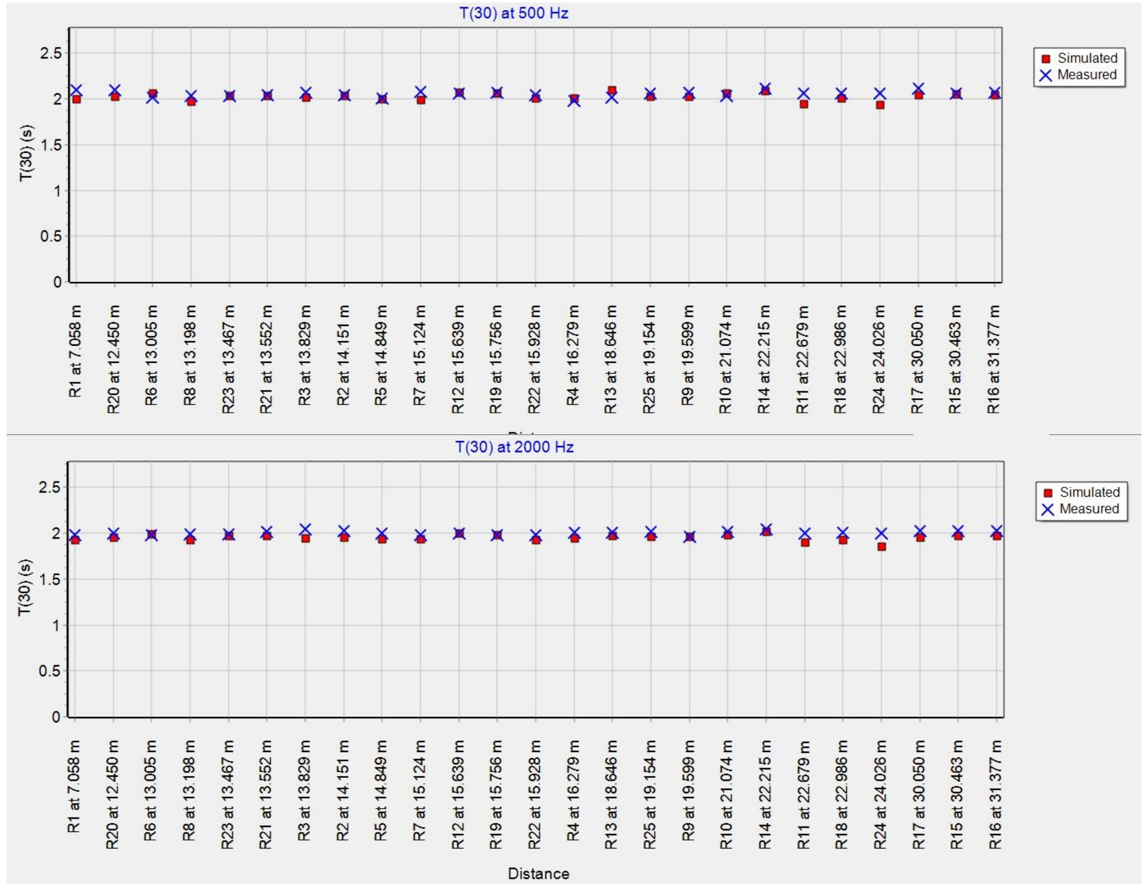

Figure 10 Comparison of measured vs simulated reverberation time (T_{30}) results

Figure 11 and Figure 12 show views from the final calibrated model. The colour of the surfaces is proportional to the sound absorbing properties with the darker colours generally being more absorbent.

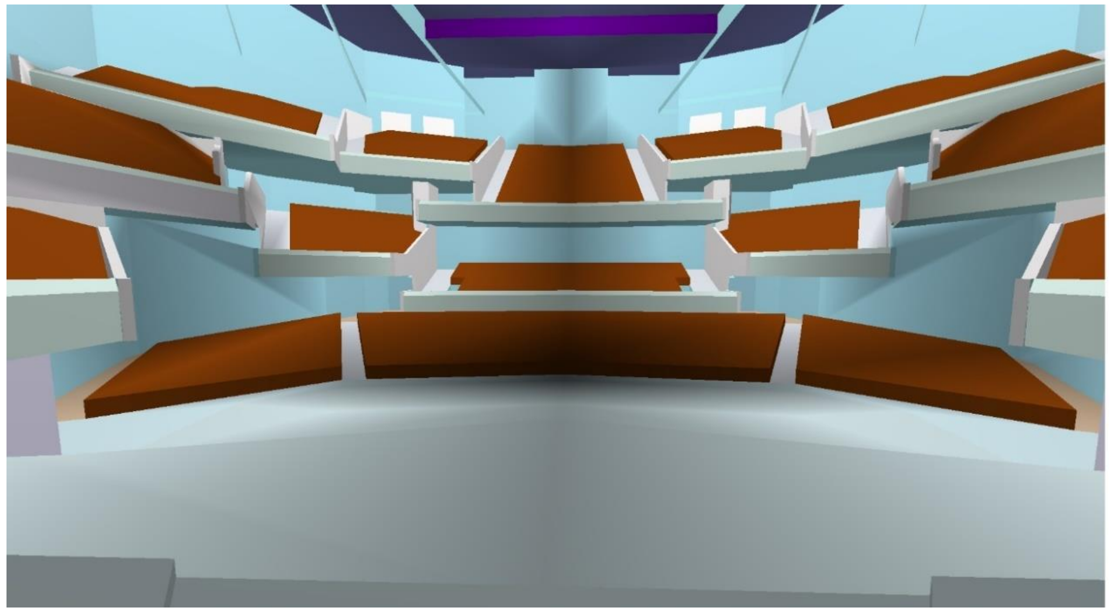

Figure 11 View of the calibrated Odeon model – from the Stage

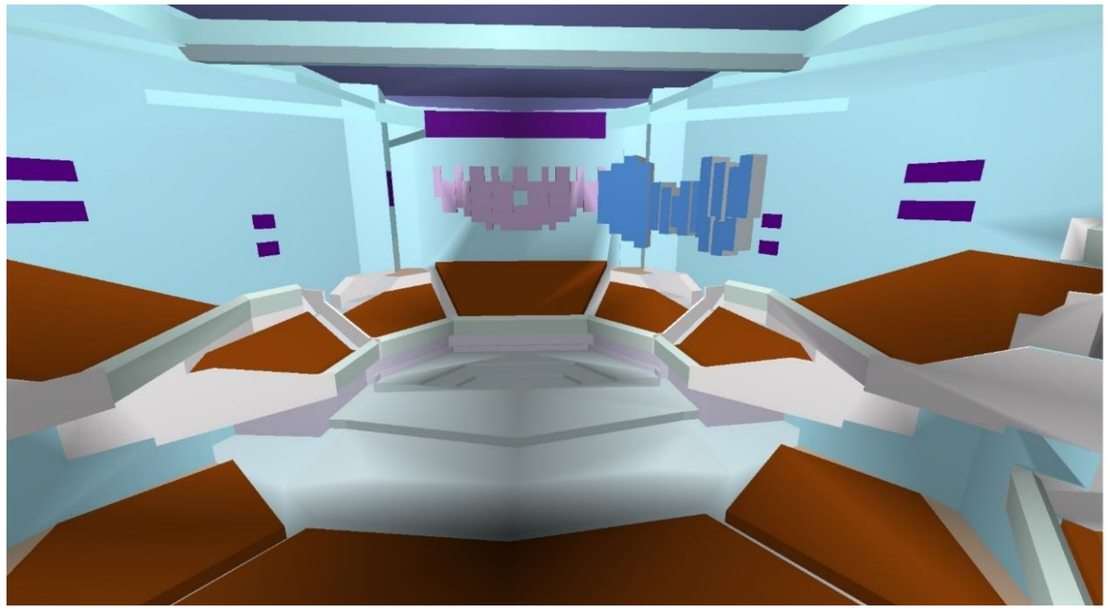

Figure 12 View of the calibrated Odeon model – from Tier 11

3.4 Basis of modelling

The key goal of the acoustic modelling is to assess the effect of the LiveNation proposals on the unamplified acoustic conditions within the hall.

We have based our acoustic modelling of the LiveNation proposals on the information that they have provided (See Section 2).

3.4.1 Seating

The key acoustically significant change is the replacement of the existing fixed seating in the stalls with removable seating that will allow for a standing audience for the Academy use.

The product to be used is the Espace 628.00 fully upholstered seat with a Pullmaflex core. Acoustic test data from a reputable testing laboratory has been provided by LiveNation and is summarised in Table 1.

This absorption data has been used in our acoustic modelling of the LiveNation proposals.

Table 1 Absorption data for Espace 628.00 fully upholstered seating

	Octave-band centre frequency (Hz)					
	125	250	500	1000	2000	4000
Espace 628.00 seat – Fully upholstered with Pullmaflex core (absorption coefficient, α)	0.32	0.41	0.57	0.67	0.72	0.73

3.4.2 Stalls floor build-up and floor finish

30 mm birch ply is proposed on timber joists. The rake angle of the stalls remains essentially the same as existing. The precise existing build-up of the floor is unknown. The finish is parquet flooring, and this had a reasonably solid feel when walked on, however it did have a degree of responsiveness when walked on (eg, unlike a solid concrete floor) so is expected to be providing a degree of low frequency absorption. The proposed new birch floor is expected to provide a similar performance.

We have assumed that all the existing carpet at stalls levels is being replaced with vinyl. The important aspect of this in the model is in the aisles (ie not under the seating), and in the model this equates to 110 m^2 of carpet on timber being replaced with vinyl on timber.

3.4.3 Stage build-up

Our benchmark acoustic testing was carried out with the stage in its largest configuration, ie, both stage extensions installed, and the acoustic modelling was carried out on this basis. When assessing the LiveNation proposals we have taken that the stage build-up will remain unchanged and that LiveNation are not proposing to make any alternations to the stage.

4 Model results

A summary of the acoustic modelling results is provided in this section.

For ease of reference, we have generally shown the relative differences between the current simulated acoustic conditions and the LiveNation proposals.

To ensure the unamplified acoustic conditions remain unchanged, there should be little relative difference between the various acoustic calculated acoustic parameters.

4.1 Just Noticeable Differences (JNDs)

The expected variation in acoustic conditions, presented in the modelling results below, can be contextualised by discussing the Just Noticeable Differences (JNDs) for the key acoustic parameters assessed, ie, T_{30}, EDT, C_{80} and STI.

A Just Noticeable Difference is the amount a parameter needs to change before it is noticed at least half the time by a sample group of people and relates to human perception or the perception of the 'human ear'.

The JNDs for the key acoustic parameters are shown in Table 2.

The reverberation time, T_{30}, does not have a corresponding JND as the perceived reverberance of a space is better characterised by the Early Decay Time (EDT).

Table 2 Just Noticeable Differences (JND) for different acoustic parameters

Acoustic parameter	Subjective impression	JND
Early Decay Time (EDT)	Perceived reverberance	5% relative change [1]
Musical Clarity (C_{80})	Clarity of sound	1 dB [1]
Speech Transmission Index, STI	Speech intelligibility	0.03 [2]

[1] Acoustics —Measurement of room acoustic parameters - Part 1: Performance spaces (ISO3382-1:2009)

[2] A just noticeable difference in C50 for speech, J.S. Bradley et al - Applied Acoustics, Volume 58, Issue 2, October 1999, Pages 99-108

4.2 Reverberation time

Figure 13 shows the relative difference in Reverberation Time (T_{30}) in each octave band between the current simulated acoustic conditions and the LiveNation proposals, averaged across all the stalls positions.

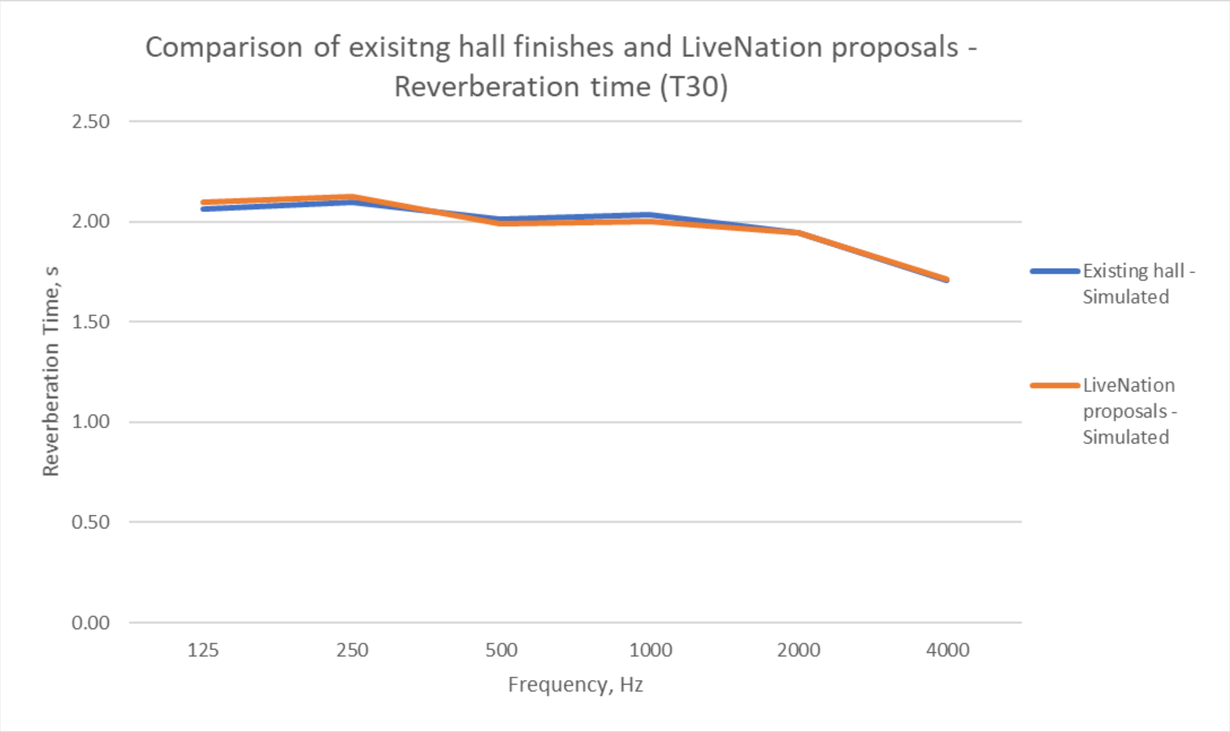

Figure 13 Comparison in reverberation time in each octave band frequency – Stalls

Figure 14 shows the relative difference in Reverberation Time (T_{30}) between the current simulated acoustic conditions and the LiveNation proposals, at all the sample locations in the hall. The reverberation times are an arithmetic average of the values in the 500 Hz and 1 kHz octave bands.

The acoustic modelling results show that there is little expected difference in the overall reverberation time within the hall, if the LiveNation proposals are implemented.

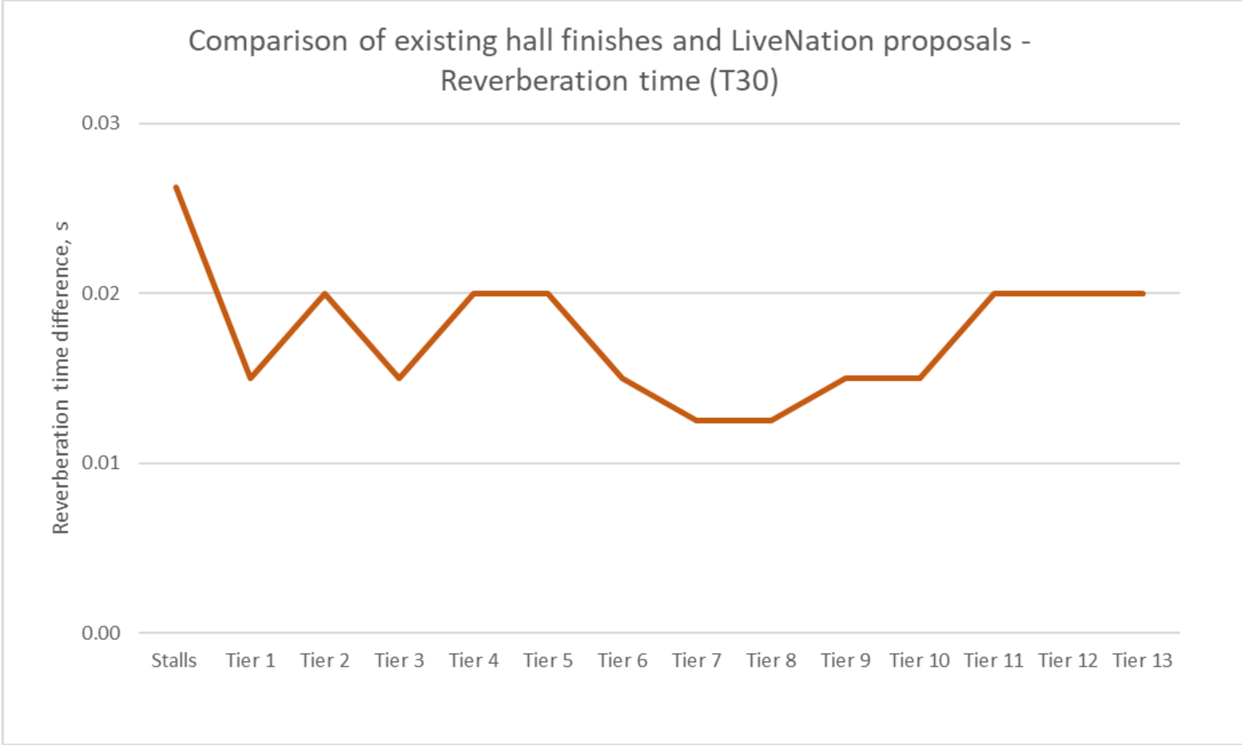

Figure 14 Relative difference in reverberation time for LiveNation proposals in each zone

4.3 Early Decay Time (EDT)

The Early Decay Time (EDT) correlates to the subjective impression of reverberance within a space.

Figure 15 shows the relative difference in Early Decay Time (EDT) between the current simulated acoustic conditions and the LiveNation proposals, across the hall. Figure 16 shows this same difference but as a percentage relative to the current simulated conditions within the hall. The JND for EDT is shown as a red line in Figure 16.

The acoustic modelling shows that there is little expected difference in the calculated Early Decay Time within the hall, if the LiveNation proposals are implemented. However, it is noted that the largest changes occur in the stalls which is to be expected.

The predicted percentage change in EDT is well below the Just Noticeable Difference (JND) for all areas of the hall.

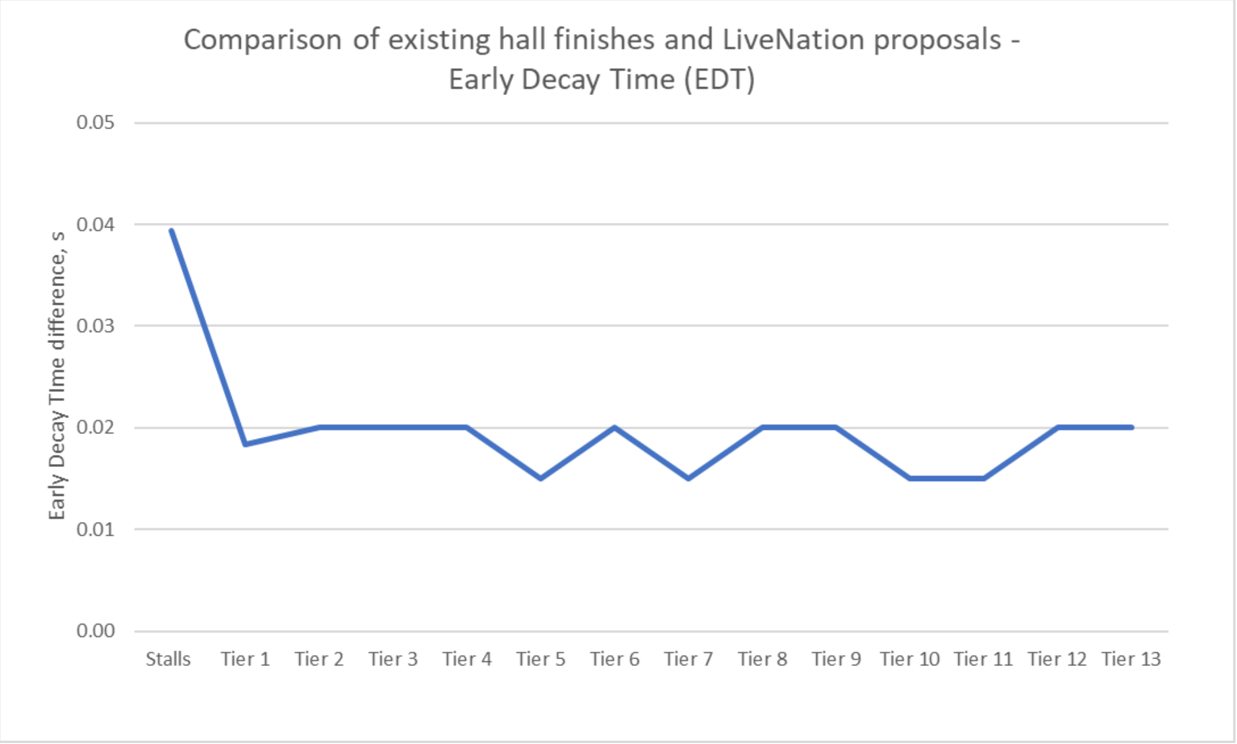

Figure 15 Relative difference in Early Decay Time (EDT) for LiveNation proposals in each zone

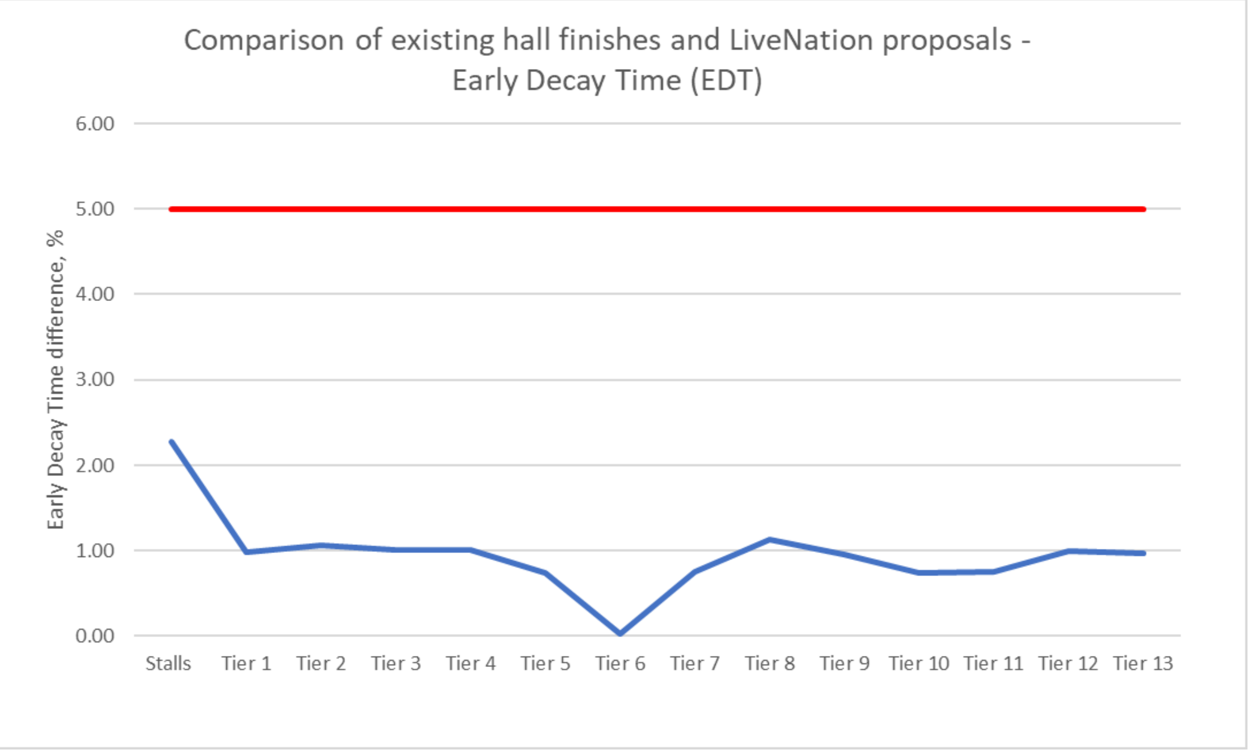

Figure 16 Relative difference in Early Decay Time (EDT) for LiveNation proposals in each zone – Percentage

4.4 Clarity

Clarity relates to the perceived clarity of sound within a space. It is a ratio of the amount of sound arriving before 80 milliseconds, compared to after 80 milliseconds.

Figure 17 shows the relative difference in musical Clarity (C_{80}) between the current simulated acoustic conditions and the LiveNation proposals, across the hall. Note that the results show the LiveNation proposals relative to the existing conditions and a negative value indicates improved Clarity from the LiveNation proposals.

The relative difference in Clarity (C_{80}) between the current conditions and the LiveNation proposals is less than 0.2 dB and typically less than 0.1 dB and this is well below the JND for Clarity of 1 dB, which is shown as a red line in Figure 17.

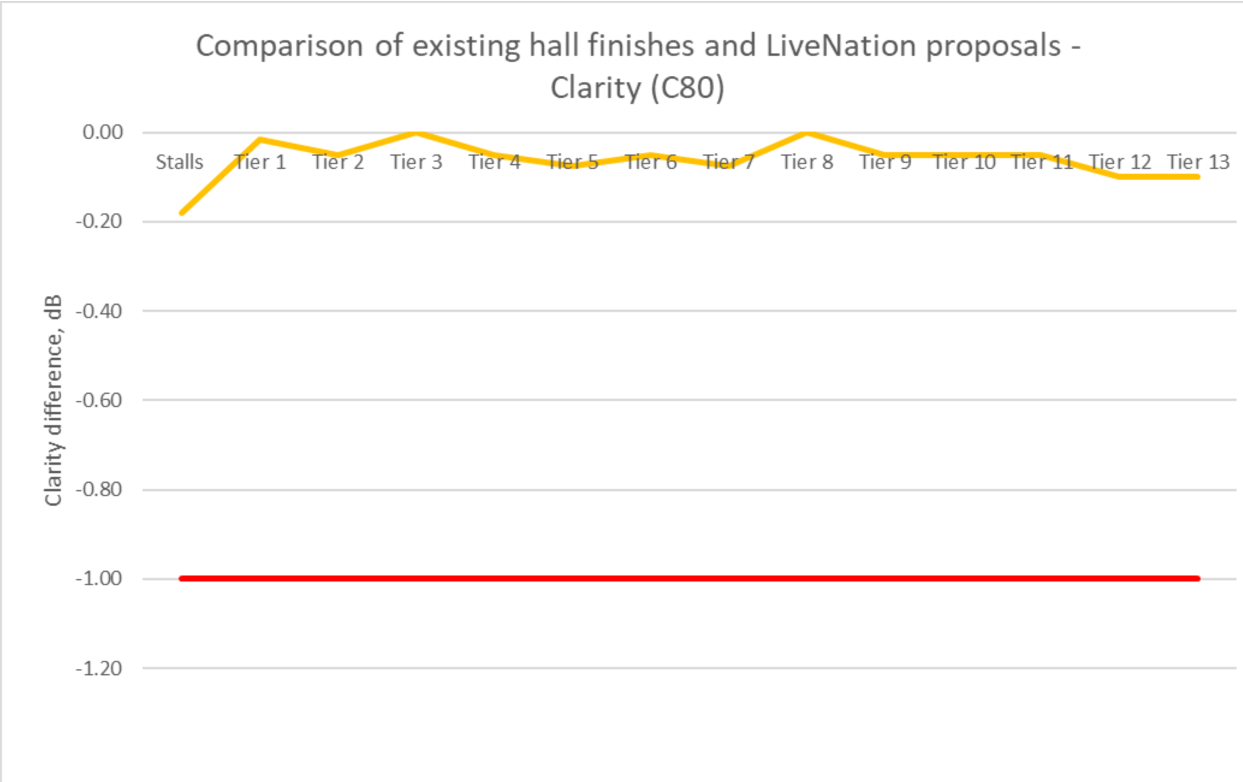

Figure 17 Relative difference in Musical Clarity (C_{80}) for LiveNation proposals in each zone

4.5 Speech intelligibility

Speech Transmission Index (STI) is a measure of the transmission quality of speech with respect to intelligibility, ie, how easy it is to understand speech. It varies on a scale from 0 to 1 which is shown visually in Figure 18.

When the Speech Transmission Index is measured through a public address system it is known as STIPA.

Figure 18 classification of Speech Transmission Index on a scale of 0 to 1

The largest variation in STI between the simulated current finishes in the hall and the LiveNation proposals was 0.01 and this occurred in two stalls areas. Typically, the variation is close to zero.

This indicates that there is little to no expected change in speech intelligibility for the unamplified acoustic conditions within the hall.

5 Discussion

The modelling results in Section 4 show that there is little predicted difference between the current simulated unamplified acoustic conditions within the hall and the conditions if the LiveNation proposals are adopted.

As expected, the largest differences are predicted in the stalls, where the changes are being made.

5.1 Assessment

The relative differences predicted by the acoustic model are all comfortably within the Just Noticeable Differences, including in the stalls.

Reverberance is predicted to increase by around 2% in the stalls and by 1% elsewhere, well within the 5% to make a Just Noticeable Difference.

Clarity is expected to reduce by around 0.2 dB in the stalls and by 0.1 dB elsewhere, well within the 1 dB reduction required to make a Just Noticeable Difference.

The Speech Intelligibility (STI) is predicted to reduce by less than 0.01, ie within the 0.03 required to make a Just Noticeable Difference. This is not an important result because intelligibility of unamplified speech is not a key requirement for speech, which is expected to be delivered through a new in-house PA system.

5.2 Occupied hall

The modelling exercise has looked at the effect on the acoustics of the hall when unoccupied, taking into account benchmark tests in the unoccupied hall.

When the hall is occupied, any effect of the changed seating and floor finish in the stalls area is likely to be reduced, as the absorption provided by an audience will essentially be the same before and after the changes.

We believe it is unlikely that an unamplified classical music event would take place with an audience in the tiers but not in the stalls, so the situations in which any adverse effect of the proposed alterations seem unlikely.

The changes are unlikely to have any adverse effect on amplified events, both music and speech based, where the main factor will be the success the new PA system.

6 PA system

The speech intelligibility in the hall using the existing in-house PA system was measured to be generally 0.45 – 0.6, ie, 'Fair' (see Figure 18).

A new in-house system should be capable of increasing the intelligibility to at least 'Good' (0.6-0.75) throughout but achieving Excellent (>0.75) is less likely, primarily due to the high reverberation time in the hall (rather than high background noise) and the distances from the loudspeakers to the seats.

Reducing the distances between the loudspeakers and seats as far as possible and having good coverage of speakers over all the seating tiers will be the main driver for this, however loudspeaker positions will likely be governed by architectural considerations (eg, rigging points and sightlines).

The natural reverberation time (T_{30}) of the hall is around 2.0 s, which results in pleasant natural acoustic conditions within the hall but may be too long for amplified acoustic performances. To reduce the reverberation time additional acoustic absorption could be added to the hall in the form of suspended drapes.

Any proposed drapes should be removable and capable of being stored away when not in use, as such drapes will provide additional absorption which is likely to reduce the reverberation time, even if retracted.

7 Recommendations

7.1 New stalls floor build-up

One of the risks of the proposals is that the precise sound absorption being provided by the stalls flooring is unknown, particularly at low frequency.

One feature of the hall is that it does not have a significant bass rise in reverberation but is relatively flat with respect to frequency. The hall could be described as lacking in ‘warmth’, although we are not aware of such criticism.

Changing the floor build-up significantly risks changing the absorption of a relatively large surface area. If the new floor were to absorb more low frequency sound than the existing, this could further reduce reverberation time at low frequency, which could be detrimental.

Conversely, if the new floor build-up absorbs less low frequency energy, a rise in reverberation time is possible, although a small degree of rise is unlikely to be detrimental.

On balance, a like-for-like type replacement is recommended, and the current proposal of 30 mm birch ply on a timber build-up is a sensible approach, as this will likely be similar to the existing parquet flooring which is likely to be on a base timber layer.

We recommend the existing build-up be checked and the final decision on the floor build-up be based on the findings.

If the void depth between the underside of the birch ply and the solid surface below is likely to be larger than the existing void depth in the existing floor build-up, we recommend the void be filled with 100 mm rockwool insulation.

7.1.1 Flat floor in front of the stage

Similarly, a like for like replacement is recommended in the flat floor area in front of the stage. Figure 3 (bottom left corner) shows new floor boarding on timber battens. This flooring should also be at least 30 mm thick birch ply, battens should be at no more than 600 mm centres, and the void below should be filled with mineral wool insulation.

7.2 Seating

All new seating should have the minimum sound absorption coefficients shown in Table 1.

We also recommend the underside of the seat pans be fabric covered to match the existing and minimise the risk of any reflections off the underside of unoccupied seats.

7.3 New stage drape

A new blackout cloth and associated rigging is proposed.

It is recommended that this be a heavy wool serge type material with a weight of at least 500g/m^2.

7.4 Contract specification text

It is recommended that specification language is added to the LiveNation contract to ensure the unamplified acoustic performance of the hall is not significantly altered.

Items that should be addressed are:

- Quality of build language: The new floor should be installed so as to ensure that it does not ‘squeak’ or ‘creak’ when walked on
- The stalls flooring shall be replaced on a ‘like for like’ basis
- The Stage build up shall not be significantly altered and any minor changes must be on a ‘like for like’ basis
- The new PA system should aim to provide an STI of at least 0.6 ‘Good’ at all seats in the hall
- No equipment shall be permanently installed that causes a noise level above NR20 at any seat in the hall.

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