Shaping concert halls
"EuroRegio2016"

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Abstract

The architectural design of many recent opera houses and concert halls has moved on from the traditional combination of parterre and balconies, to increasingly complex 3D concepts in which the traditional "acoustic" elements (balcony fronts, soffits, ceilings…) are no longer easily recognisable as individual elements. Consequently, the line between acoustics and architecture is becoming even thinner and more diffuse.

This dynamism leads to the problem that by the time that the acoustic "checking" (by means of computer and/or scale models) of the design is finished, the room shape has already been determined to a large degree, driven by design factors other than acoustics. To face this challenge, we believe it is necessary to blend acoustic analysis in real time (or near real time) with architectural design tools. In addition, this establishes a collaborative forum in which both the architect and acoustic consultant can push each other's creativity boundaries forward.

Architectural parameterisation tools, such as Grasshopper, facilitate design in which both architecture and acoustic analysis and optimization are advanced simultaneously. Recent examples of projects with real-time 3D optimizations are presented.

Keywords: room acoustics, acoustic design, grasshopper, parametric architecture.

PACS no. xx.xx.Nn, xx.xx.Nn

1 Introduction

There are many ways in which architecture has increased in complexity over recent decades, even though this complexity is often masked by streamlined geometric shapes, which visually hides the complexity from concertgoers.

Historical halls, such as Musikverein, Amsterdam Concertgebouw, Stockholm Concert Hall and Palau de la Musica Catalana, showcase very ornamented combinations of the same few architectural elements such as a stage, parterre and balconies. However, despite this ornamentation, the structure and the embedded engineering techniques are relatively simple and are in contrast with the intricacy underlying the design of several contemporary halls, such as the Paris Philharmonie, Guangzhou Opera house, Wuxi Grand Theatre or the upcoming Fuzhou Opera Hall, to name but a few.

In the latter projects, engineers have to precisely integrate their respective requirements into the complex geometry of such contemporary halls. This can lead to a “race for control” of each square meter of the hall – as we know, materials and shape will influence the acoustical quality of the hall, regardless of whether they are designed for acoustics, technical systems or for architectural reasons.

Being able to integrate acoustics into the architectural design tools enables the acoustic consultant to ‘speak the same language as the architects’. Moreover, the acoustic consultant can be more reactive and ready to explore more creative and detailed solutions based on a solid technical foundation provided by real-time analysis. For these tools to be useful, they need to be accurate, visually compelling and easy to understand.

Part 2 of this paper explores the scope and current state of the art concerning the upcoming generation of these design tools. Methods for blending acoustics into architectural software and various kinds of approaches that can be followed by the acoustic consultant are discussed in Part 3. The last section outlines four case studies in which such tools were successfully applied by Kahle Acoustics in real projects.

2 Blending acoustics into architecture tools

The integration of acoustics prediction into CAD (computer-aided design) tools can be achieved in several different ways. This can vary from the mere scripting of the Sabine equation to sophisticated FDTD (finite-difference time-domain) analysis in real time [1]. Depending on the context of the project, different approaches and software might be used.

Among the 3D (three dimensional) modelling software packages on the market, Rhinoceros is one of the best-known applications for the creation of 3D models based on curves and NURBS (Non-Uniform Rational B-Splines) surfaces, especially for the accuracy of the models it produces [2]. It also includes the possibility of easily performing mathematical operations, evaluating variable conditions and rapidly modifying very complex geometries using RhinoScript [3]. While scripting means working with “baked” shapes, the visual algorithmic plugin Grasshopper allows the user to interact with curves and NURBS in real-time.

The development of scripts in architectural software that allows the acoustic consultant to get or to input data concerning acoustics is called the development of *acoustic tools.* There are two main classes of *acoustic tools*:

1. Acoustic analysis:
    a. Acoustic analysis of a static shape: The shape is sculpted by a process of trial and error. While fast, it is not real time.
       This process can be automated using *evolutionary algorithms (EA)*. A population of *candidate solutions* is iteratively evolved over many generations. The survival of candidates from generation to generation in an EA is governed by a fitness function based on desired acoustic targets. Over time, the quality of the solutions in the population improve [4]. The evolution is finished once it has found a satisfactory solution [5][6].
    b. Real-time analysis: the acoustic analysis runs in the background while the geometry is being sculpted manually or parametrically. This method provides real-time feedback of the acoustical impact of the modifications being made to the geometry.

2. Reverse engineering (acoustic-based design): several acoustical targets are set. Those targets are translated into geometrical constraints while shaping the concert hall. The method generates any allowed shape that will achieve the acoustic targets, which can vary for example from a maximal ITDG ("Initial Time Delay Gap", see for example Beranek [7]) for side reflectors to the target acoustic signature of the room, as explored by Bassuet and Boning [8].

Sometimes real-time and interactive iterative design is quintessential for the design process, for example during workshops with architects. At other times during the design process, acoustic optimisation and more detailed analysis of the geometry can be performed 'off-line', so as to explore the free range given by the architect. Even off-line work should still be fast and efficient while at the same time exploring the full solution space.

3 What is the scope for acoustic design tools?

The Standard ISO-3382 provides objective acoustical criteria which any good concert hall should demonstrate. However, it does not create a link between the shape of the concert hall and these criteria. Therefore, in order to establish this link, the acoustic consultant should define specific parameters so as to understand the acoustical influence of each surface.

Any type of *acoustic tool* will use simplifications of real acoustic behaviour. An understanding of what is being done, what simplifications are being made and how to interpret the results is therefore essential for the acoustic consultant.

Acoustic tools are commonly used to perform raytracing between a source, the surfaces under study and the audience. This provides an understanding of the role of each surface and the ability to modify it (manually or parametrically) in order to reach the desired acoustic goal. Since this technique is based on 'geometric acoustics', it is very easy to display typical acoustic parameters, such as area covered, initial time delay gap, incidence angle or energy attenuation with respect to the direct sound.

In addition, there are other geometrical acoustical parameters that can be considered as well:

- Average early energy across the audience depending on the the efficient solid angle, the total area occupied by the audience and a specific average value of the angle of incidence of early reflections on audience planes, based on solid angle theory by Jurkiewicz et al. [9].
- G_{early} estimation, by computing the early sound response of the room in real time using the Image Source technique. This same approach, applied on stage with a 1m distance between source and receiver, can be used to provide an estimated value of ST1.
- Strength of a ray reflected from a curved surface, based on the geometrical approach proposed by Rindel [10], adapted to NURBS by Wulfrank et al. [11].
- Estimate of frequency limits associated with reflector size and panel arrays, based on the reflecting surface relative to the Fresnel-Zone (Rindel [12]) or considerations concerning the low frequency limit of panel arrays (Skalevik [13]).

The aim of using such acoustic tools is not necessarily to calculate ISO criteria. Evidently, very relevant simulated geometric and acoustic parameters can be compared to those of built halls where the acoustic quality is known.

4 Case studies

Four case studies are presented in the following section of this paper. All cases presented were designed by Kahle Acoustics using real-time design tools, each one with its own particularities:

- The final solutions for L'Opéra des Nations were achieved in a very short period of time in which many design decisions were taken and executed in 'real-time'.
- Fuzhou Opera Hall presented a shaping challenge due to the large number of acoustic possibilities and different design options. For this project, reverse engineering methods were used to shape the continuous skin of the auditorium.
- The acoustical optimization of the side reflectors in the Théâtre de Carouge was carried out simultaneously with the architectural design of these elements.
- Since the main concert hall of the Spuiforum project presented a high level of complexity to be optimized manually, the design and optimization of the acoustic reflectors were carried out parametrically.

4.1 Opéra des Nations, Geneva

L'Opéra des Nations in Geneva, which opened in February 2016, is a temporary opera hall constructed entirely from wood, designed by Swiss architects Brodbeck-Roulet. It is a transformation of the Théâtre éphémère of the Comédie-Française into an opera hall. This is achieved by increasing the width of the room, adding an orchestra pit, creating a new distribution for the old ceiling reflectors, and increasing the acoustic volume to correspond to opera use.

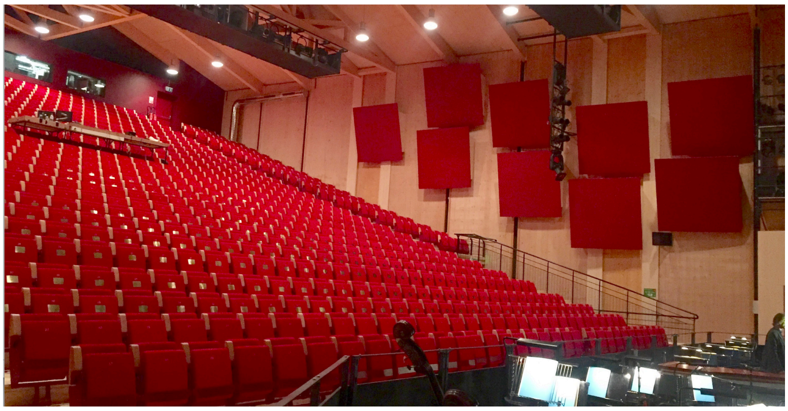

Figure 1: The new Opéra des Nations in Geneva.

One of the main challenges of this hall was to design an acoustic strategy to overcome the 28m width of this reshaped hall. This was to be achieved with the existing 2 x 2.5m, 20mm bowed sound reflectors from the old theatre, which were originally placed on the ceiling, while the side walls were empty.

Based on the assumption that reflections coming from the lower part of the room can generate both stronger loudness and better source presence when compared to vertical reflections [9], and that an increased ceiling height would be beneficial for opera, it was decided to move 18 of these reflectors to the side walls. The other 12 reflectors were set above the orchestra pit for enhanced projection. For this temporary hall, the architect decided to make the acoustic elements clearly visible, rather than blending them too much into the architecture. It is interesting to note that some musicians and audience members noticed 'the acoustics' even before having listened to the performance.

Several layouts were proposed to the architect for the panels on the side walls. The first idea was to assemble the panels together into three clusters on each side wall. This solution was rejected, fearing that it would be physically uncomfortable for the audience to have such heavy clusters floating over their heads. The next option was a solution intended to hide a ventilation duct, with the final solution being the decomposition of the clusters and to the creation a layout of individual panels.

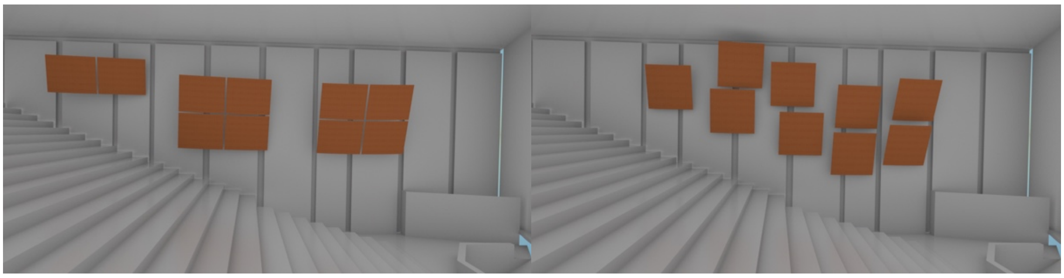

Figure 2 : (left) First layout proposal, three clusters of four, four and two panels. (right) Chosen layout, eight individual panels randomly distributed.

Once the basic layout was chosen, an acoustic strategy was defined. For the first half of the audience, each member should receive a single reflection from the panels - with some superposition on the centreline to compensate for the greater distance to the reflectors. The second half of the audience should be double covered to compensate for the decrease in acoustic energy at the rear of the hall. The 8^{th} panel on the Figure 3 is more strongly angled in order to send energy to the opposite side of the rear parterre, widening the acoustic image for the last few rows.

The energetic criteria were analysed using an Image Source technique up to 3^{rd} order. Every surface large enough to meaningfully contribute in medium frequencies was included. The curvature of the surfaces was also taken into account [11]. All the rays found between the source and the receiver were time sorted by their arrival time.

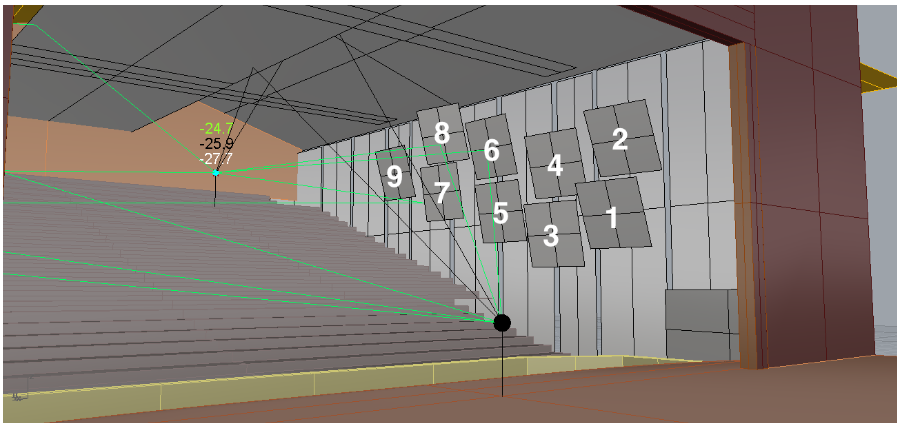

Figure 3: Image-source method between a source and receiver, calculated up to 3rd order. This gives an estimate of the direct energy (in white), very early energy (0-20ms, in black) and early energy (20-100, in green) all in dB.

The position of each panel was then determined during a workshop with the architect. The architect had the freedom to create a visually appealing layout, while a Grasshopper script running in the background automatically orientated the panels in order to maintain the desired acoustic strategy.

A visualisation that may be easier to understand is shown in the Figure 4, it demonstrates the correspondence between reflectors and reflection coverage. The area covered by a reflection is painted in the same colour as the reflector that is responsible for the reflection, which creates a very visual description of the function of each acoustic element.

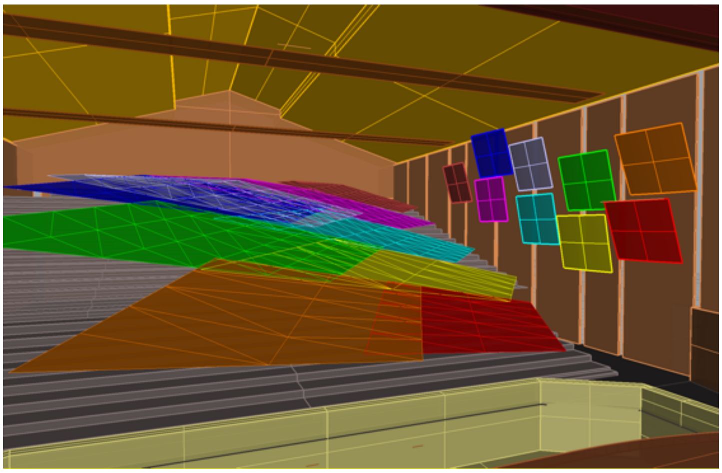

Figure 4: *Screenshot during the workshop with architect. The area covered by each reflector is shaded in the same color as the reflector.*

4.2 Fuzhou Opera Hall

Fuzhou Opera Hall, which is due to open in 2017, is part of the Fuzhou Grand Theatre. It is being designed in collaboration with PESark, Helsinki, as the winner of the international architectural competition in 2014. A 1660-seat opera house based on the Italian horseshoe tradition, it will host Chinese and classical Western operas.

The opera hall features a continuous skin around the whole auditorium. This skin mutates from walls to balcony fronts to ceiling. As can be seen in the images, classic acoustical optimization of individual architectural elements would not have been possible for this room, simply because those architectural elements no longer exist as individual entities. Instead, they are architecturally linked (and parametrically designed), which means that any change to a single element would affect other linked elements.

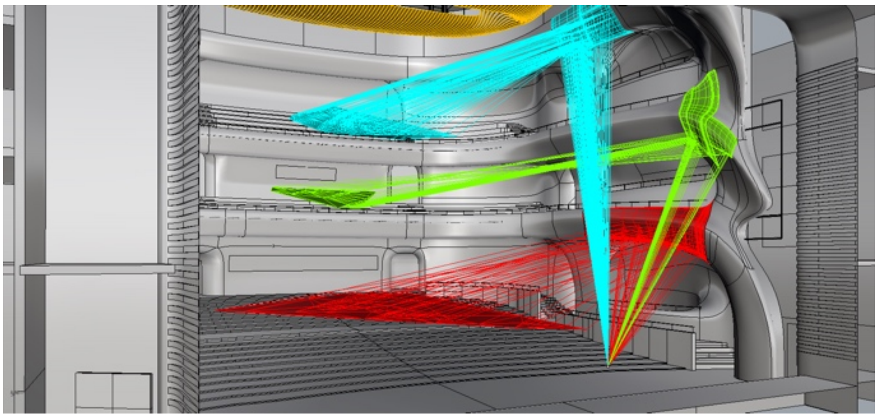

Figure 5: Reverse engineering being applied while shaping the opera hall.

To face the challenge of optimizing the whole skin of the auditorium, reverse engineering was used. Almost every square meter of the hall was given an acoustic target that would vary, for example by creating early reflections to excite the late reverberation. Each surface of the hall was automatically orientated depending on its acoustic target (sometimes different targets were used as options). The combination of the individual orientation of each patch generated the overall shape for the auditorium. By integrating this set of patches, the architects were able to create a smooth continuous skin for the auditorium.

A smooth surface that mutates is a potential source of convexities that can create undesirable focusing effects for the audience. Therefore, after the hall was shaped, a focussing study [11] of the whole room was performed. This analysis discovered several cases of sound concentration that were solved by fine-tuning the skin of the hall during an online real-time workshop with the architects.

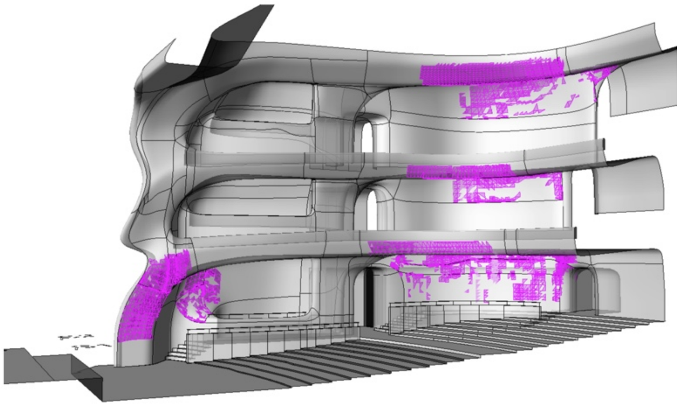

Figure 6: Sound focusing study of the whole shape of the opera hall. In violet the problematic areas that were solved out by reshaping and/or adding micro-shaping.

4.3 Théâtre de Carouge, Geneva

The main space of Théâtre Carouge is a rather steep, single rake 480-seat proscenium theatre designed by Pont12 Architects. In this hall, the main early reflections are provided by the side walls. After several suggestions, the preferred design option for those walls was a parametric design based on a series of superposed, vertically inclined, wood bands or 'bandes acoustiques'. The three main parameters for those continuous panels were: a) curvature in plan, b) a decrease in height depending on how far into the hall and close to the audience the panel was, and c) a progressive and individual tilting of each reflector panel.

As known from experience, for an inclined audience, tilted reflectors with a constant vertical angle do not create a correct coverage. A progressive change of the angle is therefore needed in such cases. This is the reason why the reflector panels change from a strong off-vertical tilt near the proscenium to nearly vertical at the end of the parterre.

The parametric design was implemented in Grasshopper, which was used to acoustically optimise the position and inclination of the continuous reflector panels.

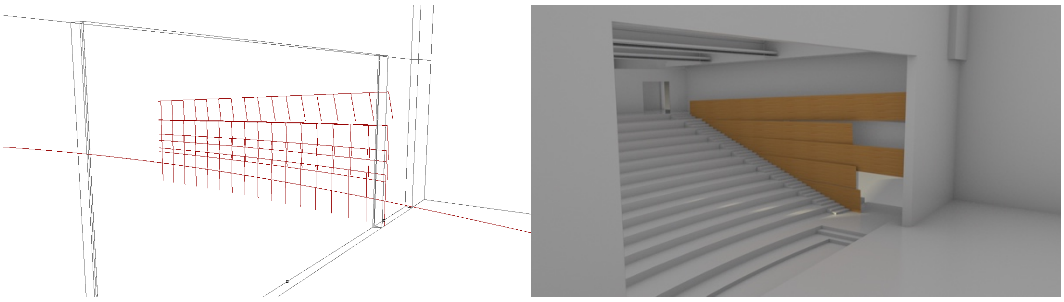

Figure 7: Parametric design of the side wall in the Théâtre de Carouge. (left) Parametric structure of the wood beams. (right) Rendering of the optimized side wall.

The convexities created by progressively morphing a surface from vertical to horizontal were checked so as to ensure that they did not create any detrimental focussing effects. The target refection zones for each panel were determined depending on the arrival time in order to create a clear sound and a good intelligibility for the theatre. The energy and number of side reflections is low enough to maintain a good source localisation.

4.4 Spuiforum, The Hague

A 1500-seat concert hall, designed by Neutelings-Riedijk Architects, home to the Residentie Orkest De Haag, was conceived on the top floor of the Spuiforum project, including a Dance Theatre and a Music Conservatory in addition to a Concert Hall. This project was stopped during the design phase, with a replacement project currently under development. However, the interest of this concert hall is that the design was finalised and optimized using Grasshopper.

Figure 8: (left)Rendering of the Spuiforum Muziekcentrum by Neutelings-Riedijk Architects. The concert hall (Koepelzaal) is placed on the top of the building. (right) Rendering of the concert hall.

The main architectural feature of this hall was a big cupola. Acoustically, focussing effects and an inhomogeneous sound field had to be avoided while optimizing early reflections and using the architectural language of decorative cladding elements in front of the big curved side walls. The lower level of the cladding elements was to be used as an audience balcony.

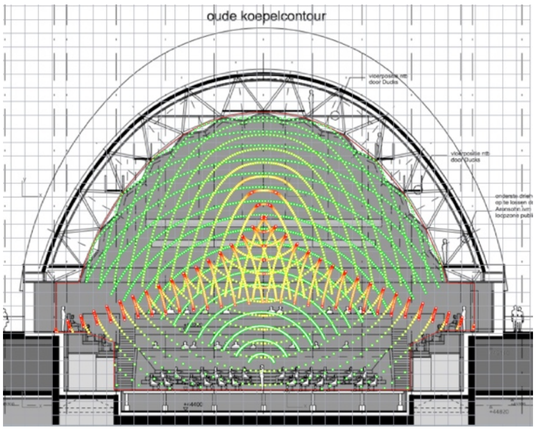

Figure 9: 2D geometrical analysis of the sound focusing created by the cupola of the Koepelzaal. This analysis does not take into account the cladding elements.

The cladding elements were not only used for breaking up the focusing, but also to create early reflections in 1st and 2nd order back down to the audience. Since the process of manually finding the correct dimensions and orientation for every balcony cladding element would have been extremely time consuming, a parametric model of the whole cupola was constructed in Grasshopper.

The parametrical design started with the geometric principles of the cupola in short section. From the short section, the cupola was extruded, creating the outer shell of the hall. From this shell, the cladding was designed. Amongst others, the number of rows and columns, the height and the inclination of the cladding were set as parametric options.

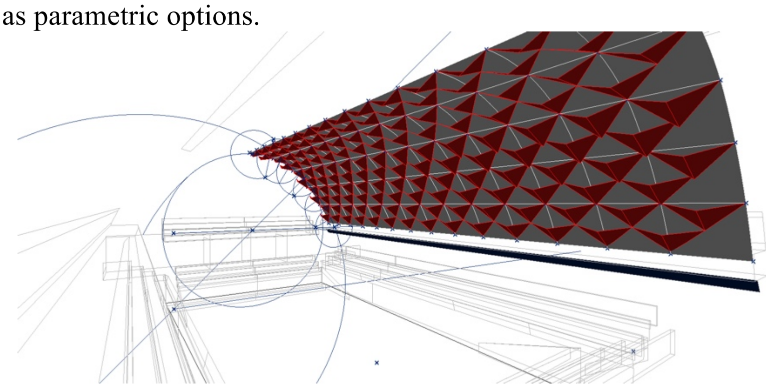

Figure 10: Parametrical design of the cladding elements for the Koepelzaal.

With this set of individual elements, creating a homogeneous acoustic coverage of the parterre was challenging. Each cladding element could only provide acoustic reflections to a limited audience area. The area covered by two consecutive elements was not continuous, therefore it was necessary to combine elements from several rows together. The parameters used for this optimisation were the height and inclination of each cladding element.

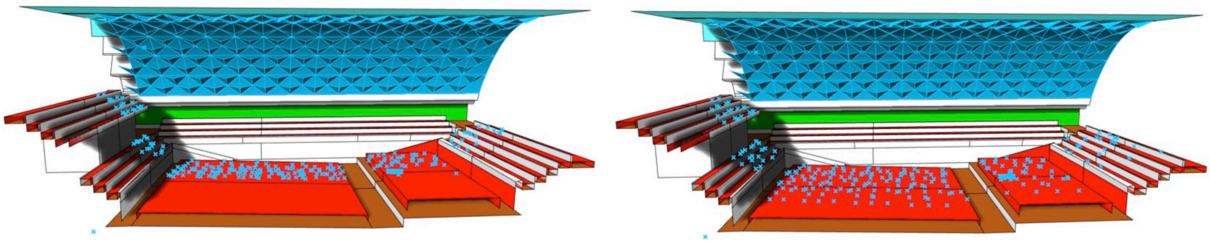

Figure 11: 3D optimization of the cladding elements. In red the audience planes. The blue dots are the impacts of the acoustic rays with the audience. (left) Inhomogeneous acoustic coverage, before optimization. (right) homogeneous acoustic coverage, after optimization.

Further acoustics optimisations were done on the hall. For example, a progressive inclination of the balcony fronts and angled stage walls. CATT acoustics was used as a validation of the whole set of optimisations.

5 Conclusions

"Often the use of existing tools leads to existing solutions. Through the creation of new tools, new ways of thinking and new solutions can be found." [14]

Blending acoustics into architectural software opens a new way for acoustic consultants to go further in their designs. It brings the acoustic consultant into a more creative and active position regarding the design process by 'speaking the same language as the architects'. In order to do so, the acoustic consultant can, and should, create specific design and analysis tools, for facing and overcoming the particular problems of each project. In addition, the 'solution space' for any problem can be explored, either specifically for every project or in general to add new solutions using different architectural languages.

Acknowledgements

The authors would like to express their gratitude to the different architects involved in the case studies detailed above, for giving us the opportunity to explore solutions in fruitful discussions and workshops.

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