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Sound Decisions: Moving forward with Acoustics

Ray-tracing computer-aided-design tools in auditoria design – past and future

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ABSTRACT
How to give an audience the best experience of a performance, including the best acoustic and sightline conditions, has always been one of the most important aspects of auditoria design. Ray-tracing techniques have been used in both acoustic and visual design, taking advantage of the ray-like transmission of sound and light. The methods initially developed from 2D manual ray tracing, with paper and pen, to 3D computer-aided software such as Odeon and CATT. Recent 3D ray tracing implementation using Grasshopper in Rhino allows reflection coverage and sightline condition analysis to be carried out with real-time manipulation and feedback. These tools continue to become easier to use and also provide more accurate results. The development of these tools, along with the increasing speed of computer processors, enables a more user interactive approach to design and iterative development of an optimized outcome. In rooms as acoustically and architecturally complex as music auditoria, it allows for true collaborative development of the physical room characteristics by the design team, with the acoustics and other functional characteristics considered since the early design stage. In the near future these tools will be extended, for example, to combine ray-tracing tools with a virtual reality design environment, or to automatically optimize the design with parametric design tools, to achieve the best acoustic and visual results. This paper follows the history or ray tracing and takes a glimpse at what lies ahead.

1 INTRODUCTION

Since the time of the ancient Greeks, architects and designers of performing arts spaces have been working on how to provide the audience the best experience of going to performances, in both visual and auditory aspects. Although light (electromagnetic wave) and sound (mechanical wave) have very different natures and properties, they do have things in common, and the most important characteristics that was used in the optimization of auditorium design is their ray-like transmission.

In most situations, light travels in straight lines in the air. Apart from specular reflection surfaces such as a mirror, flat glass and calm water, most common objects have diffusive surfaces. To be able to see an object, the light diffused from the object need to travel to the observer's eyes without any obstruction. Therefore, by connecting an imaginary straight line between the target and the observer the observer will be able to see the target provided there is no obstacle in the way. This is the simple principle that is used in all ray-tracing sightline analysis.

The propagation of direct sound has similar behaviour as light and good sightlines relate to good direct sound (Barron, 2009). However, sound waves have much longer wave lengths than light so most common hard flat surfaces such as a wooden floor, concrete wall, plaster board panel can act as reflective surfaces for audible sound waves. Therefore, for the analysis of sound propagation, not only the direct sound, but also reflected sound need to be considered. In an auditorium, the early reflections are a very important factor for the perceived loudness of direct sound and clarity (C80). Late reflections form the reverberant sound, and reverberation time (T) is one of the defining characteristics of an auditorium (Barron, 2009). Lateral reflection also contributes to apparent source width (ASW) and listener envelopment (LEV), which are also important subjective attributes relating to spaciousness in an auditorium (Beranek, 2012). Reflections of sound follow the law of reflection and are usually tracked using ray-tracing method, a special case of which being the image source method.

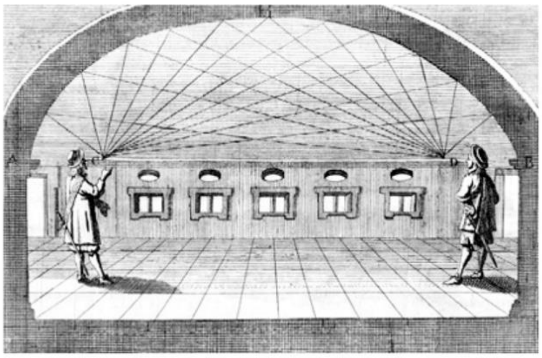
The ray-tracing methods for sightline and sound reflection in auditoria have evolved significantly over the years. They developed from simple pen and paper drawings on a plan or section to computer-aided tools that calculate rays in 3D. With the increase in computer speed these calculations have become faster and more precise and could consider more influential factors. This paper will give a brief introduction to the historic development and the current and future ray-tracing tools.

2 ACOUSTIC RAY-TRACING

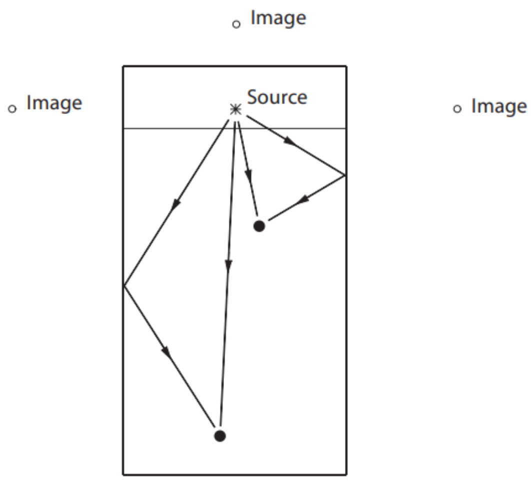
For acoustic ray-tracing in auditoria, sound reflections are the main consideration. Walls and ceilings need to be designed with the right angle and curvature to provide the best early sound reflections from stage to the audience and sound anomalies like echoes and focusing need to be avoided. Due to the complexity of room geometry and to simulate the wave-like propagation of sound, physical scale models have sometimes been built during the design of large auditoria. Recently, computer ray-tracing software also take into account absorption and diffusion and therefore can provide more detailed results.

2.1 Simple method

The simple method uses image source ray-tracing for early reflections. Ray-tracing is usually done manually in 2D, either in the floor plan to study the side wall reflections or in the section to study the ceiling and overhang reflections. A mirror image of the source is created on the other side of the reflective surface to get the most accurate reflection path. Due to the increasing number of image sources and reflections when the reflection order increases and the difficulty of manual tracing, normally only first or second order reflection is considered.



Source (Kircher, 1970)
Figure 1: Early illustration of acoustic ray-tracing in 1650



Source (Barron, 2009)
Figure 2: Early wall reflections in an auditorium

The simple method provides an intuitive indication of the important early reflections and is very flexible, enabling quick adjustments to the orientation of surfaces. This simple method can describe the reflections from flat reflective surfaces and can also be used to study the coverage of one-dimensionally curved surfaces. It is still used nowadays in the early conceptual design stage of a project. However, it's often limited to one plane and thus cannot analyse more complicated geometries such as double curved surfaces. Also, analysing higher order reflections takes a great deal of work is very inefficient. It's a good qualitative analysis but cannot easily provide quantitative results.

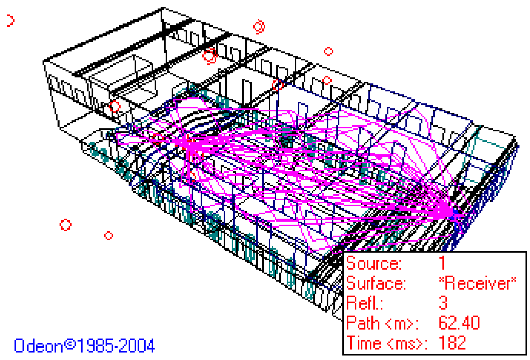
2.2 Physical scale model

Using the similar ray-like property of light and sound, laser studies in simple and complex 3D models have been used to determine the sound coverage in the seating area from reflecting wall and ceiling surfaces. Laser light was used to track the travel path of sound while mirrors or foil were used to represent reflectors. Historically this has been particularly useful during the early design workshops for large theatre and concert hall projects.

Source (Authors, 2004)
Figure 3: 3D laser light study on an early concept design for Philharmonie de Paris

2.3 Ray-tracing software

Computer modelling has been used in acoustic calculations since the 1960s (Schroeder et al., 1962, Krokstad et al., 1968). Most modern acoustic software such as Odeon and CATT use image source method for early lower order reflections and use random ray-tracing for late higher order reflections. For the image source method, the software uses the same principle as simple method but, with the aid of the computer's calculation ability, the mirroring of the sources taking place in 3D. More orders of reflections and more complex models can also be studied. With the random ray-tracing method, a number of rays are randomly emitted from the source. Higher orders of reflections can also be taken into account. When higher order reflections are combined with absorption and diffusion of the surfaces, the absorption of the air and estimation for late reverberation can be provided.

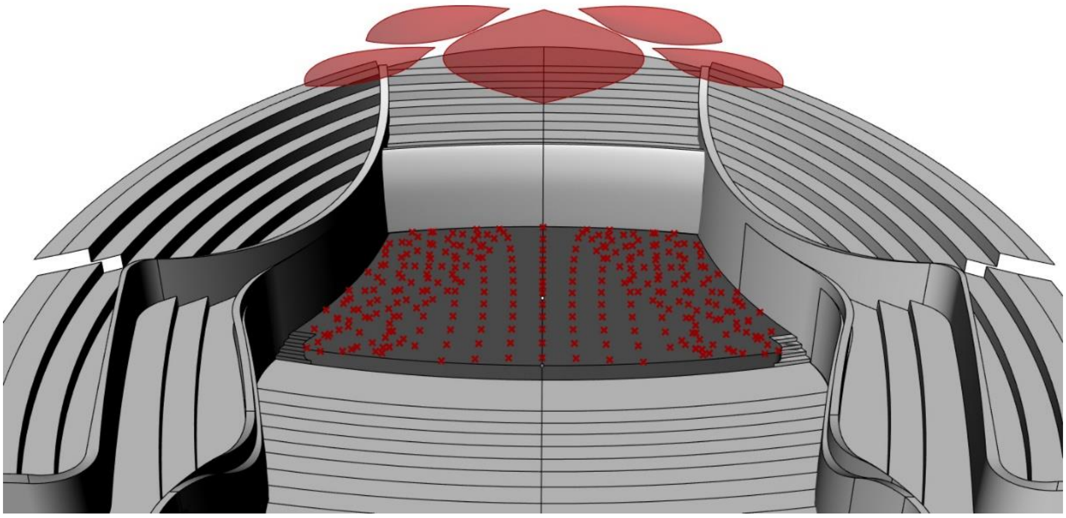


Source (Odeon A/S, 2019)
Figure 4: 3D ray-tracing in a concert hall

However, due to the randomness of the rays, the precision of the result is determined largely by the number of rays and therefore is related to the calculation time. To determine a more precise result a longer calculation time is needed. Also, for existing acoustic simulation software, complex models need to be imported from other software, making the process of adjustment very difficult. In addition, curved surfaces are considered as combinations of small flat surfaces which limits the accuracy of the results.

2.4 Ray-tracing programs based on modelling software

Apart from specialized software for acoustic ray-tracing, some simple programs have been created for real-time reflection analysis based on 3D modelling software such as Grasshopper for Rhinoceros. Marshall Day Acoustics has developed programs for reflection analysis up to second order reflections. It allows simple input from the original model and calculates in real-time the reflection coverage of 3D reflectors.



Source (Authors, 2016)
Figure 5: Grasshopper reflector coverage analysis used in the design of Jiangsu Grand Theatre, Nanjing, China

Compared to the simple method, it allows reflection calculation in 3D and can well calculate the reflection coverage of curved surfaces. Compared with ray-tracing software, it is based on architecture models in Rhinoceros, and doesn't require exporting into another software. The input is much simpler, and the calculation is in real-time, allowing direct adjustment on the models. It's very convenient for designing and optimizing the form of reflectors and is easy to use for architects. However, at the current state of development, it can only calculate up to second order reflections and cannot trace late reflections, and therefore can only be used for early reflection analysis.

3 SIGHTLINE RAY-TRACING

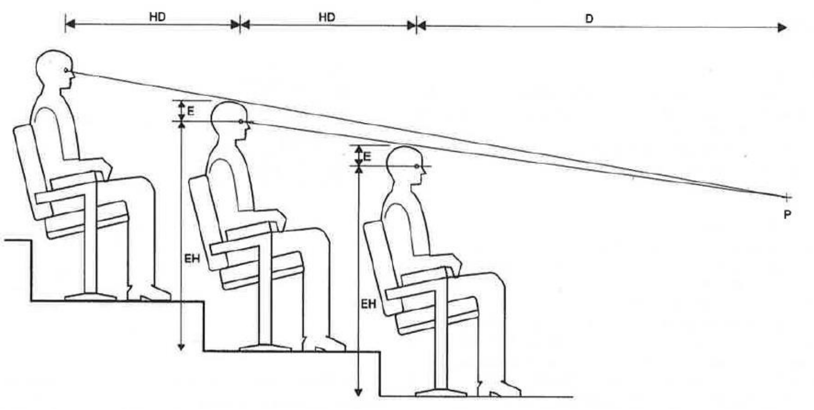
Compared to acoustic reflection ray-tracing, the simpler aspect of sightline analysis is that it only considers direct rays. But on the other hand, it's more sensitive to minor interruptions and therefore requires higher precision. Generally, steeper seating rake results in better sightlines, but it also reduces room volume and presents a higher level of sound absorption to the direct sound. In auditorium design it is therefore important to optimise the seating layout in a way that meets the acoustic and theatre design of the specific venue. In contrast to acoustic ray-tracing methods which have gradually evolved through the years, sightline ray-tracing methodology in auditoria hasn't developed until the recent years.

3.1 Simple method

The simple method of sightline analysis is usually done in section. For a target point on stage, every row of audience need to be able to see over the heads of the row of audience in front of them, or between the heads of the row in front of them and over the heads of the second row in front (Russell, 1838). This is usually done manually through drawing or using C-value for calculation.
C-value is a vertical distance describing how far the line of sight of a person goes above the eyes of the person in front. C-value is not regulated by any standards, but designers can choose the value based on generally recommended values (John et al., 2007).
Then the height of the step can be calculated using:

$$N = \frac{(R+C)\times(D+HD)}{D} - R \quad (1)$$

where
N is the riser height;
HD is the seat row depth;
R is the vertical height difference between the eye and the target point; and
D is the horizontal distance between the eye and the target point.
(Sports Grounds Safety Authority, 2018)



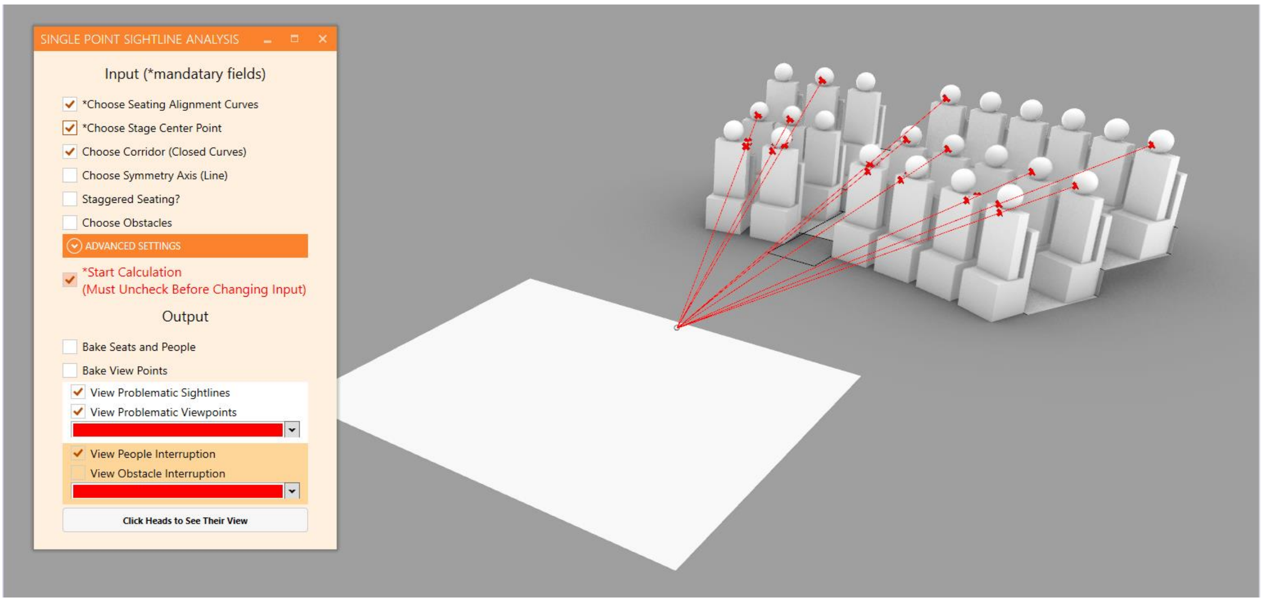
Source (Adler, 2007)
Figure 6: Section sightline analysis and C-value (marked as E in the figure)

The simple sightline method can only ensure the sightline condition for the audience on one section and is only good for a traditional auditorium with a standard section across the whole audience area. But for more complex design, especially irregular parametric design, the simple method cannot work for all seat locations.

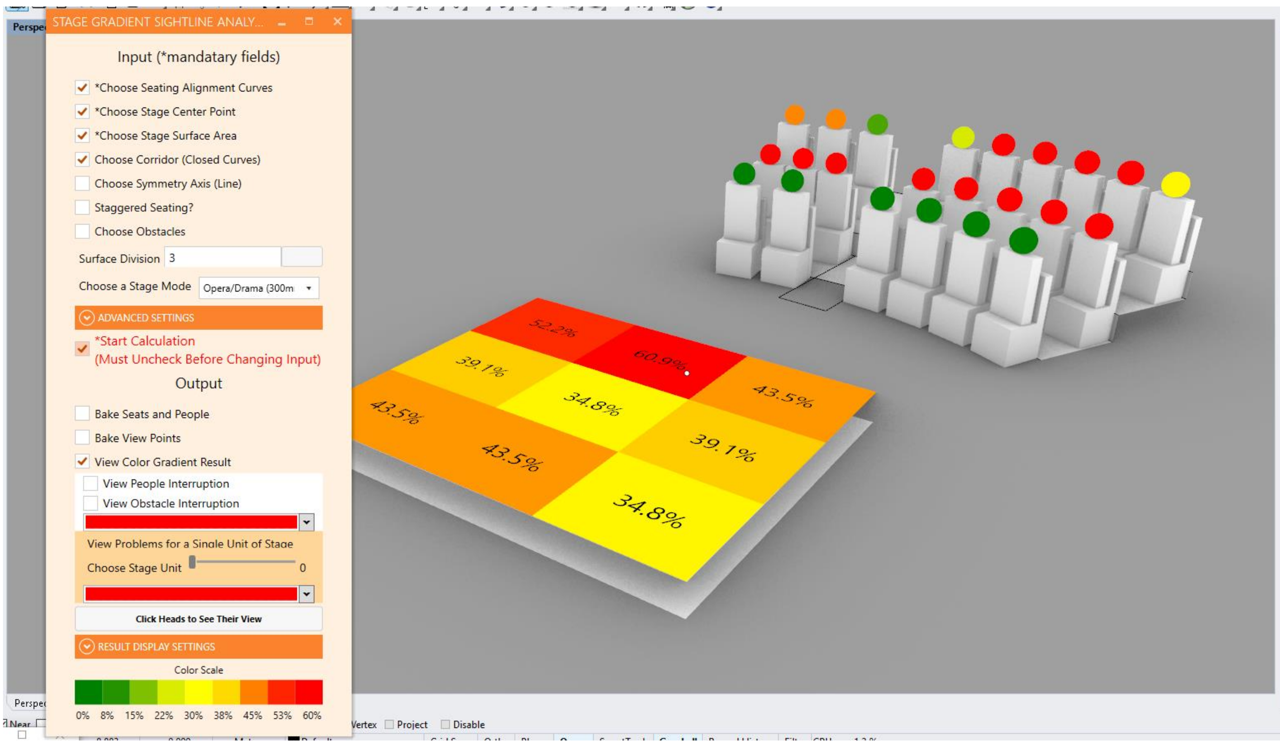
3.2 Computer-aided sightline tools

In the recent years, some computer aided sightline analysis tools have been developed based on parametric design platforms. Instead of performing the analysis in one section, the calculation can be done in 3D. Furthermore, multiple target points on stage can be analysed at the same time and a statistical result developed.
Marshall Day Acoustics has developed sightline analysis tools based on Grasshopper for Rhinoceros. The main algorithm connects a straight line between target points on stages and each point of view of the audience. The program detects if any of the sightlines are interrupted by audience heads or other obstacles such as balustrades and other architecture features.

The program can generate seats and audiences based on simple geometry input, either a curve for each row of seats, or a point for each seat if an existing seating plan is used. The program has adjustable parameters and option for staggered seating. It gives the result graphically including reporting on the problematic sightlines and viewpoints for a single target point on stage but also using colour maps to present the overall sightline conditions. The “Human UI” plugin developed by Design Computation Leadership Team (2019) was used to enable a graphic user interface for easier operation.

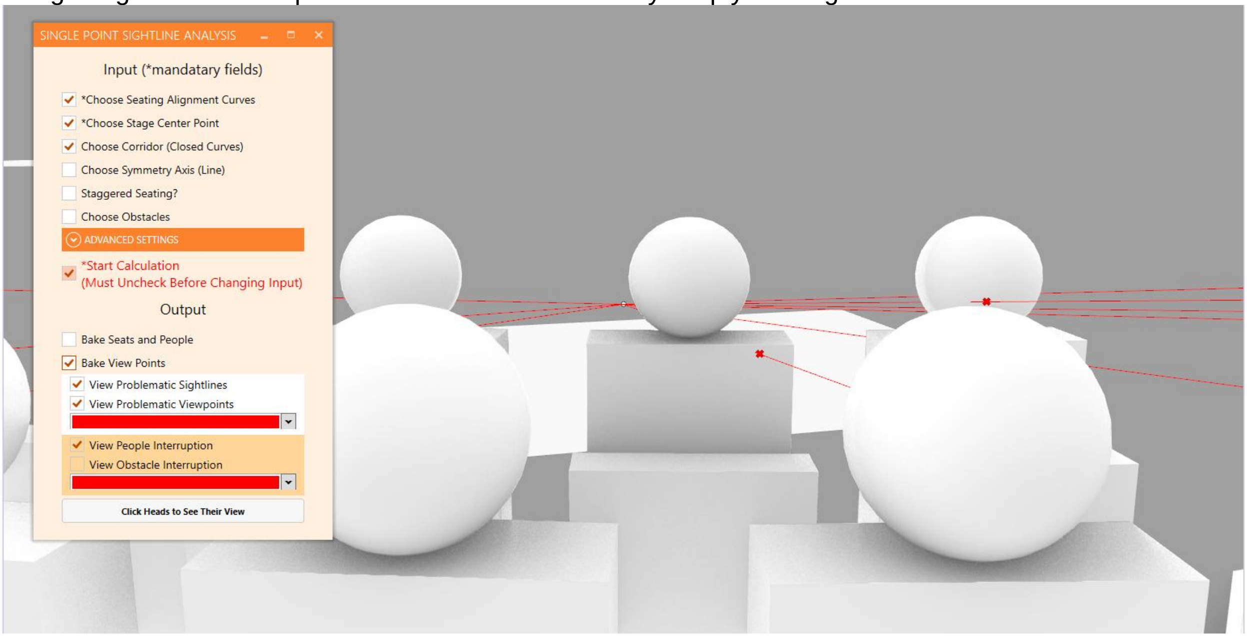


Source (Authors, 2019)
Figure 7: Single point analysis demonstration



Source (Authors, 2019)
Figure 8: Colour map analysis demonstration

The “Horster Camera Control for Grasshopper” plugin developed by Jacek Markusiewicz Architect was used to enable getting the view of a particular audience member by simply clicking on the head.



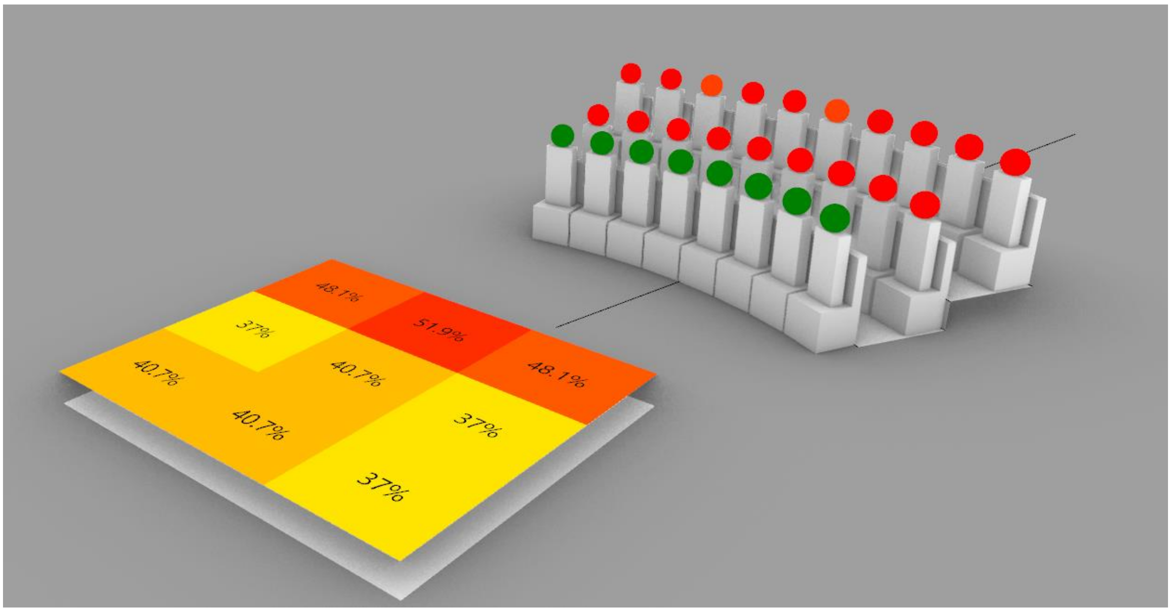
Source (Authors, 2019)
Figure 9: Viewing from an audience point of view

The computer aided sightline analysis enables calculation in 3D instead of a single section, therefore taking into consideration staggered seating and differentiating seats at different locations in the same row. It’s especially useful in the analysis for irregular and parametric design and can give a clear indication of specific problems for further refinement. The seat width, dimensions of heads and shoulders are adjustable, tailoring for different situations. The program is based on a design software commonly used by architects and makes it easier for communication between architects and consultants. This enables real-time adjustment and rapid feedback. In addition, being able to also see from the audience’s point of view gives the designer an intuitive indication of the subjective sightline condition.

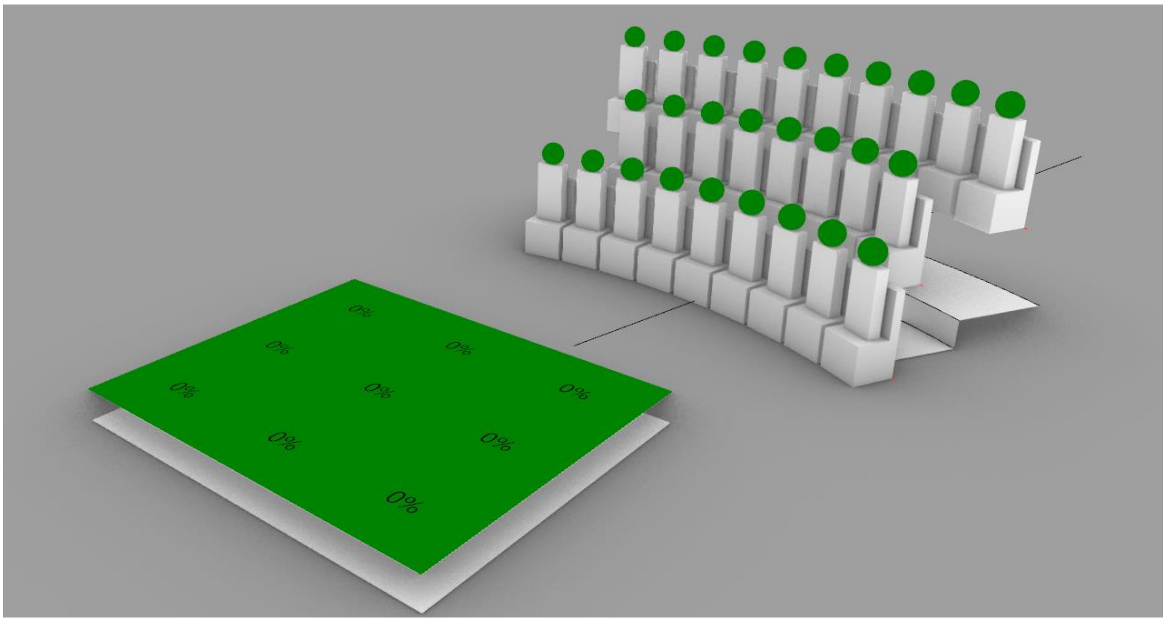
4 FUTURE EXPECTATIONS

The difficulty of changing the model and the delay in calculating the result in acoustic simulation software can hopefully be solved with faster computers with more user-centred design in the near future. Instead of separate software for modelling and acoustic ray-tracing, integrated method may be developed making use of the parametric function in modelling software, as for sightline analysis, so that acoustic analysis may combine better with the design process, enabling easier adjustment and rapid feedback.

The current acoustic and sightline analysis tools are mainly limited in analysis of an existing model. However, making use of parametric design, it’s possible to do a computer calculated adjustment to improve the design. Below is a demonstration of the current state of development. But this feature is still an unfinished prototype.



Source (Authors, 2019)
Figure 10: Sightline condition before auto-adjustment



Source (Authors, 2019)
Figure 11: Sightline condition after auto-adjustment (involving raising rake and adding staggered seating)

Furthermore, the technology of virtual reality has developed much in the recent years. In the near future, it would be possible to integrate virtual reality into acoustic and sightline analysis tools and using 3D spatial hearing technique to simulate the acoustic environment, or using VR headsets to simulate the view of different audience locations.

5 LIMITATIONS

Ray-tracing is a very efficient method for sightline and acoustic analysis in the design stage of auditoria. However, even with the most precise computer simulation, it still has some limitations:

- Ray-tracing method cannot represent the wave-like properties of light and sound. It's less of a problem for sightline analysis due to the short wave lengths of light. But for acoustic analysis, especially for lower frequencies, ray-tracing method may not simulate the propagation of sound precisely because it cannot take into the account its wave like behaviour, including diffraction, refraction and interference.
- Computer simulation is always based on a simplified version model of the real auditorium. Increasing resolution of details may increase the precision of the results but will also largely increase the calculation time. The development of computer hardware may make improvements but it can never be completely solved. And a compromise between result precision and calculation time will always need to be made.
- The influence of real-life audiences may be an important but unpredictable factor. The sound absorption and scattering of people compared to empty seats in acoustic simulations and the model of people in sightline analysis can only be an estimation using the average data, while the real situation of people, especially occupancy, can vary greatly.

6 CONCLUSIONS

Ray-tracing tools have been used in acoustic and sightline analysis in auditoria design for a long time, and have been developed to be more and more precise, flexible, fast, and easy to use over the years of evolution. The use of more precise simulation in the design stage makes the outcome of the real construction more predictable, thus saving time and money. With the development of computer hardware, more complex calculation can now be done by the computer in much shorter time. But the pursuit of more efficient tools never ends. With software developers and designers working continually towards the same goal, better tools with more features that could be useful for the design process of auditoria can always be expected.

REFERENCES

Adler, David. 2007. *Metric handbook*. Routledge.

Barron, Michael. 2009. *Auditorium acoustics and architectural design*. Routledge.

Beranek, Leo. 2012. *Concert halls and opera houses: music, acoustics, and architecture*. Springer Science & Business Media.

Cremer, Lothar, and Helmut A. Müller. 1982. *Principles and applications of room acoustics*. Vol. 1. Chapman & Hall.

Design Computation Leadership Team. 2019. "Human UI | Foor4Rhino." https://www.food4rhino.com/app/human-ui.

John, Geraint, Rod Sheard, and Ben Vickery. 2007. *Stadia: A design and development guide*. Routledge.

Kircher, Athanasius. 1970. *Musurgia universalis sive ars magna consoni et dissoni*. Ex Typographia Haeredum Francisci Corbelletti.

Krokstad, Asbjørn, Staffan Strom, and Svein Sørsdal. 1968. "Calculating the acoustical room response by the use of a ray tracing technique." *Journal of Sound and Vibration* 8, no. 1: 118-125.

Jacek Markusiewicz Architect. 2016. "Horster Camera Control for Grasshopper | Food4Rhino." https://www.food4rhino.com/app/horster-camera-control-grasshopper.

Russell, R. 1838. "Treatise on Sightlines." *Edinburgh New Philosophical Journal* 27.

Schroeder, M. R., B. S. Atal, and C. Bird. 1962. "Digital computers in room acoustics." *Proc. 4th ICA, Copenhagen M* 21.

Schultz, Theodore J., and B. G. Watters. 1964. "Propagation of sound across audience seating." *The Journal of the Acoustical Society of America* 36, no. 5: 885-896.

Sports Grounds Safety Authority, Great Britain. 2018.*Guide to safety at sports grounds*. Sports Grounds Safety Authority.