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Exploration of stage acoustic considerations with parametric tools during early design stages

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ABSTRACT

Traditional ray tracing software tools (e.g. Odeon, CATT-Acoustic, EASE) enable detailed analysis of stage acoustics; however, are typically undertaken in later design stages and lack the flexibility required for early design development. This paper assesses the use of three-dimensional modelling tools (Rhino/Grasshopper) to quickly assess the influence of architectural changes on reflections that support orchestral ensemble. This approach would enable immediate feedback, a more creative design process and better integration.

Early reflections have been found to be vital for effective orchestral ensemble. Therefore, the study focused on the investigation of early energy distribution on stage with ray tracing analysis using parametric tools (Rhino/Grasshopper). This approach also enables the consideration of effects from cross-stage shielding from the orchestra and directivity of instruments. The results have been compared to existing acoustic modelling tools to determine the accuracy and reliability.

Development of a Grasshopper design tool has been found to be beneficial in the analysis of stage conditions in the early design phase.

Keywords: stage acoustics, ensemble, grasshopper, acoustic architecture

1. INTRODUCTION

Auditorium stage design requires careful balancing of many stakeholders. While this is true for any venue, it is even more relevant for venues with complex stages or multipurpose halls with limited space and extensive onstage uses. In response to these challenges, an iterative design approach is often adopted by the architect and acoustician. The most successful of which, occurs in the early design phase while the design has scope to change.

While well-established ray tracing software tools (e.g. Odeon, CATT-Acoustic, EASE) enable detailed analysis of stage acoustics, this investigation is typically undertaken in later design stages due to the time invested in creating the acoustic model.

The use of parametric tools, like Grasshopper and Rhinoceros, to aid the design of concert venues is a well-established practice (1, 2). However, while these studies, and many more, explore the application of parametric design for optimisation of the hall from the audience perspective, much less work has been done on utilizing parametric design for acoustic stage design.

It should be noted that these parametric design tools are not intended to replace the well-established ray tracing software packages. But instead, aim to assess the use of three-dimensional (3D) architectural modelling tools, Rhinoceros and Grasshopper as integrated design tools within the early design phase.

This paper reviews how parametric tools can enable a dialogue between architectural and acoustic design to further support orchestral ensemble. To facilitate this, a ray tracing routine has been developed in Grasshopper. This research explores its ability to analyse the stage conditions, assess the acoustic effects of architectural interventions and investigate the effects of cross-stage shielding and directivity of instruments.

To assess the use of the routine, the stage conditions of two venues have been analysed: a simplified example of a multi-purpose hall, and one larger concert hall, the Perth Concert hall.

2. STAGE ACOUSTICS BACKGROUND

Early investigations and ongoing research of musician's preference on stage agrees that early sound reflections between musicians, within a temporal window, are essential for an effective orchestral ensemble. Experiments have shown that reflections arriving between 10ms and 40ms, relative from the direct sound, improve ensemble (8).

Many different approaches have been proposed to quantify orchestral ensemble. Stage support measurements (ST_{early} and ST_{late}) proposed by Gade (3) are commonly used and form part of ISO3382. Other parameters have been proposed to assess the cross-stage communication, such as the strength parameters G_{early} and $G_{7\text{-}50}$ by Dammerud (4) or the stage acoustic parameter for music conductors ($LQ_{7\text{-}40}$) by van den Braak et al. (5). Most recent research has focus in the arrival directionality of the early reflections across the stage and stage acoustics parameters such as $LQ_{7\text{-}40\ top/sides}$ by Guthrie (6) or $TS_{20\text{-}50}$ by Panton (7) have been proposed. These compare the sound energy received from above compared to the sides.

All these techniques focus on the early energy to quantify the stage acoustic conditions and ease of ensemble.

3. DEVELOPMENT OF A ROUTINE TO ESTIMATE EARLY ENERGY ON STAGE

It must be acknowledged that any modelling technique represents a simplification of real acoustic behaviour. As such, the appropriateness of a technique is largely dependent on the intended use. As discussed in previous sections, early sound energy, particularly frequencies between 500Hz, and 2 kHz, is vital for an effective orchestral ensemble (8). At these frequencies sound can be treated as rays. As such, ray tracing is widely accepted as a viable methodology for quantifying ensemble.

The ray-tracing routine developed by the authors generates in 'real-time' (or close to real-time) visual feedback of the early reflections between the source and receiver, alongside the energy of early reflections and an estimation of stage acoustic parameters. The routine allows to quickly output the effects in the early energy of architectural changes. The following sections provides a description of the routine's platform and outputs.

3.1 The platform

Nowadays, architectural concept models are prepared using 3D software such as Rhinoceros. Rhinoceros is a 3D modelling system widely used in architectural design, particularly in the early design phase. This shared platform advocates for Rhinoceros' use in the acoustic industry.

The routine/tool has been developed in Grasshopper, which is a visual scripting tool within the Rhinoceros platform is a program for designing models through the expression of parameters. As it is integrated within Rhinoceros, it allows 'real-time' manipulation of the Rhinoceros geometry. The acoustic plugin, Pachyderm, is also used to import the model geometry and undertake image source calculations.

3.2 Visual communication of the early reflections

The tool visually displays the reflections of sound through a 3D plot at the receiver's location (represented with thick spikes), and thin lines tracing the sound paths back to the source (Figure 1).

Similar to Marshall Day Acoustic's IRIS measurement software, a 3D plot shows the strength of the sound through the length of the spike (Figure 1). These spikes communicate the dominant reflections (compared to the direct level) and can be used to visually interrogate the strength, direction and delay of reflections.

Both the spikes and lines are coloured to represent the arrival time of the reflection, relative to the direct sound: where red is the direct path, orange is 'very early' energy (usually the floor bounce (0-7ms)), green is early energy (7 and 40ms), and blue is late energy (after 40ms). The time intervals given are typical examples but can be altered to calculate the chosen performance criteria.

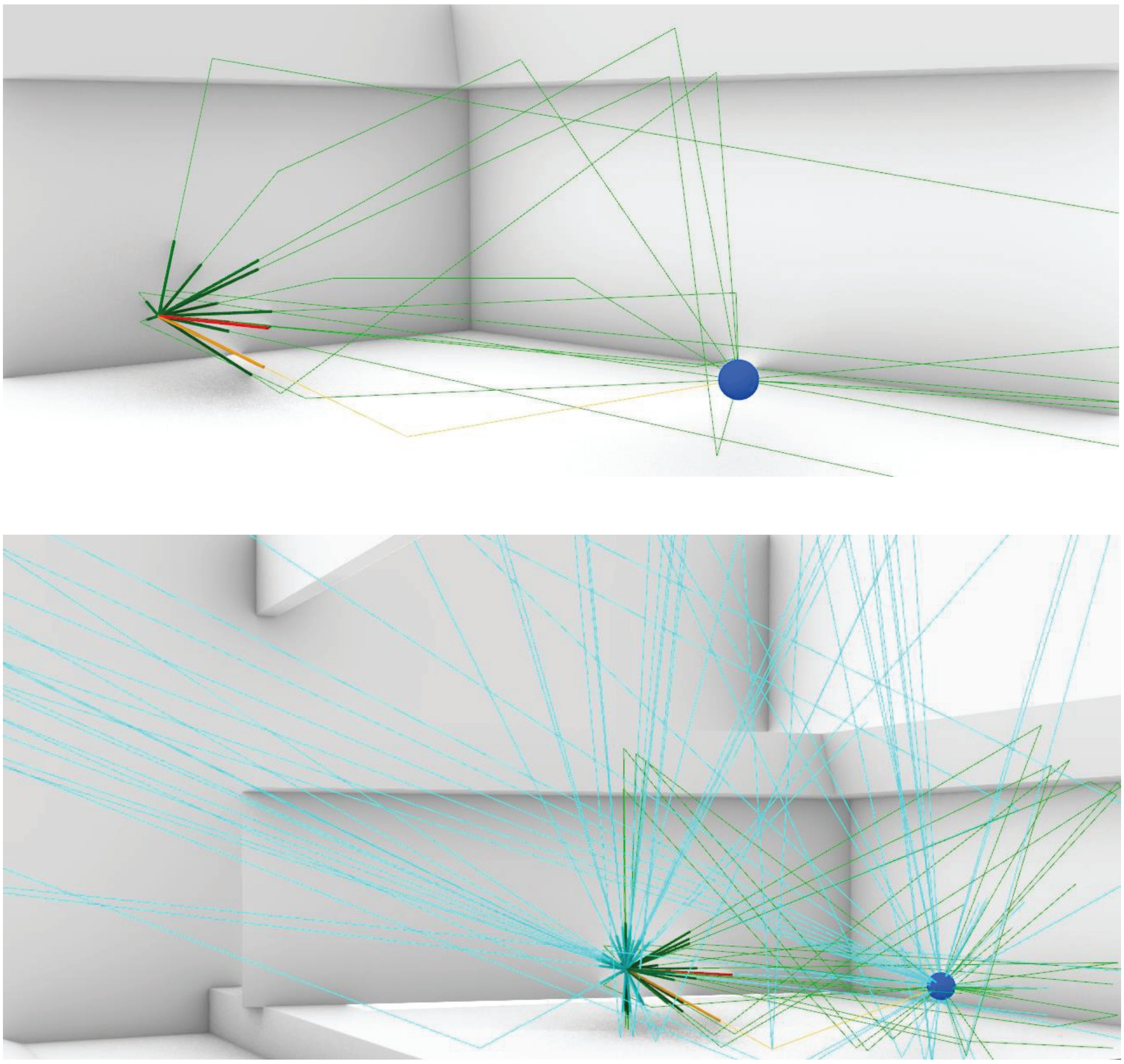

Figure 1 - Image source reflections between source (blue sphere) and receiver (combination of thick spikes)

The thin lines allow for reflections to be traced to the cause architectural geometry. Tracing back can be useful for diagnosing successful surfaces that should be promoted throughout the design, or problematic surfaces that require treatment.

3.3 Communicating numerically

The tool also calculates the energy of early reflections within the stage, to a maximum of third order reflections. Third order reflections are typically considered to be sufficient to calculate reflections within 100ms. As such, the early energy component of traditional stage acoustic parameters can be calculated. However, late energy cannot be calculated accurately without lengthening the computation time and reducing the effectiveness of the desired quick feedback.

While there a several different approaches, some stage acoustic parameters compare the early energy received with the total or late energy. This routine can only be used to assess the changes in the early part of these parameters, but not to obtain its total value which includes the late energy. However, stage acoustic parameters, such as ST_{early}, EEL, G_{early}, G_{7-50} (3, 4) do not take into account the late energy (> 100ms) and so can be successfully calculated with this routine.

4. ESTABLISHING AN ARCHITECTURAL/ACOUSTIC DIALOGUE

The routine can be used to assess architectural elements, describe the acoustic effects of architectural changes to a client or architect, or study the acoustic effects of the source directivity and shielding for occupied stages. This section discusses a few case studies, exploring the uses of the developed routine.

4.1 Assessing architectural elements visually

The routine can be used to review existing stage conditions by quickly identifying which architectural elements provide early reflections within the stage environment. This section shows key acoustic features of the Perth Concert Hall stage environment.

Perth Concert Hall is a 1727 seat hall in Western Australia. It is a rectangular hall with the stage surrounded on three sides with 3.5m high walls and convex balcony fronts. The ceiling is located approximately 18m above the stage. Ceiling reflections are diffused due to the coffered ceiling.

As shown in Figure 2 the balcony fronts provide early reflections to the orchestra from above. Furthermore, with the balconies offsetting to the stage, the underside of the balcony fronts and walls also provide cornice early reflections.

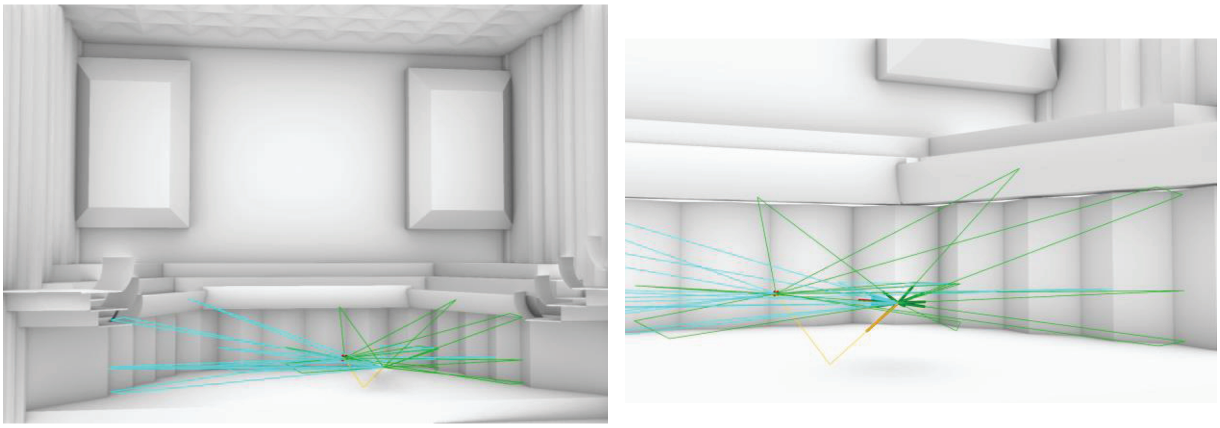

Figure 2 - Perth Concert Hall

4.2 Effect of architectural changes

In a workshop, the architect and acoustician use a 3D model to test possible design directions. As such, it is powerful to have a tool that provides immediate acoustic feedback to these changes.

This routine visualises the effect of architectural changes and communicates them in a shared language. Expressing complex relationships between surfaces in a simple and easy to digest medium, reduces the barrier to entry and advocates for a collaborative design approach. An example of a typical early design change could be making changes to a reflector. Altering the location, size or angle can be easily done within Rhino/Grasshopper. The routine then immediately visualises the sound reflections so that the impact of the change can be understood. In contrast, a more detailed modelling tool could be used, however, time would be taken in converting the model and the immediacy and momentum of the workshop would be lost.

A simplified multipurpose hall's stage has been used to assess the acoustic implications of architectural changes around the stage. This research explored the implications of the inclusion of an orchestra shell and stage risers.

A representative sample of sources and receivers have been chosen to analyse the stage conditions for different orchestra members. A simplified representation of an orchestra is shown in Figure 3and the source/receiver positions chosen for this study are shown in red: 1st Violin, Viola, Flute, French Horn, Trumpet, Bassoon, Cello, Oboe and Conductor.

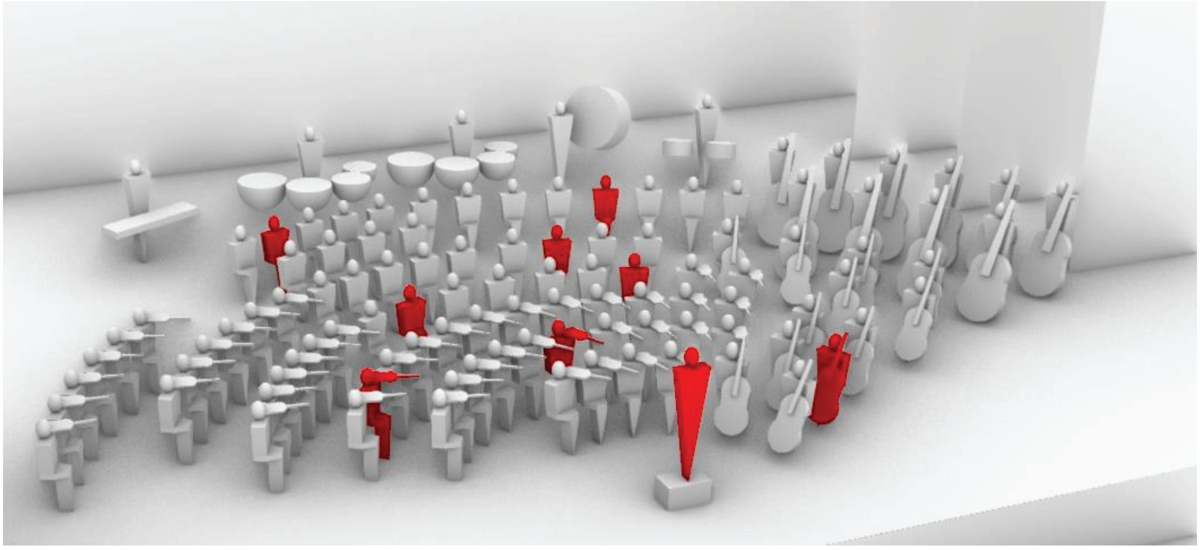

Figure 3 - A representative sample of sources and receivers highlighted in red

4.2.1 Introducing an orchestra shell

Incorporating an orchestra shell into a multipurpose hall is a typical design solution for increasing early reflections on stage. However, this case study is intended to illustrate the ability of the routine to provide immediate visual and statistical feedback to the architect and client. As discussed earlier, this direct feedback is powerful when communicating design intent and advocating for change in a design workshop.

As shown in Figure 4 below, the modelled stage with a large open proscenium and no orchestra shell (left) provides few useful early reflections (green). In most locations no early reflections are received within the desired time interval. However, the inclusion of the orchestra shell (right) provides a good level of early reflections from above, which facilitate support and cross-stage communication.

The difference of early energy between with and without orchestra shell can also be seen in the 3D receiver shown in Figure 4 and enlarged in Figure 5.

These visual plots quickly communicate the change in stage environment to the architect or client in a form that they can understand and interrogate. For example, when comparing the two plots, it can be seen that a larger number of spikes arrive from above and approximately 45 degrees to the right. These extra rays represent the overhead and cornice reflections from the shell's overhead/side walls panels. These reflections can be seen in the wider traced rays. This inherent visual nature of the tool is far more digestible for a client or architect.

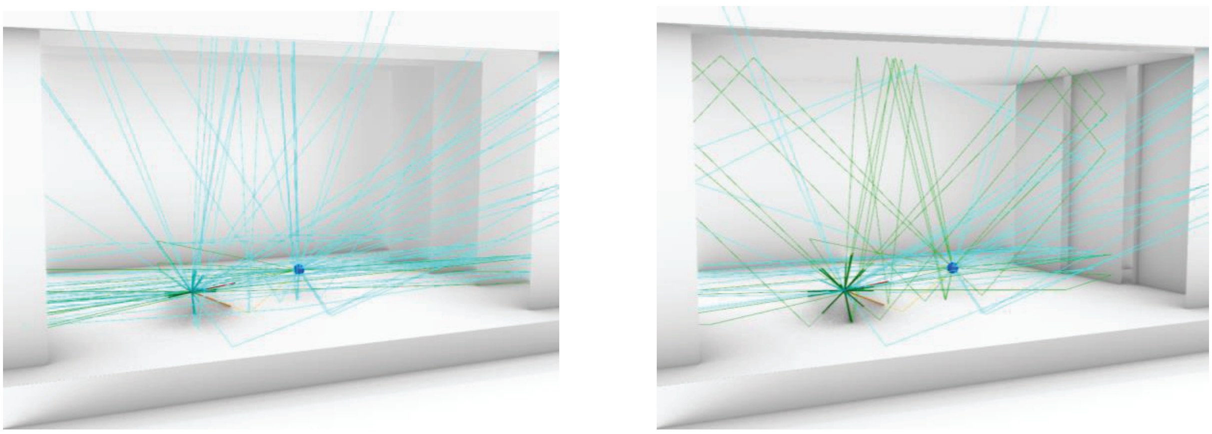

Figure 4 - Sound reflections on stage without orchestra shell (left) and with orchestra shell (right)

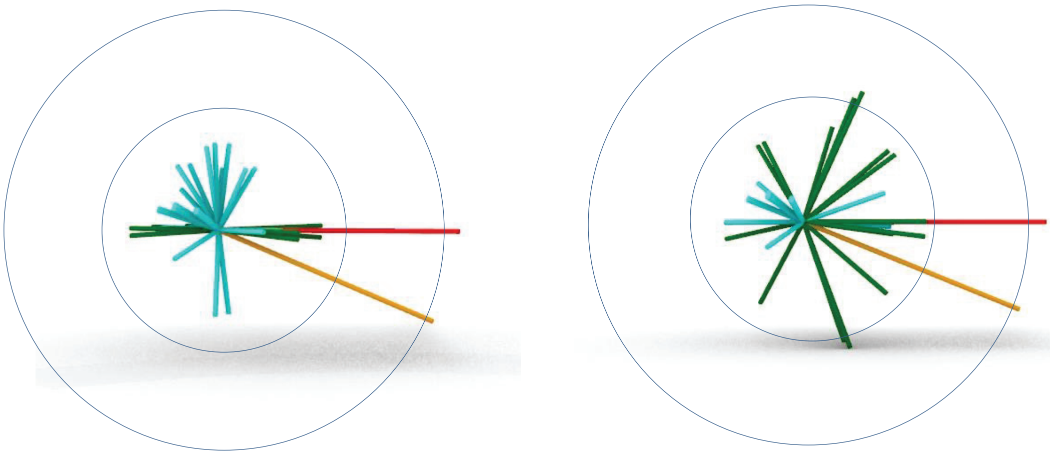

Figure 5 – 3D receiver plots without orchestra shell (left) and with orchestra shell (right)

Besides visual representation of the raytracing, the developed routine can also estimate the early energy and a selection of stage acoustic parameters (e.g. ST_{early}, G_{early}, etc). Table 1 compares the 'early energy' ($SPL_{7\text{-}40}$) received at 1m from the source and the stage support, ST_{early}, from different musicians' locations.

Stage acoustic parameters that include the direct sound and floor bounce show little difference between scenarios (1 – 2 dB) for most source/receiver scenarios. This is due to the strength of the direct sound and floor bounce, which might not be audible with the occupied stage. Therefore, it is considered that the energy received without the direct and floor bounce will represent better the cross-stage communication. This aligns with the latest stage acoustic parameters proposed in recent research by van den Braak et al. ($LQ_{7\text{-}40}$) (5), Panton ($TS_{20\text{-}50}$) (7) and others (4, 6).

Table 1 shows an increase of approximately 6 dB of the early energy ($SPL_{7\text{-}40}$) with the orchestra shell when calculated 1 meter from three different sources (violin, trumpet and oboe). An increase of 6 – 7 dB is predicted for ST_{early}. This change shifts the expected performance from poor to optimum for symphony music recommended (3).

Table 1 - Change of Sound Pressure Level at one meter from the source

Source	Shell	$SPL_{7\text{-}40}$ (dB)	ST_{early} (dB)	Recommended ST_{early} (dB)
Violin Front	No	-	-21.4	-10 to -14
	Yes	51.5	-14.5	
	Change	N/A	+6.9	
Trumpet	No	48.8	-18.9	-10 to -14
	Yes	54.4	-12.2	
	Change	+5.6	+6.7	
Oboe	No	-	-20.4	-10 to -14
	Yes	50.9	-13.8	
	Change	N/A	+6.6	

4.2.2 **Stage Risers**

Stage risers provide a visual connection between musicians, while projecting sound from the orchestra to the audience. With a greater visual connection, the direct sound between musicians should also improve due to diffraction and less shielding.

The early energy between instruments across the stage was analysed with this tool in a flat orchestra scenario and with risers at difference heights (Figure 6). Both scenarios included an orchestra shell and shielding from music stands and musicians.

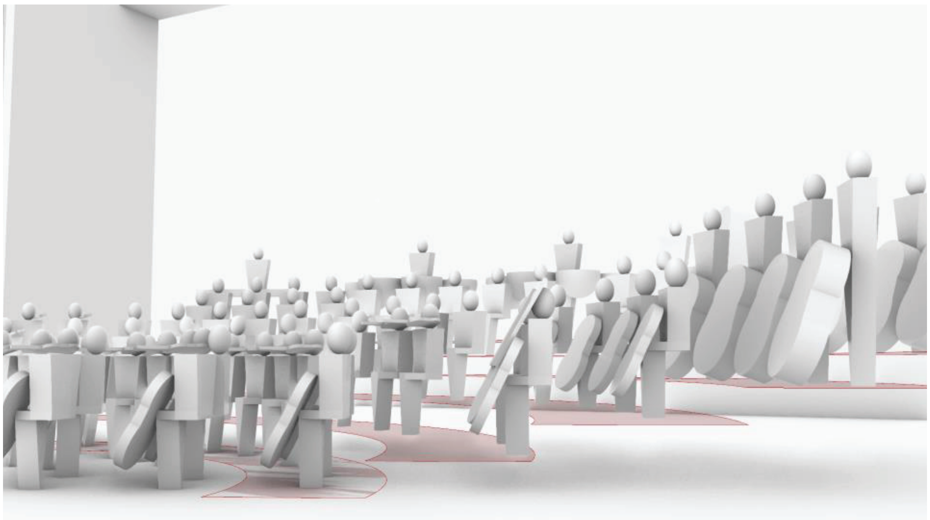

Figure 6 - Stage risers' arrangement (three first rows of strings flat at 0m, 4th row of strings and 1st row of winds at 0.25m, 5th row 0.5m, 6th row 0.75m, 7th row 1m and percussion at 1.25m)

As the tool is based on a ray tracing technique, diffraction around musicians' heads is currently not considered. As such, the improvement obtained was lower than expected and several positions showed that the direct sound was still blocked.

As shown in Figure 7, for a flat floor, the direct path is blocked by two heads. However, with the risers this path, while not being completely clear, only has the side of one head blocking the sound. This improvement in the visual connection between the musicians in a real orchestra would be expected to result in a better direct sound connection between musicians (9).

Some positions did not show an appreciable change in the early energy received (7-40ms), but others showed approximately a 1dB improvement (e.g. the 1st violin received two early reflections that previously arrived after 40ms).

Figure 7 - View from Trumpet to Violin - flat floor (left), stage risers (right)

Being able to position a camera and see the stage as a musician would, communicates the change in height simply and effectively to a client or architect. This experience can be quickly enhanced further by transitioning the view simply and quickly into Virtual Reality.

4.3 Effects of the directivity and shielding of instruments and musicians

On-site stage acoustics measurements are typically undertaken with an omnidirectional source and without the musicians on stage. It has been appreciated for some time that this does not communicate a realistic test of the actual performance stage conditions.

The effects of the directivity of the different instruments and cross-stage shielding due to musicians and stands can have a significant impact on the sound received between musicians (9). Changes in the stage acoustics conditions due to these items are discussed in the following sections.

4.3.1 Considering shielding

As discussed, it is often difficult to undertake stage acoustic measurements with the musicians on stage. Generally, this is due to the difficulty and expense of incorporating the orchestra in the measurements. When possible, measurements are undertaken with chairs and stands; however sometimes these measurements are undertaken with an empty stage.

With the developed routine it is easy to include objects such as musicians, chairs and stands and then estimate the effect of cross-stage shielding on the stage acoustics. At low frequencies the direct sound will diffract around the instruments and musician's heads. However, at 500 Hz – 4kHz the obstacles in the stage will reduce the direct sound creating shadow zones within the orchestra (10).

A selection of musicians and large instruments (shown in Figure 3) have been incorporated into the Rhinoceros model to analyse the shielding effects from musicians/instruments. As discussed in the risers' section, the routine is based on ray-tracing and at this point it does not consider any diffraction. Therefore, it provides a binary response to shielding (it will consider that the sound does not arrive at the receiver if the ray is intercepted by an obstacle). However, some degree of diffraction of the direct sound would be expected around musicians' heads.

The analysis with the developed routine showed that the direct sound and floor reflection is shielded in most scenarios with a flat floor arrangement. An average reduction of 4dB was calculated in the early energy (7-40ms); however, in some source/receiver combinations a higher reduction was observed. Figure 9 shows the range of early sound energy reduction due to shielding for four sources (the trumpet, violin, french horn and cello) to the rest of the musicians. This reduction typically represents the low-level reflections from the side walls/shell, which are blocked by the orchestra. Figure 8 shows a comparison of the energy plots received with an empty stage and with musicians on stage.

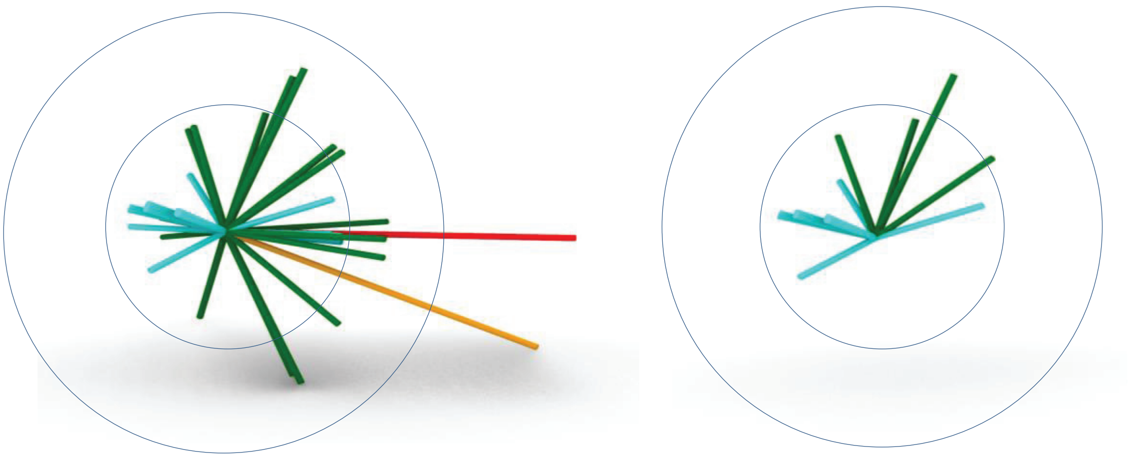

Figure 8 - 3D receiver plot (from the oboe to violin) without shielding (left) and with shielding (right)

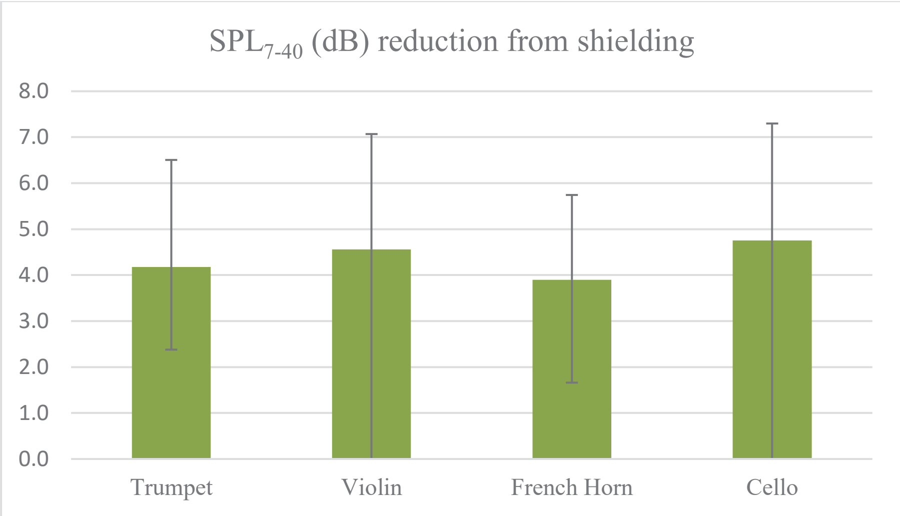

Figure 9 - Average reduction of early energy due to shielding for different sources

4.3.2 **Considering directivity**

Directivity can be a significant influence on the sound level experienced on stage, and therefore the degree that a player can hear themselves and other musicians.

The developed tool can easily include the directivity of the instruments in the raytracing and calculation of parameters. Directivity of the instruments has been exported from Odeon's database and imported to the calculations. As described in the measurements of the directivity by J. Pätynen, T. Lokki (11), the position of the musicians' head has been defined as the centre position.

Figure 10 shows the directivity of the trumpet at 4kHz, and the 3d receiver plot from the trumpet with and without directivity to the calculated position. The plot shows that the length of the direct sound (red) and early reflections from above (green) is reduced due to the directivity of the source; however, the length of the floor bounce increases due to the trumpet being more directional at this direction. A direct comparison of the energy received can be seen in close-up views of the energy plots from an omnidirectional source and the directivity of the trumpet at 1 kHz and 4 kHz (Figure 11).

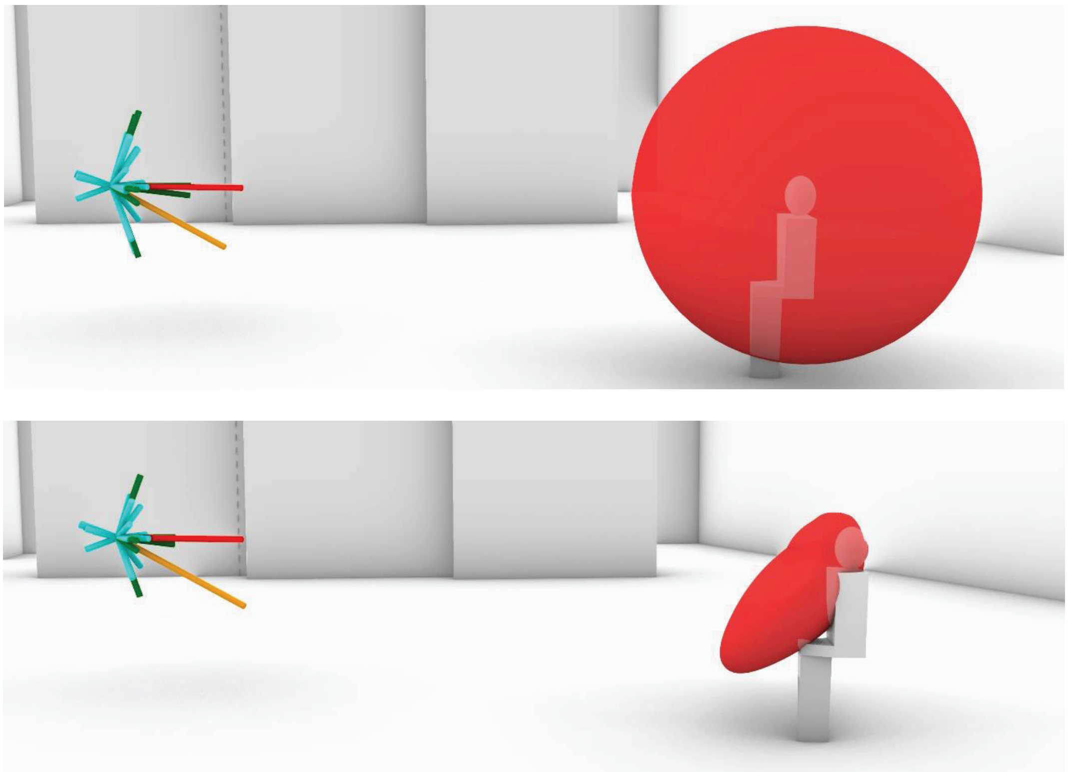

Figure 10 - Comparison of trumpet directivity (top: omni-directional; bottom: 4 kHz)

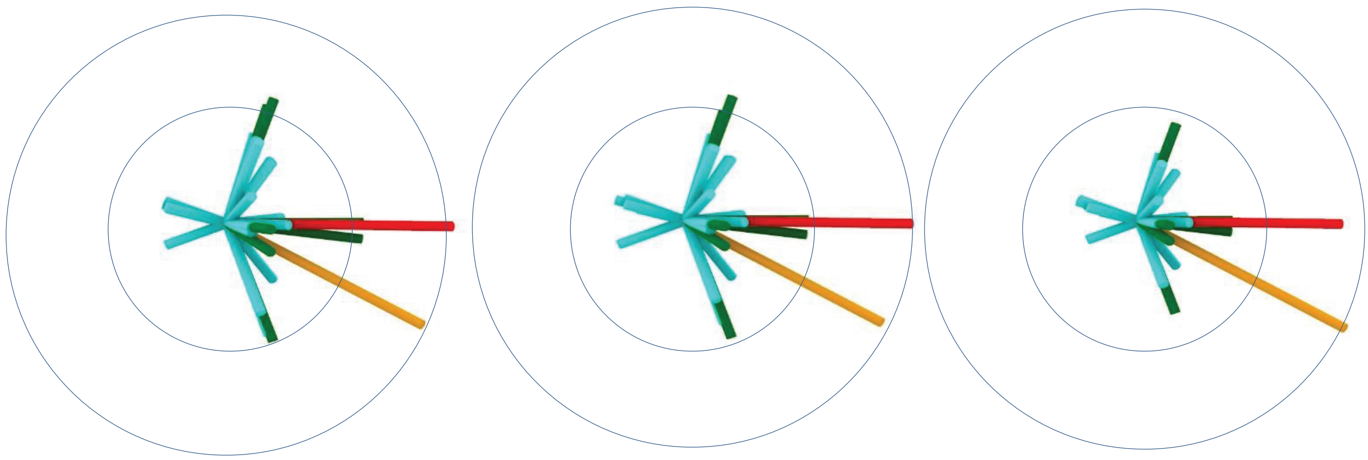

Figure 11 - 3D receiver plot from the trumpet, Omni-directional (left), 1 kHz (centre), 4 kHz (right)

When looking between each source (trumpet and violin) and the remaining receivers, a general reduction of 2-8dB was observed in the early energy (between 7 and 40ms), due to the directivity of the sources when compared to an omnidirectional source.

The change in early energy predicted between omni-directional and directional sources, alters with each instrument and frequency. However, the two instruments selected for this study were the trumpet and violin. The change in the early energy received (SPL_{7-40}) from the violin and trumpet to other musicians is shown in Figure 12 and 13.

The trumpet is highly directional at 4kHz. As such, a reduction of 6-8dB reduction in the early energy was observed at 4kHz, compared to a reduction of 2-3dB at 1kHz.

For the violin, which is less directional at 4kHz, a reduction of 3-5dB was found.

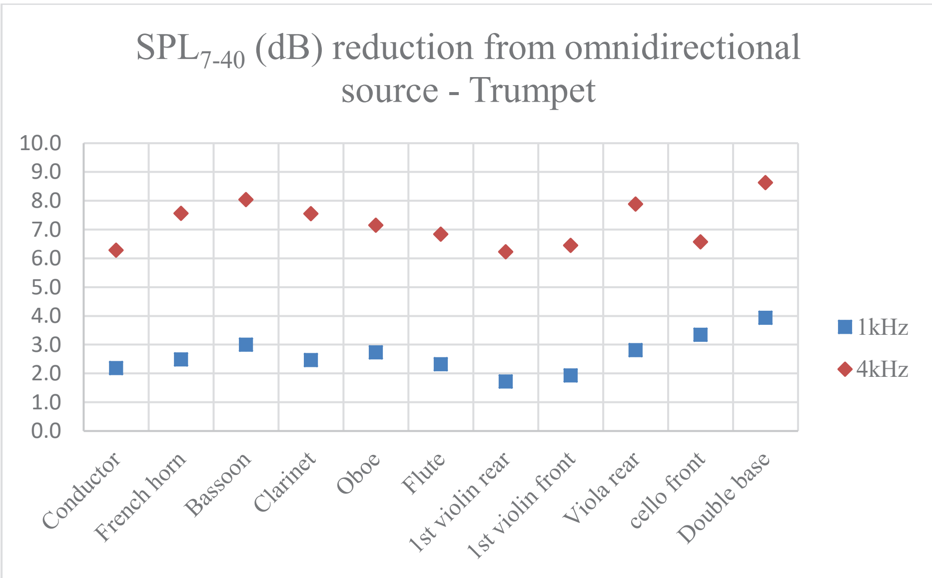

Figure 12 - Early energy sound reduction from trumpet to musicians compared to omnidirectional source

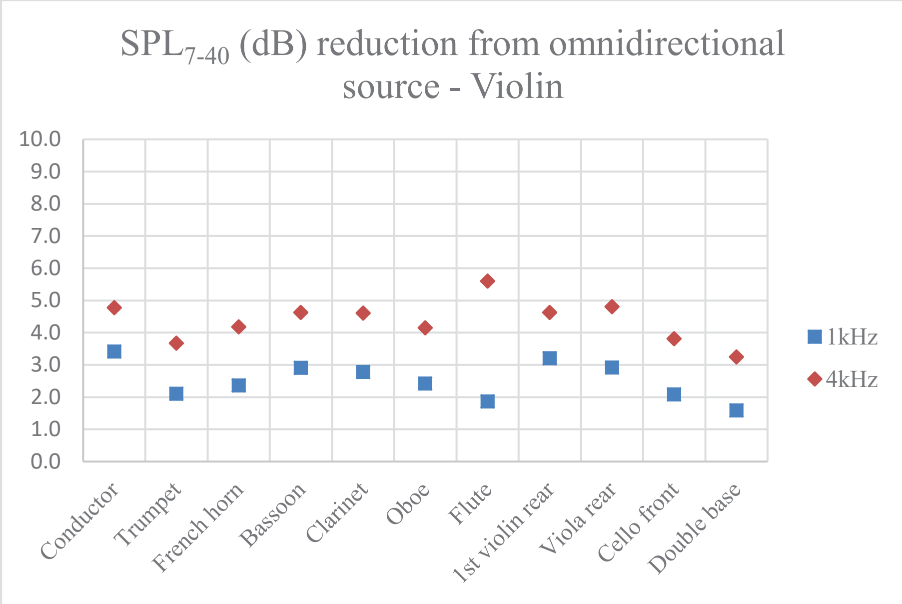

Figure 13 - Early energy sound reduction from violin to musicians compared to omnidirectional source

5. VALIDATION OF THE ROUTINE

The statistical parameters generated by the developed routine were compared to an established ray tracing software, Odeon. Table 2 summarises the results. A high level of agreement was for both the Open Proscenium and Orchestra Shell scenarios.

Table 2 - Comparison of the routine results to Odeon – based on a source with a sound power level of 80 dBA

	Open Proscenium			Orchestra Shell		
(dB)	Odeon	Rhino	Difference	Odeon	Rhino	Difference
SPL_{direct}	54.3	54.3	0	54.3	54.3	0
$SPL_{0\text{-}50ms}$	57.3	57.3	0	58.8	58.8	0
$SPL_{0\text{-}80ms}$	57.7	57.8	0.1	59.5	59.2	0.3
$SPL_{7\text{-}40ms}$	22.5	-	-	52.0	52.1	0.1
ST_{early}	-20.4	-20.5	0.1	-13.8	-13.7	0.1

6. CONCLUSION

The developed Grasshopper/Rhinoceros routine was found to be useful for both designing and assessing stage designs in an accessible way. The routine proved to be able to produce both meaningful graphics that communicated reflection direction and strength to the client, and stage acoustic parameters that aligned with results from Odeon.

The power of the routine comes both in its accessibility from an architectural perspective, and its affinity towards providing ‘real-time’ visual and statistically feedback for architectural design issues. Through the inherent visual nature of the tool, outputs are more digestible for a client or architect.

As Rhinoceros is a predominantly architectural programme, little time is lost converting files and simplifying the model. Furthermore, the immediacy of the results allows the acoustician and architect to make meaningful design changes within a workshop.

Results from the routine suggest that average reduction of 4 dB in early energy (7-40ms) can be found when considering shielding from the orchestra.

Depending on the instrument, a reduction of up to 6-8dB in early energy can be found when considering instrument directivity.

Further research will be undertaken on improving the management and calculation of curved surfaces and diffraction of sound around musicians’ heads.

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