Acoustic Design for an Auditorium Project
Using Building Performance Simulation to Enhance Architectural Quality

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Abstract: This paper reports a consultancy work for an auditorium project. The consultancy work considers four important acoustic design issues for auditoria: volume and seats; control of reverberation time (RT); diffusion of sound; elimination of defects. Odeon 5.0 was used to simulate the reverberation time and sound propagation and diffusion. Case studies were used to discuss the simulation results and to propose design guidelines. For a small auditorium, the design recommendation is about how to minimize sound absorption and to achieve sufficient reverberation. Sound defects were found in the stage outlet and rear walls. The design recommendations based on the consultancy work helped architects improve their design and enhance architectural quality.

Keywords: Architectural acoustics; building performance simulation; auditorium; design quality.

1. Introduction

Contemporary architectural design is shifting from a prescriptive approach towards a performance based approach (Anderson, 2014). There is an intensive debate about the two approaches (Xie and Gou, 2017). The prescriptive is dogmatic, restricting creativity and cannot guarantee design quality or performance; while the performance based approach is using information technologies to encourage design innovation and predict design performance. On the other side, the prescriptive approach is easy to understand and operable for architects, while the performance based approach required special techniques which is beyond the capacity of architects. This paper demonstrates how building performance simulation helps architects in a heuristic approach. Particularly, this paper uses an interior design project for an auditorium as a case study. Auditorium required special consideration for acoustics. Being part of the design team, the authors used acoustic simulation to estimate the reverberation time and sound distribution. The authors also used case studies to discuss the design implications and to propose design recommendations.
2. The Auditorium Project

The project's client is Diocesan Boys' School (DBS) Hong Kong (Figure 1). The Diocesan Boys' School is one of the most prestigious boys' schools in Hong Kong, located at 131 Argyle Street of MongKok. Founded in 1869, it is one of the oldest secondary schools in the city. This prestigious private boys' academy in Hong Kong has become renowned for its music programs. The auditorium was to be built to accommodate the emerging needs of music performance. The architect is Thomas Chow Architects (TCA). The project has a very tight schedule so that in the early design stage, acoustics was not fully considered. The architects were not confident about its acoustic performance; therefore, the authors were invited to help them to verify their design and improve the design quality especially on architectural acoustics during the construction stage (Figure 2).

Figure 1: The location of the auditorium and the project under construction (photographed by the authors in 2012)

Figure 2: The project under construction (photographed by the authors in 2012)
3. Design Objectives

The acoustical environment for an auditorium project can be enhanced in following respects (Barron, 1993):

- The floor area and volume of the auditorium should be kept at a reasonable minimum for adequate loudness in every part of the auditorium.
- Optimum reverberation characteristics should be provided in the auditorium to facilitate whatever function is required.
- The sound energy should be uniformly distributed within the room.
- The room should be free from acoustical defects (distinct echoes, flutter echoes, picket fence echo, sound shadowing, room resonance, sound concentrations and excessive reverberation).

First of all, there should be adequate loudness in every part of the auditorium, especially in remote seats. The problems of providing adequate loudness result mainly from the inverse square law and excessive absorption by the audience attenuating the direct sound before it reaches the listener (Egan, 1988). Above all, the floor area and volume of the auditorium should be kept at a reasonable minimum, thus shortening the sound paths. The following table details recommended Volume-per-seat values for various auditoria (Table 1). The volume for the DBS auditorium is 7,324 m³ (The calculation was conducted in SketchUp 8.0). The total number of seats is 800. So, the Volume-per-Seat is 7,324 m³/800 = 9.2 m³. The value falls into the range for Concert Halls. For other criteria, the authors conducted building simulation to verify its performance.

<table>
<thead>
<tr>
<th>Type of Auditorium</th>
<th>Minimum</th>
<th>Optimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rooms for Speech</td>
<td>2.3</td>
<td>3.1</td>
<td>4.3</td>
</tr>
<tr>
<td>Concert Halls</td>
<td>6.2</td>
<td>7.8</td>
<td>10.8</td>
</tr>
<tr>
<td>Opera Houses</td>
<td>4.5</td>
<td>5.7</td>
<td>7.4</td>
</tr>
<tr>
<td>Catholic Churches</td>
<td>5.7</td>
<td>8.5</td>
<td>12</td>
</tr>
<tr>
<td>Other Churches</td>
<td>5.1</td>
<td>7.2</td>
<td>9.1</td>
</tr>
<tr>
<td>Multipurpose Halls</td>
<td>5.1</td>
<td>7.1</td>
<td>8.5</td>
</tr>
<tr>
<td>Cinemas</td>
<td>2.8</td>
<td>3.5</td>
<td>5.6</td>
</tr>
</tbody>
</table>

4. Building Simulation

4.1. Reverberation Time

Reverberation is the persistence of sound in a particular space after the original sound is removed (Meyer, 1978). Reverberation Time (RT) is the time required for reflections of a direct sound to decay by 60 dB below the level of the direct sound (Knudsen, 1932). For acoustic design, RT remains a prime consideration. Historically values between 1.0 and 1.5 seconds have prevailed (Olson, 1967). For the fullness of instrument playing, RT for symphony concert hall is usually higher than 1.5. For a concert hall, the RT should be between 1.4 and 1.7. The choice of appropriate RT for a recital hall is at the same time more difficult but less critical than for a full symphony concert hall. In a small hall, reflections arrive earlier and this means that maintaining satisfactory clarity should be less of a concern. The suitable choice of reverberation time, as it affects loudness, should therefore be less stringent in the smaller hall (Ham,
1987). For symphony concert halls, the recommended reverberation time is a function of programme only. Different sources in the literature give different recommendations and the final selected values should be influenced by experience of individual halls, as well as the acoustic intentions of the designers (Beranek, 2004). A shorter reverberation time will enhance musical definition. A long reverberation time will give a more sumptuous sound with better blend but less clarity.

Odeon 5.0 was used to estimate RTs in the DBS auditorium. The method estimates a mean absorption coefficient, which is inserted in the Sabine, Eyring and Arau-Puchades formulas to give an estimate of the reverberation time (Christensen, 2009). Instead of simply taking the areas of the surfaces and multiplying by the corresponding absorption coefficients to obtain the total absorption in the room, Odeon also sends out ‘particles’ from the source, assuming diffuse conditions thus reflecting them in random directions, keeping a count on how many times they hit each surface. Surfaces that are hit very often then carry greater weight in the overall mean absorption coefficient of the room. Surfaces, which are not detected at all in the ray-tracing process, are left out of all calculations and surfaces which are hit on both sides are included twice in the calculation. As a result the estimated reverberation time corresponds to the sub-volumes in which the selected source is located. Note however that if a part of the area of a surface, which is present in the sub-volume, is located outside that sub-volume (e.g. if two sub-volumes share the same floor surface) then area and surface estimates for the statistical calculations may not be entirely correct.

In Odeon, two mean absorption coefficients are inserted in the Sabine and Eyring formula to calculate reverberation times. The mean absorption coefficients used for the Arau-Puchades formula are derived in similar ways except that separate values for surface hits, area and the corresponding mean absorption coefficient are calculated as projections onto each of the main axis of the room. The DBS model was based on the architects’ design scheme and the principle of material selection is to minimize the sound absorption (Figure 3). The condition was the auditorium occupied (audience on the wooden chairs); one speaker was located in the center of the stage. The result was shown in Figure 4 (estimated RTs) and 5 (absorption sources). The estimated RT for the DBS auditorium at the mid-frequency (500 Hz) cannot fall in to the range 1.4 - 1.7 seconds. The RTs at the high-frequencies (1000 Hz, 2000 Hz etc.) are even lower than 1.0 seconds. Undoubtedly, the audience absorbed the largest part of sound; the ceiling in the wake of the audience. Considering the absorption due to audience that is hard to change, efforts should be made on the ceilings.

![Figure 3: Material settings for ceiling (top), walls (middle) and bottom (chairs)](image-url)
4.2. Sound Distribution

Averagely distributing sound energy is of importance to achieve a good acoustic design. In an enclosed space, the direct sound decreases in level in the same way as outside. Most of the sound energy we receive in enclosed spaces has been reflected by walls and ceiling surfaces. The geometries of reflection for light and sound are identical. The reflected wave behaves as if it had originated from the image position (Schultz and Watters, 1964). But, for sound, much larger surfaces are required owing to the much longer wavelengths involved. An acoustic mirror is a large, plane, massive surface of, for instance, concrete or timber. Sound reflected by one surface will continue to be reflected between the room surfaces, until its energy is removed by absorption. “3D Billiard” in the Odeon software was used to simulate the sound energy propagation and distribution. Figure 6 shows the result. One of outstanding issues is that the upper part of the stage obstructs the sound propagation to the audience. The direct sound (deep red balls) has not yet reached the rear wall, but some balls have been reflected eight times (green balls) in the stage. It means that the outlet of the stage needs acoustic treatment. Reflectors should be considered.
4.3. Sound Defects

Any time the surfaces of a room focus the sound which is reflected from them, they create spots of high intensity and other spots with low intensity. This is generally undesirable in an auditorium since we want a uniform, evenly dispersed sound to all listeners (Andrade, 1932). The “3D Billiard” again, is used to display sound effects such as scattering, flutter echoes or sound focusing. A number of billiard balls are emitted from the source and reflected by the surfaces in the room. To visualize any sound effect, a large number of billiard balls (10,000 balls) were used. The results are shown in Figure 7. As expected, the real walls of the stage contributed to a sound focusing in the front of the auditorium. The focused sound energy will cause sound distortion, which should be avoided. The main reason is that the real wall is concave. This form should be avoided in auditorium design.
5. Case Studies

Table 2 refers to several famous concert halls in the U.K (Barron, 1988, Barron, 1993). They are Wigmore Hall and Queen Elizabeth Hall in London, Maltings Concert Hall in Snape, and Music School Hall in Cambridge. The DBS case is very similar to the Maltings Concert Hall, Snape (around 800 seats and 7500 m3). The Maltings (a large complex of mid-nineteenth century) was converted into a concert by Arup in 1967. The simple lines and straightforward finishes in generous-size spaces offer a delightful environment for the high-quality music provided in this auditorium. The auditorium is rectangular in plan, using existing red brick walls which were grit-blasted and sealed. To achieve a suitable internal volume the walls were extended upwards 1 m. The roof structure was completely new with a 45° gabled section. For the roof, two layers of 25 mm tongued and grooved timber boarding were used, set at 45° relative to one another. The timber roof trusses and steel ties are all exposed on the auditorium interior, yet the construction is stiff enough to ensure little low-frequency absorption. In acoustic terms, the exposed roof elements can be expected to contribute to good diffusion. Use of seats without upholstery is unusual in modern auditoria, as it results in large changes of reverberation time with occupancy (Barron, 1988). The case study showcases a way for auditoria with small volumes to achieve good reverberation times. The DBS is suggested to increase the volume by enlarging and elevating the ceiling and roof.

Table 2: Case studies

<table>
<thead>
<tr>
<th>Concert Hall</th>
<th>Number of seats</th>
<th>Volume (m³)</th>
<th>RT (s)</th>
<th>Interiors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wigmore Hall, London</td>
<td>544</td>
<td>2900</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Queen Elizabeth Hall, London</td>
<td>1106</td>
<td>9600</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>Maltings Concert Hall, Snape</td>
<td>824</td>
<td>7590</td>
<td>1.6</td>
<td></td>
</tr>
</tbody>
</table>
We also proposed an over-stage reflector used in the selected projects to reflect sound onto the audience. It is due to the concern about inadequate clarity at the rear of the new large concert halls, but some acousticians criticized the harsh quality they imparted to the sound. In the Queen Elizabeth Hall the reflector is movable between a reflecting and non-reflecting position. Subjective tests conducted at the time of opening suggested that the audible effect of the reflector was small but that in general the preference was for the vertical, no-reflection condition. For solo piano, however, the reflector was favoured in its down position. The fact that the subjective effect of this reflector proved to be small is not wholly surprising given the relatively small size and narrow width of the wall, which creates other reflections of similar delay to that of the reflector. With a massive auditorium shell (the walls here are 375 mm thick concrete), the bass reverberation time will rise. For symphony concerts many consider this to be highly desirable but for chamber music the argument for a bass rise is less clear.

We also found sound focus due to the concave stage walls. This sound defect can be avoided by decorating the surfaces (using boundary element methods) of the concave walls to distribute the sound energy (Figure 8). Out of this technique have come ‘wavy’ surfaces optimized for their directional reflection characteristics (D’Antonio and Cox, 2000, Hargreaves et al., 2000). An impressive use of this technology also is shown in Figure 7. It is a scattering wall in a rehearsal hall with circular geometry in plan. The shape of the wall is based on a wave motif optimized for diffusion using boundary element techniques (Architects: Patel Taylor; acousticians: Arup Acoustics; diffuser design and installation: RPG) (Orlowski, 2000).

Figure 8: Rationale of focusing and distribution (Orlowski, 2000)
6. Design Recommendations

The research identifies the following key findings and design recommendations.

- The project is a small auditorium with volume at 7,324m³ and seats at 800. The experience learnt from small auditorium is to elevate the roof to increase the reverberation. The openings (holes) for daylight access in the DBS auditorium could be enlarged and elevated to increase the volume and consequently increase the RT.
- Reverberation Time was estimated under occupied conditions. The estimated RT was lower than the expected RT (1.4-1.7 s). The results show that the auditorium needs design on reducing absorption. Sound absorptions from ceilings and walls must be minimized during material selections.
- The sound diffusion in the DBS auditorium is not advantageous at the outlet of the stage. Reflectors should be placed to distribute the sound energy to the audience.
- Sound energy focusing was found in the front of the auditorium. The rear wall of the stage should be designed to avoid sound focusing. A scattering wall in a rehearsal hall was studied as a good example to shape the wall to “wavy” surfaces to suppress focusing caused by concave walls.

Based on the consultancy work the authors conducted, the architects completed the fit-out and interior system (Figure 9). First, the architects kept the interiors simple to maximize the volume, minimize the sound absorption and achieve appropriate reverberation time. There are no excessive decorative elements in the ceiling system or on the walls. The roof is exposed to the audience. This also benefits daylighting. Second, the architects changed the stage outlet to make it open and reflective. Over-stage reflectors were used to maximize early reflection towards audience. Third, the architects use timber panels to reshape the rear walls of the stage to minimize the sound focus and diffuse sound from the stage to the audience.

Figure 9: The completed project (courtesy of Thomas Chow Architects)

In this project, reverberation time is one of key design criteria for auditorium acoustics. A significant portion of the consultancy task is to achieve optimal reverberation time. Both prescriptive design
approaches such as checking seat-volume ratio and performance-based design approaches such as simulating reverberation time are used. Prescriptive design, as a traditional design method and rule of thumb, is of great important and useful in the very beginning of the design stage. Performance-based design using computer simulation can be instrumental in schematic design, especially material selection and interior installation and construction optimisation. In this study, the quality of the acoustics of an auditorium also covers the shape and size of the enclosure and related acoustical defects such as concentration and focus. Through the visualization of sound distribution, these defects can be detected. Actually, prescriptive approaches for acoustic design such as room geometrical analysis can also help architects to avoid sound defects such as echoes, dead spots and flutter. Preferably, the performance based approach can produce more evidence-based outcomes to convince architects and clients to improve their design and construction.

7. Conclusion

The performance studies in this project came to a late stage; so, some acoustic defects (such as sound focus due to the concave shape) were not avoided in the early design stage. Anyway, this project demonstrates how building performance studies can help architects enhance design quality. In response to the debate raised in the beginning of this paper, the authors believe that the building performance simulation indeed is an important instrument which should be used in architectural design and that the way of using building simulation should be heuristic instead of dogmatic, to truly help enhance the design quality.

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References