USING NON-WAVE BASED MODELLING TO EXPLORE HOW MUCH ACOUSTIC DIFFUSION IS TOO MUCH IN A CONCERT HALL

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1 INTRODUCTION

This paper explores the relationship between acoustic surface diffusion and acoustical character in concert halls by using geometric modelling. Measurements were undertaken in a small concert hall to use as a baseline, which is then transferred into ODEON to experiment with the acoustic parameters further. Using the ODEON modelling results, the relationship between amount of diffusion vs scattering coefficient to achieve optimal objective parameters in a concert hall according were visualised. These trends were then tested on existing famous concert hall models.

2 EXISTING KNOWLEDGE

2.1 Diffusion in Auditoria

In concert halls and performance spaces, acoustic diffusion is an important aspect of the room. It will provide diffuse reflections across all angles, reducing unwanted strong reflections or focusing. However, in modern concert hall design, there is more and more diffusion being added, with some new halls having almost all surfaces diffuse, such as the Elbphilharmonie in Hamburg. Recent research has shown that engaging concert hall acoustics are made up of temporal envelope preserving reflections, which means that rooms are identified by the strong early reflections[1]. This relies on the early acoustic signature of the hall and less on the diffuse and reverberant sound field. Therefore, too much surface diffusion can reduce the effect of this early acoustic signature, which in turn can make the acoustics of the hall less engaging.

Reflections from textured surfaces at least partly follow Lambert's law of reflecting acoustic energy to all directions irrespective of angle of incidence. They therefore tend to "hold" acoustic energy close to the stage, as surfaces closer to the stage more strongly irradiate than surfaces further away[2]. When measuring in real halls however, a decrease in variation of reverberation time with increased diffusion is shown. Conversely, a higher variation in sound strength, relating to source-receiver distance, when there is an increase in diffuse surface texture.

Measurements of both speech and sound were undertaken by Wettschurek in the 1970s, testing the perception thresholds of early reflections using a binaural virtual acoustics system[3]. Wettschurek's research showed that when the perception threshold measurements were being undertaken, reflections at different delay times and directions had very different subjective effects[3]. Additionally, the overall listening level had an influence on the subjective quality, even when the reflection level was close to the perception threshold[4]. An example of this is during a musical crescendo, the side reflections are more perceivable than the frontal or rear reflections. Therefore, this research is consistent with the listening experience, and that concert halls lacking lateral reflections also typically exhibit poor dynamic spatial responsiveness[4]. This is a prime example of too much diffusion in a concert hall being a negative feature, as the early reflections will not be as strong as the reverberant and diffuse sound field. On the other hand, in Mike Barron's research he states that overall, the diffuse sound field with a suitable reverberation time is likely to offer good acoustics[5]. However, subjective diffusion (i.e., envelopment in the listeners position) and good values for strength and clarity can be achieved in other ways, without need the space to be physically highly diffuse[5].

2.2 Simulating Diffusion in Computer Models

In order to easily predict and design a hall with regards to diffusion, computer models can be used. Computer models have been used in this research using data based on physical measurements taken in the small concert hall. Ray-based methods such as ray tracing and radiosity are considerably faster and less computationally expensive than wave-based methods. However, the negatives include the loss of accuracy in low frequencies and the wave nature of sound demonstrated in phenomena (e.g., diffraction) not being considered[6]. The ray tracing method uses a large number of particles, which are emitted in various directions from a source point. These particles are then traced across a room, and lose energy at each reflection, dependent of the absorption coefficient of each surface[7].

2.2.1 ODEON modelling

The ODEON computer model for acoustics in auditoria is intended for use both in design (by quickly predicting room acoustical indices) and in research (by forming the bases of an auralisation system and promoting the study of various phenomena in room acoustics). Both conflicting demands use either image source methods or particle tracing methods, as described above. Therefore, ODEON uses a hybrid model, in which rays discover potential image sources up to a specified transition time or order. Then, the same ray-based process is used in a different way to deal with late reflections and generate a dense reverberant decay[8]. This hybrid method uses a combination of ray tracing and a secondary source method for more accurate calculation of the late reflections. The rays are considered carriers of patches of acoustic energy, which is reduced after each reflection of the ray according to the absorption coefficients of the surfaces; the secondary sources are located in each reflection point during the ray tracing. Every receiver point in a room subsequently gathers data from all the sound energy from all visible secondary sources in the room. In combination with the Vector based scattering this method has proven to be very efficient, especially in complicated room geometries[7].

Therefore, for the positives described with the ray-based methods, particularly in ODEON, and the negatives of wave-based predictions methods, including cost and availability of software for this project, ODEON will be used to complete the acoustic modelling experiments in this project.

3 METHODOLOGY

3.1 Baseline Concert Hall Testing

The acoustics of a small concert hall in London (volume of 680m3) were measured to provide accurate data for a baseline model to undertake further experiments on. The idea was to measure across the whole audience area at positions that could be replicated in a computer model. In addition to measuring the acoustics of the hall with all the diffuse wooden wall panels exposed, i.e., in the halls natural state, comparative measurements were made using the exact same technique and locations, with the removable drapes being drawn across the side walls. These measurements would then give a clear indication of the effects of the side wall surface diffusivity, as well as the overall reverberation time of the hall.

Even though the majority of acoustic parameters could be measured by a single omni-directional microphone, measurements with extra channels could yield extra spatial information. Therefore, a secondary condenser microphone was used in a figure-of-8 pickup mode, to measure the lateral energy fractions. The microphones were set up adjacently with the omni-directional microphone on top, to ensure minimal disruption of either microphones to the other ones, and to ensure different room modes would be as minimal as possible. This technique enabled the comparison in time of the early sound waves arriving at the omni-directional microphone, with the reflections arriving from the side, due to the figure-of-8 microphone facing the side walls and creating a null point in the pickup pattern facing the stage and rear wall.

3.2 Computer Modelling Experiments

Once the real-world hall had been measured, the subsequent step in the project was to create a computer acoustic model, replicating the acoustic parameters of the real-world example hall measured, in order to experiment further. Models were initially created in Sketchup, and subsequently loaded into ODEON for further testing.

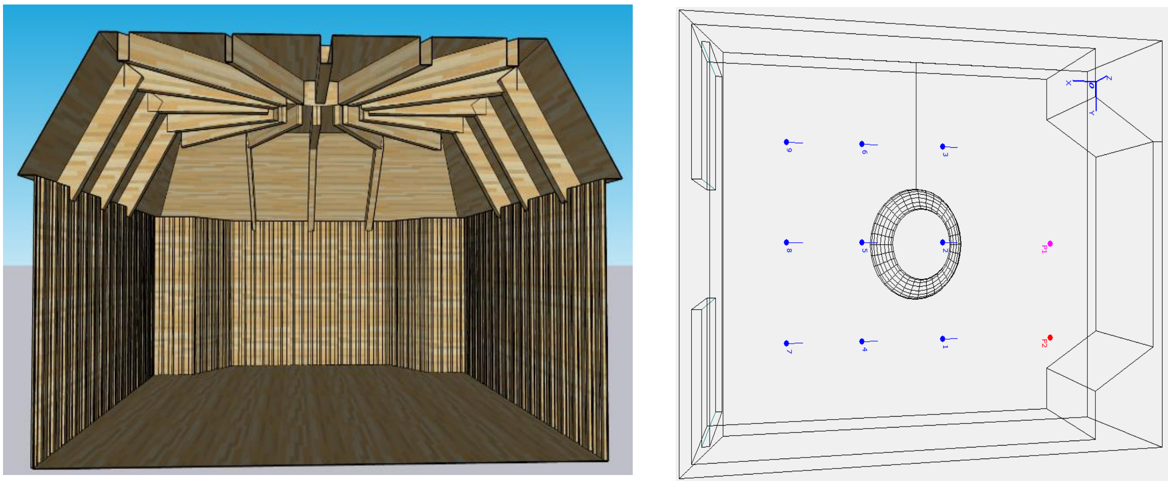

Figure 1 – Diffuse Wall Sketchup Model (left), Odeon model (right)

The first exercise in ODEON was to replicate the real-world conditions in the simulated model. The modelling parameters were set up as below, with a high number of late rays, and an impulse length of 3 seconds, to ensure that the model would be as accurate as possible. An additional number of late rays could be added, but this slows down the computer processing and leads to being able to complete less variations/experiments.

These base models were then run and experimented with until they gave similar and representative results of the real-world measurements. Several scenarios were undertaken, which included comparison of the two base models (Flat or Diffuse), comparison of drapes and no drapes, and comparison of different scattering coefficients in different key locations in the hall. As will be explained in the discussion, the flat wall model scenario gave more accurate results than the diffuse base model, and therefore was used for the further testing scenarios, experimenting with both amount of scattering, and location of scattering surfaces.

Three existing European concert halls were chosen to undertake the further modelling of diffusion. Instead of using only subjectively "good" concert halls, all of a similar geometry, it was decided to understand what role diffusion plays in subjectively "bad" concert halls, so a wider range of halls were used. The two subjectively "good" concert halls used were the Grosser Musikvereinssaal in Vienna, and the Concertgebouw in Amsterdam, which are rated by Beranek's research as the 1st and 5th best halls respectively. On the other hand, according to Beranek's research, the Barbican Large Concert Hall in London, is subjectively the 3rd least popular hall[9].

Similarly, a number of modelling scenarios were undertaken for each hall. Firstly, the amount of current diffusion in the hall as modelling was calculated (typically between 20-23% of surfaces at 0.7 scattering coefficient), which formed the basis of the experiments. The absorption coefficients in the model included all seats, drapes, flooring, and walls etc, and were not altered to keep the consistency of the models. Further modelling scenarios were run for all three existing concert halls to understand the impact of diffusion in the hall and testing the relationship (as discussed later in the results) of the % of surfaces required to obtain subjectively good parameters.

The location of diffusion and highly scattering areas greatly impacts effects of diffusion. Therefore, to obtain accurate results, rational and prudent thought had to be administered to decide which areas to increase the scattering coefficients, which would have the greatest impact in the hall. These mainly included the side and rear walls, ceilings and sometimes audience areas. Therefore, areas such as the stage shell and balcony areas etc were not altered, as these would not have had as great an effect on the main audience areas and receivers. As a result of all the modelling scenarios considered in this project, the trends were gathered to create a visual representation of the relationship between amount of diffusion vs scattering coefficient to achieve optimal objective parameters in a concert hall according to the ODEON modelling, with the flexibility of around +/-5%.

4 RESULTS

Figure 2 below presents the comparison of real-world measurements and base models, typically using ODEON Test models 1 (flat walls with scattering), and 3 (Diffuse walls with no scattering).

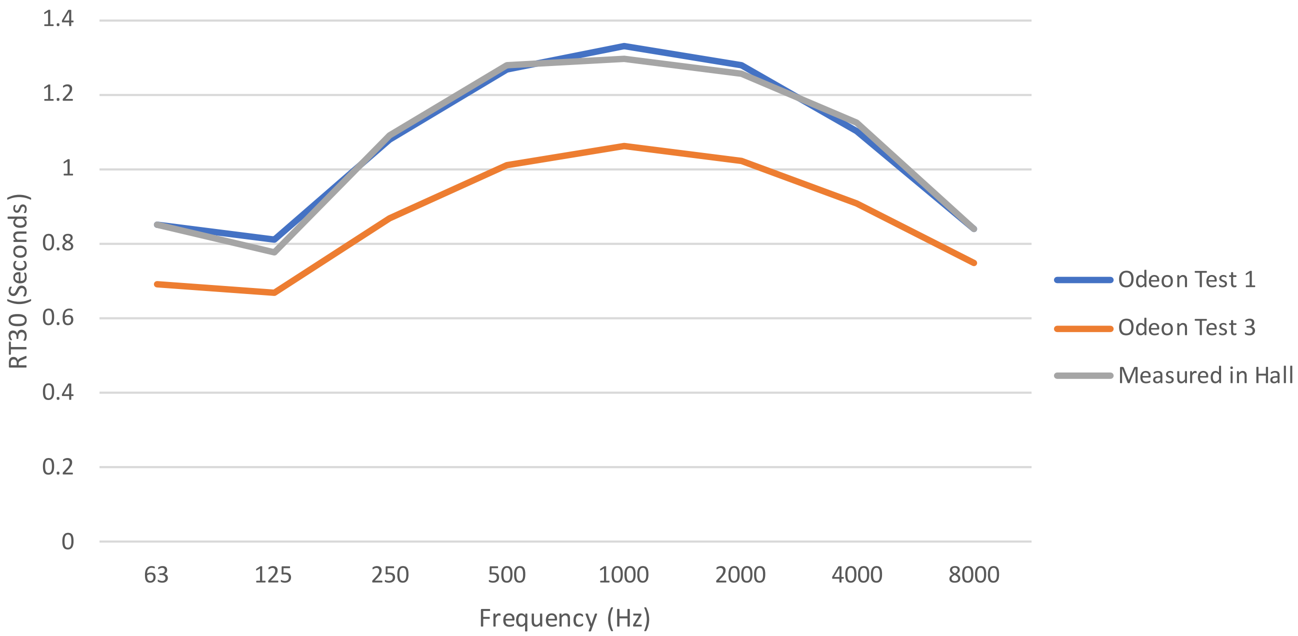

Figure 2 - RT30 Comparison between Real Measurements and both Flat and Diffuse Base Models

The modelling results in the “flat-walled” hall are very similar to the measurements made in the real-world hall with regards to RT and EDT. This is due to the model having a similar amount of diffusion and an almost identical volume/surface area, therefore ODEON in this case can be trusted as producing realistic results. On the other hand, the RT and EDT measured in the geometrically “diffuse wall” model with no added scattering, are around 0.2 seconds lower, particularly in the mid frequencies.

Figure 3 below present the effects of the location of highly diffuse surfaces around the flat-walled base model, as single figure averages. The amount of diffusion rather than location was the main factor for reverberation time, with the RT gradually increasing with added diffusion. The EDT stayed consistent through all variations (ranging from 1.23-1.25 seconds), which is negligible.

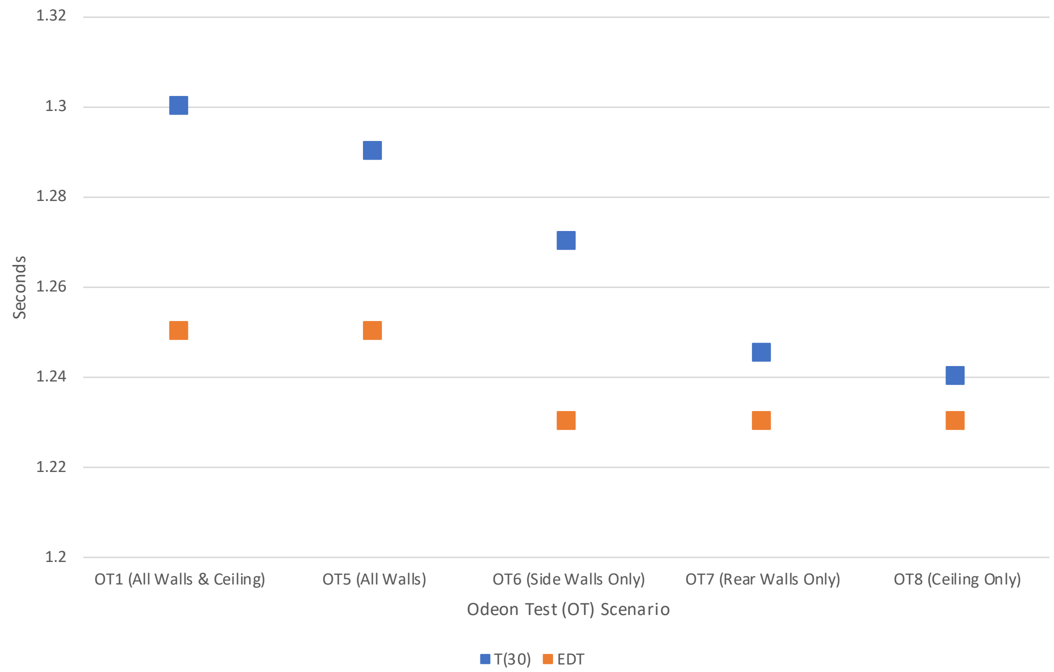

Figure 3 - Placement of Diffusion Averages - RT30 & EDT

Figure 4 below presents the effects of the amount of diffusion in the flat walled base model, as single figure averages. The RT and EDT as expected reduces when the scattering coefficient increases and is longer when the scattering coefficient is reduced.

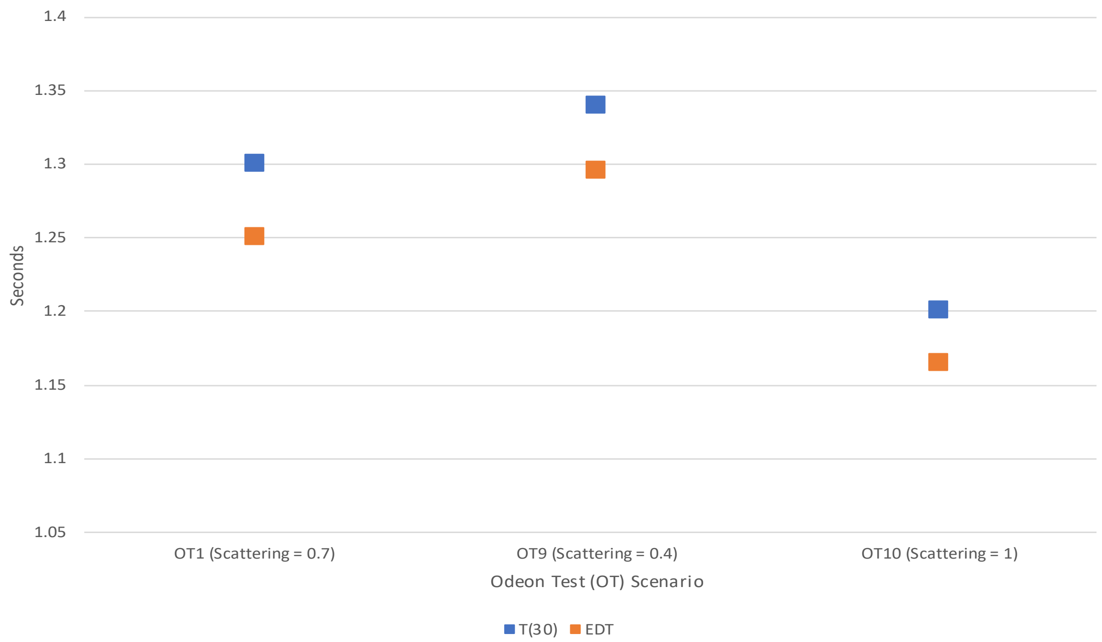

Figure 4 - Amount of Diffusion/Scattering Averages - RT30 & EDT

4.1 Final Relationship / Formula

As a result of all the previous modelling scenarios presented above, the trends were gathered to create a visual representation of the relationship between amount of diffusion vs scattering coefficient to achieve optimal objective parameters in a concert hall, according to the ODEON modelling, with the flexibility of around +/-5%. The relationship presented below in Figure 5 has been created by modelling many variations of the base models to match up to the real-world measurements. As presented in the graphs above, different scenarios have been modelled with ranging amounts of diffuse surface areas, to the amount of scattering per diffuse area. Numerous iterations of the model were experimented with by gradually increasing and decreasing diffusion parameters in the hall. The trend line presented below shows the percentages required to achieve the objective parameters in the small concert hall measured in the real-world scenario – which are considered subjectively good acoustics and therefore a satisfactory target for other concert hall designs.

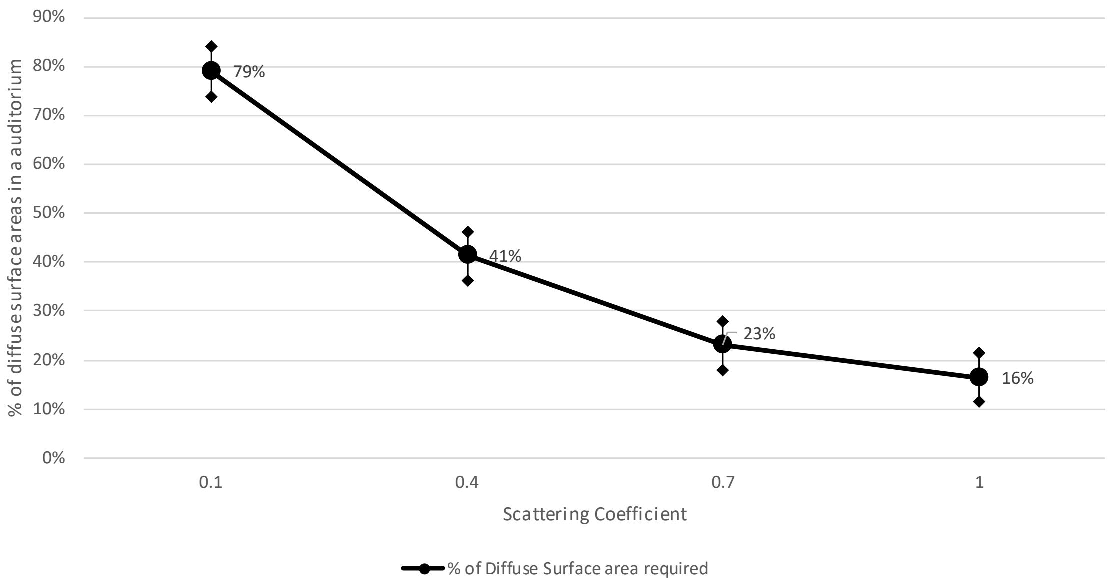

Figure 5 - Relationship between amount of Diffusion vs Scattering Coefficient to achieve optimal objective parameters in a concert hall.

4.2 Existing Concert Hall Results

As a result of the ODEON modelling, the relationship presented in Figure 5 above was tested on three existing concert halls. The results of which are presented in the tables below:

Table 1 - ODEON Modelling Results Summary of Test Scenarios 11-15 in the Musikvereinssaal

	Test Scenario	T30	EDT	C(80)	LF(80)
Musikvere-inssaal	OT11 – As modelled (23% at 0.7)	2.95	2.8	-2.20	0.194
	OT12 – 20% more (42% at 0.7)	2.90	2.9	-2.20	0.198
	OT13 – 20% less (2% total at 0.7)	2.99	3.0	-2.00	0.194
	OT14 – 41% at 0.4 (testing theory)	2.83	2.8	-2.30	0.195
	OT15 – 16% at 1 (testing theory)	2.85	2.9	-1.90	0.193
Concertge-bouw	OT11 – As modelled (20% at 0.7)	2.64	2.6	-2.80	0.130
	OT12 – 20% more (40% at 0.7)	2.56	2.6	-2.60	0.131
	OT13 – 20% less (0% total at 0.7)	2.71	2.6	-2.30	0.125
	OT14 – 41% at 0.4 (testing theory)	2.56	2.6	-2.30	0.126
	OT15 – 16% at 1 (testing theory)	2.54	2.6	-2.00	0.125
Barbican Concert Hall	OT11 – As modelled (20% at 0.7)	1.76	1.8	-0.80	0.153
	OT12 – 20% more (40% at 0.7)	1.83	1.9	-0.70	0.156
	OT13 – 20% less (0% total at 0.7)	1.96	1.9	-0.80	0.146
	OT14 – 41% at 0.4 (testing theory)	1.79	1.8	-0.40	0.154
	OT15 – 16% at 1 (testing theory)	1.96	1.9	-0.80	0.173

5 DISCUSSION

In concert halls and performance spaces, acoustic diffusion is an important aspect of the room, as it will provide diffuse reflections across all angles, reducing unwanted strong reflections or focusing. However, too much surface diffusion can reduce the effect of this early acoustic signature, which in turn can make the acoustics of the hall less engaging.

Results from both measurements of the real-world small concert hall and computer simulated acoustic models have presented trends that reinforce the theories described above.

Overall, the real-world small concert hall measured for this project presented desirable results for a hall of its size, with the exception of envelopment (LF80). In this hall, the main question asked in this project of ‘how much is too much diffusion’, A potential conclusion is that this hall has too much diffusion, as the listener envelopment suffers as a direct result of the diffuse surface textures and lack of strong side and rear wall reflections.

The calculation results of ODEON are comparable with real-world measurements when considering RT, EDT and C80. However, the comparison of the real-world small concert hall to the ODEON base models, and to an extent the larger existing concert hall model, lacked consistency when modelling listener envelopment (LF80). This potentially could either be an anomaly in either the ODEON measurement software, or in its calculation programming.

The results of the Musikvereinssaal ODEON modelling showed little variation of RT, EDT, C80 and LF80. On the other hand, for the Concertgebouw, the variations were slightly larger, particularly for clarity and envelopment, however all still less than the just noticeable difference limits. This is likely a result of the volume of the larger volume of the Concertgebouw and therefore objective parameters can vary across the larger space. For these two models, the results suggest that in these subjectively good concert halls, the amount of diffusion has less of an impact than the level of scattering coefficients for these featured diffuse surfaces.

Test results of the scattering coefficient vs amount of diffusion relationship in the Barbican Hall, however, did show greater variance, compared to the other two concert halls. In particular, the LF80, ranged between 0.14 to 0.17 when different amounts of scattering coefficients were added to the model. Potentially this may be a result of diffusion having a greater impact in this subjectively “bad” concert hall, due to other issues such as volume and room geometry.

With regards to the location of diffuse surfaces in concert halls, according to the ODEON results, having diffuse surfaces on the main side walls and ceilings detrimentally impacts the clarity and envelopment for the receiver, as a result of the lack of clear strong reflections from the stage.

The results of experimenting with scattering coefficients showed that the relationship between scattering coefficient levels to the amount of diffuse surfaces is not linear, and less diffuse surfaces with a higher scattering coefficient has more of an effect on the listener experience in a hall then a more diffuse surfaces with a lower scattering coefficient.

Therefore, when considering how much diffusion is too much in a concert hall, the statistical amount of diffusion is less of a factor, when compared to retaining strong early reflections from side walls and ceilings and the amount of scattering provided by diffuse surfaces. For example, a hall with a high amount of diffusion, can still be a subjectively “good” hall, if it still has strong early reflections on the side walls and ceilings,(i.e., the Musikvereinssaal), when compared to a hall with geometry that does not provide strong lateral reflections, (i.e., the Barbican Concert Hall).

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