BNAM 2024
Baltic-Nordic Acoustics Meeting
May 22 - 24 2024 Espoo, Finland

# Turku Fuuga – Acoustic Design of an Intimate and Immersive Concert Hall

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A new music centre is currently under construction in Turku, Finland, containing a 1300-seat concert hall dedicated to symphonic concerts and a 300-seat multipurpose hall primarily designed for chamber music concerts and orchestra rehearsals. The centre will become the new home of the Turku Philharmonic Orchestra. Design work started in early 2021 and opening is planned for spring 2026. The architectural design is led by PES-Architects, with the acoustic design by Kahle Acoustics and Akukon Ltd.

This paper describes the acoustic intentions for the main symphony hall and the specific design process developed for the project. The typology developed for the hall aims above all at acoustical excellence, while also seeking to transform the traditional frontal shoebox shape into a new, more intimate paradigm. The design is entirely based on curved surfaces, requiring precise analysis of the acoustical behaviour of 3D curved shapes and an appreciation of their potential to convey early reflections with optimum delay, strength and direction of arrival. Excellent clarity and strong acoustic impact are expected from this concert hall, since the design optimisation – with architects and acousticians working within the same 3D parametric environment – has achieved multiple early reflections to all audience seats.

Particular consideration was also given to the spatial distribution of the acoustic volume, aiming at maximizing the audience's sensation of being immersed in and enveloped by the music.

Inspired by successful precedents and displaying very promising acoustic simulation results, anticipation for the forthcoming Turku Fuuga music centre is growing.

## 1 Introduction

The final stage of the architectural competition for the new Turku Fuuga music centre took place in the first half of 2021. The Turku Philharmonic Orchestra is currently based in Turku Konserttitalon. Built in 1952, this building is a remarkable example of Finnish modern architecture by the architect Risto-Veikko Luukkonen, and Finland's oldest concert hall. But it no longer meets the orchestra's needs. It was thus decided to build a new home for the orchestra.

Concert hall acoustics specialist Tapio Lokki was appointed as client advisor at the start of the project to ensure that acoustic excellence was regarded a primary goal even before the design process began. In discussions with representatives of the orchestra, he defined the sound that the new concert hall ought to have. The result can be summarized as follows: the main concert hall in the music centre has to be designed for symphonic music concerts, with no acoustic compromise related to other uses. The acoustics must be powerful and reverberant, with excellent clarity and a strong feeling of immersion in the sound. From an architectural point of view, a shoebox typology is explicitly recommended, and the audience must be organised with a relatively flat parterre accommodating the majority of seats, plus additional seats in one or several balconies.

Kahle Acoustics took part in the architectural competition with PES-Architects and Akukon Ltd, putting together a team that had already completed two performing arts projects together. The developed design aims at providing a concert hall that would sound like the best shoebox concert halls, with all the qualities described in the acoustic brief, but would also enhance the feeling of intimacy and visual proximity to the stage for all audience members, compared to what a traditional rectangular-shaped concert hall can offer.

This paper will describe the design process for the new concert hall, including the initial development of the general room shape and the more detailed geometrical optimizations achieved at a later stage. The final acoustic outcome – insofar as the acoustic predictions can approach reality given that the building is currently under construction – is discussed in the last chapter.

# 2 Early design stage: development of an intimate shoebox

## 2.1 A shoebox, a vineyard, or what else?

In the design of concert halls, the shoebox typology holds a special place. It is mostly defined by its rectangular plan shape, although some other features such as a relatively flat parterre, the existence of side balconies and a large empty volume of air in the upper part of the hall are also often cited as key factors. The acclaimed shoebox concert halls of the 19$^{th}$ century, such as Vienna Musikverein and Amsterdam Concertgebouw, have contributed to making this typology a long-established reference, recognized by most as the safest design choice when it comes to ensuring uncompromised acoustic quality [1], [2]. But with modern-day demands for comfort, safety and accessibility, and above all the need for classical music to reach younger audiences, building copies of the most successful 19$^{th}$ century concert halls is not a viable option. Other concert hall typologies such as the vineyard-terraced geometries have grown in influence in the last decades, even though opinions about the resulting acoustic quality are sometimes critical [3], [4]. Modern versions of the shoebox typology have proven to be a viable solution for ensuring acoustic excellence. The 1500-seat Fartein Valen hall in Stavanger, inaugurated in 2012, is one of the most successful examples of this approach [5]. As the required acoustic characteristics for the new concert hall in Turku closely matches the observed acoustic qualities of Fartein Valen hall, it became one of the major sources of inspiration for the design.

Another major source of inspiration came from the most recent concert hall designed together with PES-Architects: the 1000-seat symphony hall of the Fuzhou Strait Cultural Arts Centre in southern China, inaugurated in 2018. An innovative acoustic optimization process was developed for that project [6], which informed the architectural design and led to a much-appreciated result. The Fuzhou concert hall is however very clearly of a vineyard type.

Would it be possible to "modernise" the shoebox typology, much further than in the Stavanger concert hall, taking inspiration from other successful precedents such as the Fuzhou concert hall to improve sightlines and visual intimacy, without compromising the distinctive acoustic quality of a shoebox? The Turku project seeks to demonstrate this through facts. Hybridisation of the shoebox and vineyard typologies is not a new concept in acoustic design [7], [8], [9], but Turku concert hall is a new take on hybridisation, retaining more of the elements that underlie the acoustic success of shoebox rooms, resulting in a concept referred to as the intimate shoebox typology.

Figure 1: Fartein Valen concert hall in Stavanger is a 1500-seat modern shoebox concert hall inaugurated in 2012, and one of the main reference projects for Turku Fuuga new concert hall

Figure 2: Fuzhou concert hall is a 1000-seat vineyard concert hall inaugurated in 2018, in the other main reference project for Turku Fuuga new concert hall

## 2.2 The Stavanger and Fuzhou precedents

Several key aspects contributing to the acoustic success of modern shoebox concert halls are integrated to the geometry developed for the new concert hall in Turku. These aspects can be seen as a legacy of the Stavanger concert hall:

- The limited width of the hall, in conjunction with side balconies attached to the sidewalls, allowing for an efficient distribution of early lateral reflections to all audience members in the parterre. These reflections, generated by the cornice between a vertical wall and a horizontal balcony soffit, are known to be crucial in shoebox halls. They are responsible for enhanced spatial perception, acoustic presence and musical dynamics [10],[11],[12],[13]. To be fully efficient, these reflections need to reach the audience sufficiently early and from an adequate elevation angle [14].
- Special attention is paid to creating similar early lateral reflections towards audience members in the balcony levels, which is not typically achieved in purely orthogonal geometries and requires specific optimization. Balcony front surfaces are typically involved in this process, in addition to other appropriately located wall surfaces.
- A large "empty" space is provided in the upper part of the volume, where no audience or other sources of acoustic absorption is present. A rich reverberation can develop there and reach the audience from many directions, generating a sensation of being immersed in the music.
- Steeply sloped parterres and balconies of many modern concert halls shadow the sound reaching the audience from a direction behind them, and simultaneously reduce the upper reverberant volume towards the rear of the hall. As a consequence, reverberation becomes weaker and more frontal / "monophonic-like", with the consequence that the audience is no longer immersed in the music. Immersive reverberation is being considered as a critical advantage that needs to be regained, both by limiting the slopes and by implementing some changes to the classic shoebox typology. The ceiling first needs to be raised from about 16m above stage floor in historic shoeboxes to about 21m in modern ones. A slight projecting angle is also implemented above the stage and the first rows of the parterre. Suspended canopy reflectors above the stage, which did not exist in the historic shoeboxes, become necessary as the main ceiling is too far from the musicians.
- However, gentle audience slopes and additional ceiling height are not always sufficient. In some modern shoebox halls, reverberation is still heard as coming mostly from around and above the orchestra, rather than from all around the listeners as it should be. Stavanger concert hall [5] has proven the possibility to further enhance immersive spaciousness when additional volumes are created along the sidewalls of the concert hall, very much like with reverberation chambers but without the tuning complexity and with limited risks of

excessive residual absorption [15]. Smaller additional volumes with larger fixed openings towards the main volume do not create an ill-coupled reverberation and double-slope decays, but rather convey reverberant sound within the space. In the proposed design for Turku concert hall, four eye-shaped volumes are created behind the side balconies. Each of these is first fed by sound coming directly from the stage, through large portions of walls treated with a 66% open sound transparent lattice. These openings are located in portions of the sidewalls that do not generate any useful early reflections. The upper portion of these walls, responsible for the critical cornice reflections discussed earlier, are kept fully reflective and effective. The so-called “eye volumes” are then also fed by reverberant sound energy developed in the upper part of the hall, through large openings in the floor of each balcony level. This reverberant sound is channelled towards the lower part of the volume, providing the audience with late lateral sound that is known to be crucial to acoustic envelopment [16].

Several successful features of the Fuzhou concert hall also inspired Turku’s design:

- Deviations from the rectangular shape are introduced in plan. Splayed walls are created around the stage, projecting sound towards the audience, and reversed-splayed walls are created at the rear of the auditorium to improve early lateral reflection coverage towards audience in the balconies. As observed in the Fuzhou concert hall [6], this also intensifies the lateral reflection coverage towards the audience more generally.
- Audience on the side balconies is subdivided into several smaller blocks, creating a more intimate setting, a better visual connection to the stage, and improved sightlines. The size of absorptive audience blocks is also limited. The subdivision of the side balconies in Turku is directly inspired from the terraced layout of Fuzhou concert hall, but the arrangement is adjusted to follow a more shoebox-like profile: limited width, two superposed balcony levels of 1 – 3 rows instead of one wider terrace level, not excessively reversed-fan orientation of the balcony fronts.
- As in Fuzhou, the design makes widespread use of convexly curved surfaces. All walls and balcony fronts are convex, except for the rear walls of the four eye-volumes that are concave but carefully checked to avoid harmful focussing effects. This gives the acoustic consultant the opportunity to precisely tune each early reflection, not only by adjusting the orientation of the surfaces to create sound reflections of appropriate delay and direction of arrival, but additionally by adjusting the curvature to control the acoustic strength and the reflection coverage [17]. Reflections off relatively narrow surfaces such as balcony fronts are inherently attenuated at low frequencies due to diffraction effects. They can therefore generate slightly harsh-sounding reflections towards limited zones of the audience (and – for a given listener – of the sound coming from only a limited portion of the orchestra [18]). Adjusting the radius of curvature is then a way of extending the reflection coverage spatially, and simultaneously ensuring a more balanced frequency content. Similarly, the right balance between reflection strength and coverage can be determined on a case-by-case basis for each individual surface in the concert hall.

Figure 3: Competition renderings of the Turku Fuuga new concert hall, in 2021 © PES-Architects

At the end of this very early design phase, the intimate shoebox typology developed from the Stavanger and Fuzhou precedents offered a very promising concept, with considerable scope for geometric optimisation and the potential to create a concert hall with truly outstanding acoustics.

# 3 Detailed geometrical optimisation process

## 3.1 Solid angle analysis – how far should the geometry be optimized?

With so much potential for optimising early reflection coverage, one of the first concerns at the beginning of the detailed design phase was whether there might be a risk of over-optimisation. Could excessive amounts of early reflections generate an overly loud sound, unable to cope with the power of a full symphony orchestra? Wouldn't extensive geometric optimisation "consume" a significant proportion of the emitted sound energy in the early reflections, at the expense of a late reverberant field that would become too weak? These concerns are generally analysed by means of predictions with geometrical acoustic software. An alternative approach was developed some years ago, precisely with the aim of answering this type of question [19]. It is based on a solid angle analysis of the geometry in which the total energy emitted by an omnidirectional sound source on stage is subdivided into 4 parts. A first part of the total emitted energy is directed towards the audience to produce a direct sound at each seat. Once received by the audience, the acoustic energy is mostly absorbed. A second part is directed towards absorptive surfaces other than the audience, and towards reflective surfaces that will send their reflections towards absorptive surfaces other than the audience. A third part of the energy is directed towards reflective surfaces that will generate early reflections towards the audience (of 1st or 2nd or higher order). These reflective surfaces are named "efficient surfaces". This part of the acoustic energy is once again mostly absorbed in the process. The remaining part of the emitted acoustic energy will contribute to the late energy. Obviously, this approach deliberately ignores what each audience member will experience at their specific location in the room to focus on the global room acoustic behaviour. In a given room, optimizing the orientation of a surface to make it efficient will increase the amount of early energy received by some audience members. Early efficiency then relates to the average over the entire audience of the early-reflected energy.

Each of the 4 parts of the total acoustic energy emitted by the source can then be expressed geometrically by subdividing the entire space around the source in 4 solid angles:

- The direct solid angle $\Omega_{dir}$ that the audience surfaces subtend at the point of the source.
- In case absorptive surfaces other than the audience exist in the hall, $\Omega_{abs}$ can be defined as the solid angle that these absorptive surfaces subtend at the point of the source. Reflective surfaces sending acoustic energy towards these absorptive surfaces are also to be included in the estimation of $\Omega_{abs}$.
- The efficient solid angle $\Omega_{eff}$ is defined as the solid angle of all efficient surfaces generating early reflections from the source point towards some receiving plane(s). Under the assumptions of geometrical acoustics, it can be estimated using a simple raytracing algorithm specifically designed to analyse the geometry of the hall and identify the zones of each surface that effectively receive energy from the source and redirect it towards the audience after one or more reflections, with a delay inferior to 80ms.
- The solid angle $\Omega_l$ containing the energy that contributes to the late part of the room response is simply obtained as the remaining solid angle: $\Omega_l = 4\pi - \Omega_{dir} - \Omega_{abs} - \Omega_{eff.}$ ($4\pi$ being the solid angle of the entire space seen from the source).

Simple formulas then provide estimates of the average values of early-reflected strength $G_{em}$ and late strength $G_{lm}$ over the entire audience (possibly also including the stage platform).

Early-reflected strength is obtained from three parameters characterizing the geometry of the hall: the efficient solid angle $\Omega_{eff}$, the total surface area occupied by audience or musicians $S_{aud}$, and a specific average value of the angle of incidence of early reflections on audience planes $\theta_m$:

$$G_{em} = 20 + 10.\log\left(\Omega_{eff}\right) - 10.\log\left(\cos\left(\theta_m\right)\right) - 10.\log\left(S_{aud}\right)$$

$\theta_m$ is defined from the individual angles of incidence $\theta a_i$ (0° for normal incidence, 90° for grazing incidence) weighted by the individual efficient solid angle $d\Omega_i$ of each reflector:

$$\frac{1}{\cos\left(\theta_m\right)} = \sum \frac{d\Omega_i}{\cos\left(\theta a_i\right)} \Big/ \sum d\Omega_i$$

The formula for the average value of late strengh across the audience is derived from statistical acoustic theory:

$$G_{lm} = 10.\log\left(31200.(1-\beta)\frac{T}{V}\right)$$

With $\beta = \frac{\Omega_{dir} + \Omega_{abs} + \Omega_{eff}}{4\pi}\alpha_a$

$\alpha_a$ is the average absorption coefficient of the audience and other absorptive surfaces in the room, and T and V are respectively the reverberation time (in seconds) and volume (in cubic meters) of the room.

Once implemented, this geometrical analysis process can quickly be repeated for various source positions to identify possible inhomogeneity in the orchestra sound caused by the geometry, or for each audience zone separately to detect if some areas are less well served than others.

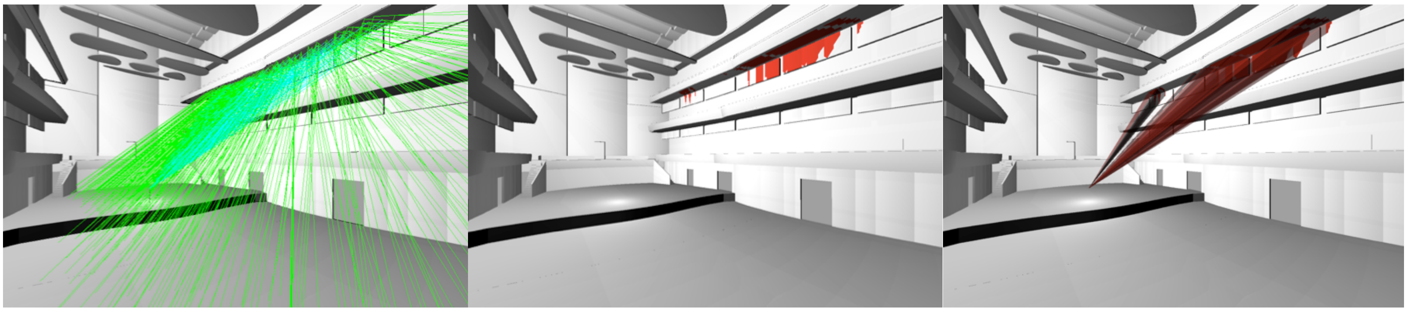

Figure 4: Example of early efficiency analysis in a 3D model of Stavanger concert hall. The picture on the left displays the results of a ray-tracing algorithm on the 2nd side balcony soffit (acoustic rays in green). The middle picture displays the corresponding efficient surfaces in red, and the picture on the right the corresponding cones representing the individual efficient solid angles for this cornice. When such an analysis is performed on the full geometry of a concert hall (which is not the case here) it needs to consider higher order reflections to properly identify all possible early reflection paths (typically up to 4th order). By definition, the corresponding efficient surfaces are those receiving direct sound from the source, even if other surfaces are involved in higher order reflections. This enables to estimate the proportion of the total energy emitted by the sound source that is used to generate early reflections as the solid angle of these efficient surfaces divided by the total solid angle for the entire space ($4\pi$)

This solid angle approach has a few advantages that proved very useful in this case. First, the effects of surface curvature are fully taken into account, as long as the raytracing algorithm is devised for that purpose (which can relatively easily be implemented in a software such as Rhino3D). Second, the geometrical analysis outcome can be visualised, providing useful explanations of the obtained results and how they could be improved by altering the geometry. Finally, the question of the extent to which a specific geometry is optimized for early reflections is directly answered through proportions of the total solid angle $4\pi$, allowing the balance between early and late energy to be easily grasped.

Two main conclusions could be drawn from the application of this method to a preliminary version of the Turku concert hall: Overall, the geometry at that point was not overly optimised for early reflections with an efficient solid angle $\Omega_{eff}$ of 1.25 sr (just under 10% of the entire space seen from the source, sr = steradians, the SI unit for solid angles) while the late solid angle $\Omega_l$ is 4.15 sr (about one third of the entire space). The risk of excessively weakening the room's late response was then not very significant at this stage. It was also observed that the early reflection coverage was not sufficiently homogeneous, with the balconies receiving much less early energy than the parterre. Measures needed to be taken to improve the reflection coverage of balconies, while that of the parterre could be slightly reduced.

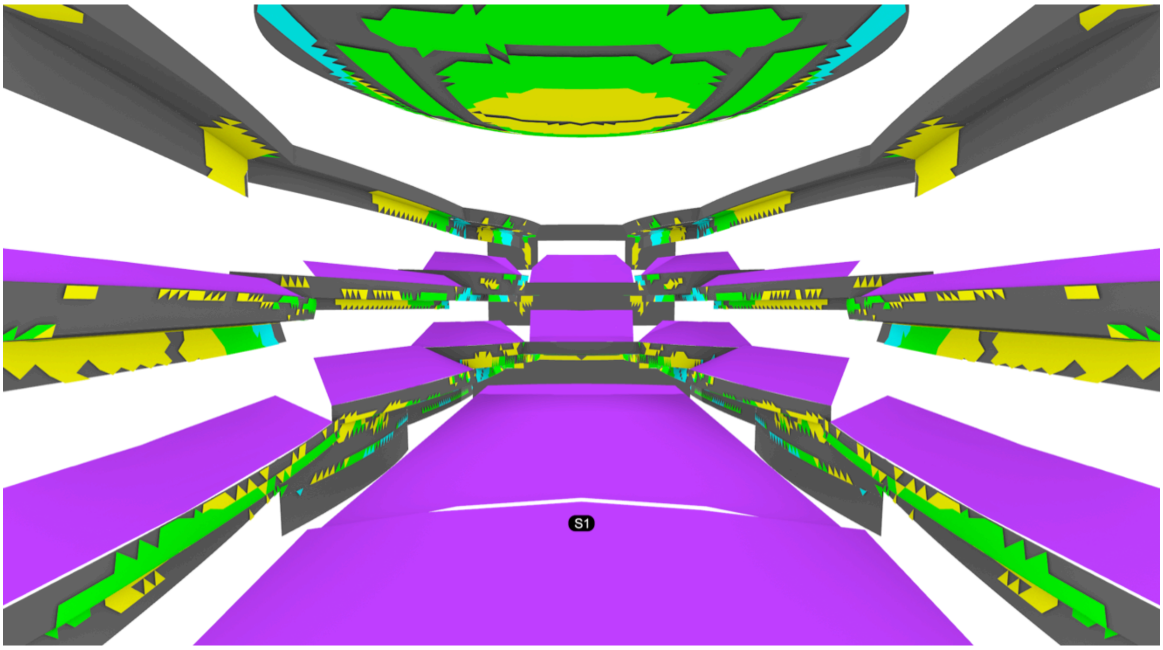


Figure 5: Visual output of a solid angle analysis performed in Rhino3D on an early version of Turku concert hall geometry, for a sound source S1 located near the conductor's podium. Receiving areas (audience and stage) are in purple, reflective surfaces in dark grey, efficient surfaces found by the algorithm are in 3 different colours depending on their delay: cyan (0 to 20ms), green (20 to 50ms) and yellow (50 to 80ms). Some of the reflective surfaces are not included in the analysis, either because they are not expected to take part in early reflections or because they were not yet well defined at this point of the project (such as the upper walls and the ceiling). Assumptions then had to be made on the additional amount of efficient surfaces and efficient solid angle that will be obtained from these missing surfaces.

## 3.2 Adjusting the detailed shape of potentially efficient acoustic surfaces

In contrast to the case of Fuzhou concert hall, it was very early on decided to limit the use of diffusive surface texture in the design of Turku concert hall. The only exception to this exclusion rule is the small concave surface areas connecting the convex balustrades of adjacent balconies (visible on figures 6, 9 and 14). The reason for excluding diffusive treatments is twofold: First, as previously discussed, the room concept allows precise tuning, with the possibility of reducing the energy of reflexions at high frequencies and increasing their spatial spread, when needed and in a very controlled manner, by adjusting surface curvature. Rather than relying on stochastic diffusion that would spread the high frequency content of incident sound in all directions with no distinction, it is possible to make decisions on a case-by-case basis. Second, the provision of early reflections with limited temporal smearing has been shown to offer decisive advantages in terms of acoustic clarity [20].

Going through the precise geometrical optimisation of each surface would go beyond the scope of this paper, but a few interesting examples can be discussed here. All raytracing figures in this paper were obtained with a Grasshopper script within Rhino3D environment. A differential raytracing algorithm [17] is used to estimate the strength of the reflections off curved surfaces based on the parameter $\Delta L_{curv}$, quantifying the influence of surface curvature: a positive $\Delta L_{curv}$ represents amplification of sound energy due to the curved surface, whereas a negative $\Delta L_{curv}$ denotes attenuation of sound energy due to the curved surface.

Figures 6 and 7 illustrate how additional early lateral reflections were provided towards the seats on 1$^{st}$ balcony level. In Figure 6, a portion of the sidewalls is tilted and curved both in plan and section. The tilt angle and both radius of curvature in two directions were adjusted to ensure that most of the possible source positions on stage generate the intended reflections, and that late reflections are not excessively strong.

In Figure 7 the shape of a balcony front surface is adjusted to provide early reflections to the 1$^{st}$ balcony. In addition to a slight curvature in plan and section, the surface is tilted with an angle that varies along its length. This leads to a complex warped (non-developable) shape that will be precisely built by carving it out of massive wood.

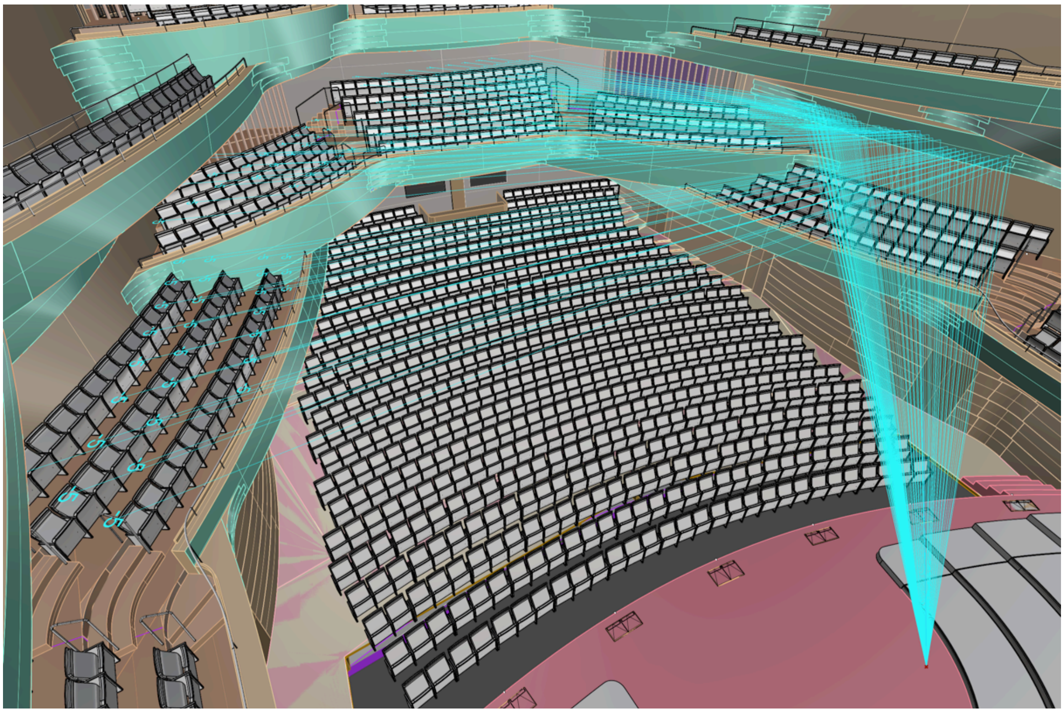

Figure 6: Raytracing on a convex and inclined wall section located on the sidewalls between 1st and 2nd balcony levels. These generate early lateral reflections towards the seats in the rear sections of 1st balcony level, and relatively late lateral reflections towards the seats in this same balcony level but located closer to the stage. $\Delta L_{curv}$ = -5dB.

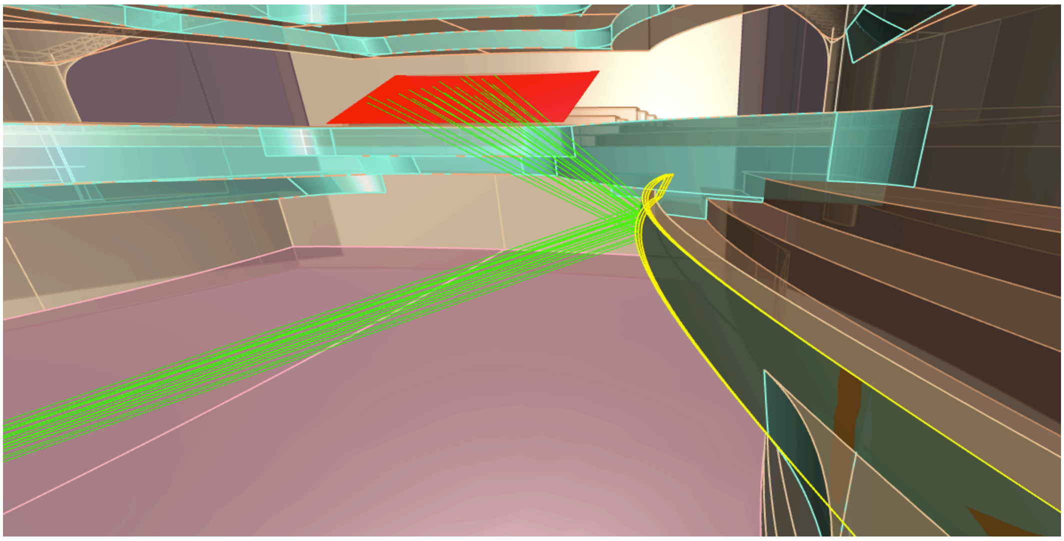

Figure 7: Adjusted shape of the 1st side balcony front to provide early lateral reflections towards the 1st level rear balcony. The balcony surface is intentionally warped.

Figure 8 shows a case of cornice reflection optimisation. Traditional cornice reflections in shoebox concert halls are 2nd order reflections generated by two adjacent surfaces: a vertical wall and a horizontal soffit or ceiling. The cornice reflection illustrated on Figure 8 is generated by the flat and perfectly horizontal soffit under the technical gallery level, together with a vertical wall portion (or downstand beam) whose shape can be freely adjusted. As all wall surfaces in this design, the downstand is convexly curved in plan. An additional convex curvature in section was introduced to provide more homogeneous coverage and to reduce reflection intensity by 3dB. The original cornice reflection with a single-curved downstand had $\Delta L_{curv}$ values ranging from -1 to -2dB, while the optimized cornice reflection has $\Delta L_{curv}$ values from -4 to -5dB.

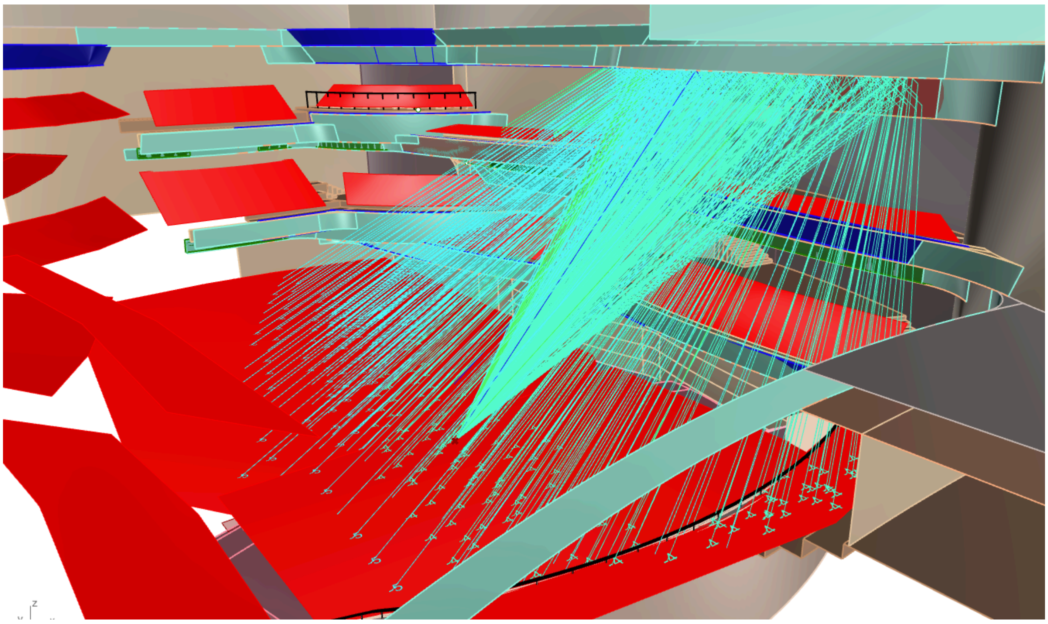

Figure 8: Adjusted shape of the downstand beams located on each side of the stage, under the technical gallery level. In addition to the convex curvature in plan, a slight curvature in section was introduced to provide more homogeneous coverage and reduce reflection intensity by 3dB.

## 3.3 Geometrical optimisations for stage acoustics

A significant part of the geometrical optimisation effort was dedicated to providing good listening conditions for the musicians on the stage platform.

The canopy reflector was initially designed as a monolithic warped disc, later split into 5 bands for the integration of stage lighting. The general disc shape is kept in plan view, but the surface is intentionally warped to vary the local radius of curvature both in long section and short section. This allows controlling the acoustic strength of the early reflections generated, with stronger reflections from instruments at the front of the stage and near the room axis (from parts of the canopy with a more flat shape), and weaker reflections from the sides and the rear of the stage (from parts of the canopy with a more pronounced convex curvature). The general tilt of the canopy projects sound from the stage towards the audience, while its rear part also allows reflections from the choir balcony towards the conductor. Each of the 5 bands is then once again very slightly curved in short section to avoid shadow zones in the reflection coverage for high frequencies.

The first round of acoustic predictions using Odeon software in the concept design phase gave fairly inhomogeneous results regarding the stage support ST1 ($ST_{early}$) parameter. Values varied from excessively high (> -12dB) to excessively low (< -18dB) depending on source position on stage. Reasons for such results had to be investigated. In the design, all surfaces generating early reflections back the orchestra are curved, some of them with a complex warped geometry. They all needed to be approximated and facetted to comply with requirements of an Odeon model. A specific verification process was developed in order to estimate the support parameter directly within Rhino3D, from the exact shape of the surfaces surrounding the stage.

In this process, a partial ST1 is estimated by summing the energy of all acoustic reflections (1$^{st}$ order and 2$^{nd}$ order) arriving between 20ms and 100ms after direct sound from a point source to receivers at 1m distance. As this method does not take into account edge diffraction and higher order reflections, the estimation is incomplete. The parameter ST1# (partial ST1) is then used instead of the standard ST1.

For each reflective surface, a colored contour corresponding to the acoustic coverage of this reflector is computed using a raytracing algorithm. If a receiver lies within this contour, a reflection path exists between the source and the receiver via the corresponding surface, as shown in figure 10. The algorithm will then provide a $\Delta L_{curv}$ (in dB) corresponding to the change of reflection strength due to the curvature of the surface [17], and a $\Delta L_{diffr}$ (in dB) corresponding to the attenuation of the reflection due to diffraction and the finite size of the surface [21].

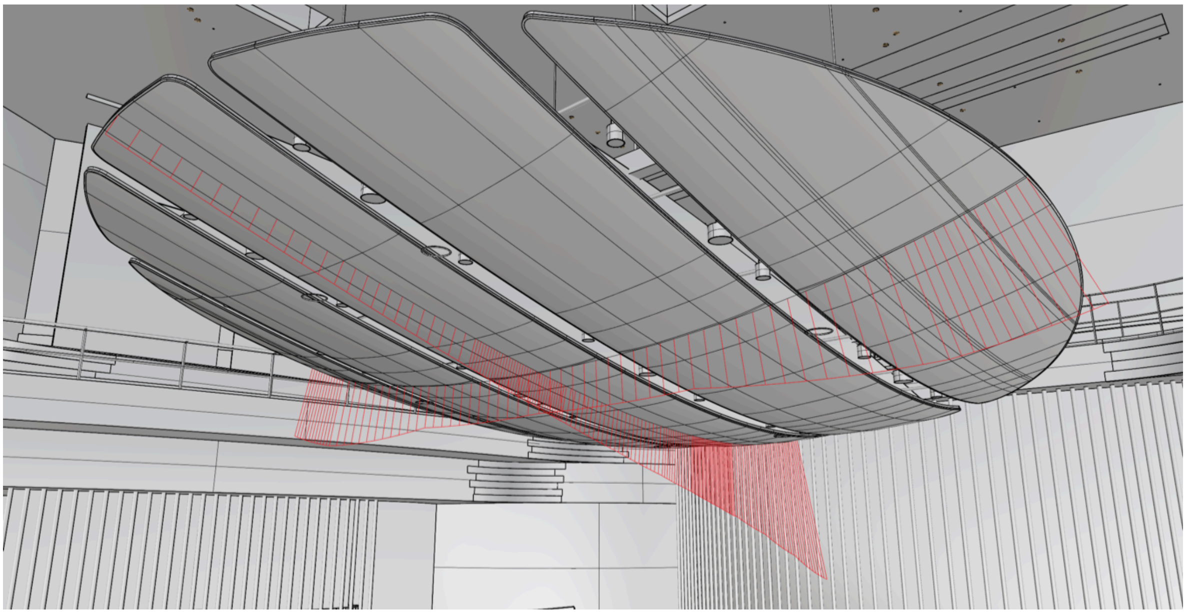

Figure 9: The canopy is shaped after a disk and convexly curved in two directions, with varying radii of curvature in both short and long sections. Lines in red are the curvature graphs of the general shape in each direction. Local surface normals are plotted, with a length inversely proportional to the local radius of curvature: longer surface normals on the sides and in the rear part of the canopy (in the direction of the organ) indicate shorter local radii. The resulting shape is warped and highly complex, but the absence of any locally concave zones needed to be precisely checked. Corresponding $\Delta L_{curv}$ values for reflections generated on stage and in the audience range between -8dB and -5dB.

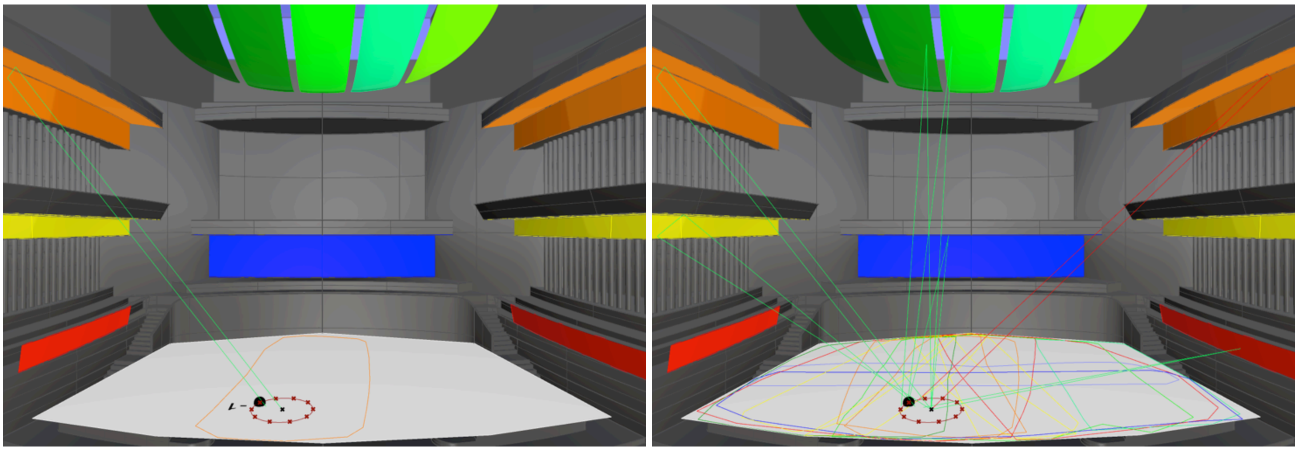

Figure 10: Left picture: acoustic reflection path via the upper left soffit (orange) from the source (center of the red circle) to one receiver at 1m (black dot). The coverage zone is indicated as an orange contour, and the calculated $\Delta L_{curv}$ is marked near the receiver (-1dB). Right picture: all possible acoustic reflection paths from the source to the same receiver, as used for ST1# calculation. Green rays have a 20ms to 100ms delay, and red rays have a delay > 100ms. In this example, reflections from the stage back wall and the organ box are not considered.

To finally obtain a spatial average value of ST1# around a given source position, this process is repeated for 10 receivers equally spaced on a 1m radius circle around the source. Results for 4 source positions are given in figure 11.

In the first simulation run, excessively high ST1# values were obtained for sources at the back of the stage. This result could be traced back to several surfaces providing early energy to this source location. Among others, the shape of the balcony front in red in figure 11 was modified to send more early energy to the front part of the stage and less energy to the rear part. This led to a twisted shape with a varying tilt angle, ending vertically towards the back of the stage. A second run of simulations was performed with adjusted reflectors and the obtained results can be compared in figure 11.

Interestingly, the inhomogeneity identified and solved using this ST1# analysis process differs from the one initially observed in Odeon simulation results. The subtle changes in curvature and tilt angle, decided on the basis of this ST1# analysis, have no significant implications for the faceted version of the geometry used by Odeon.

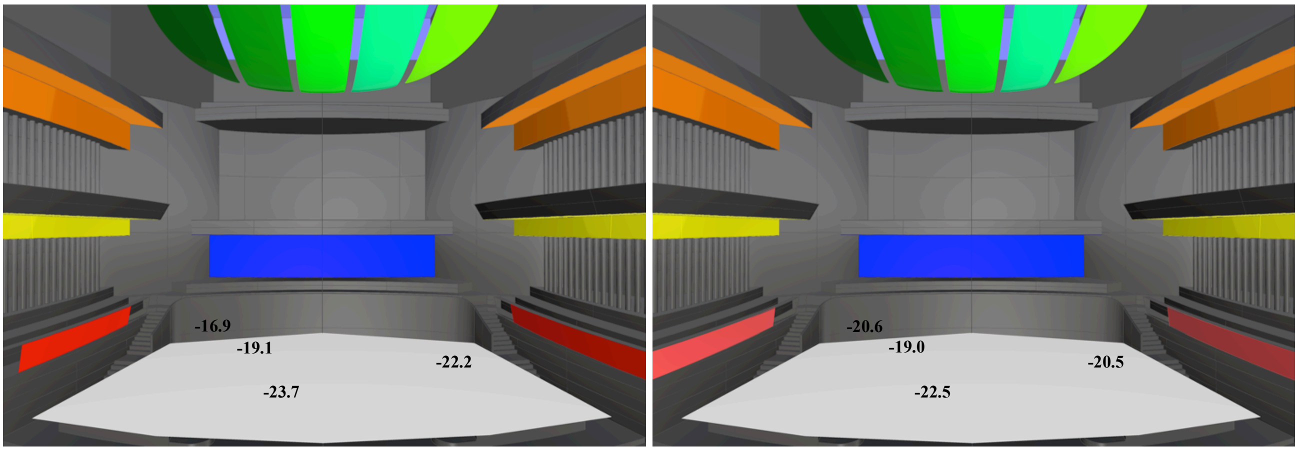


Figure 11: Estimated values of ST1# for 4 different source positions before (left) and after (right) surface optimisations. On the left, ST1# is found to be excessively inhomogeneous on stage (6.8 dB difference between extremes). On the right, after shape optimisation a more homogeneous ST1# is obtained (3.5 dB difference between extremes).

It is sometimes thought that late arriving acoustic reflexions towards the stage are dangerous and may cause disturbing echoes for the musicians. However several authors have proven that musicians need a sufficiently audible late acoustic feedback from the hall [22], [23], [24], which the present authors confirm on the basis of their experience. This desirable late acoustic feedback is ideally made up by several late reflections spread over time and arriving from different directions in space. If each individual late reflection is not excessively strong, it will not be perceived as a distinct event or "echo", but will rather play its part in building up a smooth halo of sound. In the acoustic design of the Turku concert hall, it was therefore necessary to make sure that such a desirable acoustic feedback was effectively provided, with sufficiently audible effect and without excessively isolated and distinct events that would be perceived as echoes. To do so, all relatively late reflections (from about 50ms) generated by the concert hall geometry were listed with their individual characteristics (delay, strength, direction of arrival). The level of each reflection was calculated, taking into account attenuation effects due to curvature and diffraction on finite size objects, and normalized to the level of direct sound at source-to-receiver distance of 1m. Graphs were built with this data, as displayed in figure 12.

In these graphs, three echo thresholds available from the literature ([10], [25]) are indicated as coloured lines in order to assess the risk of echo disturbance, as well as the risk that some reflections are too weak to contribute to a positive acoustic feedback to the musicians. It must be stressed that all these echo thresholds were obtained from listening tests in which a single reflection was added to an anechoic environment, which is a very different situation compared to that of a musician on a real concert hall stage. More recent studies [26] highlighted these limits, and also found that the echo threshold for rhythmical music from Dietsch and Kraak [25] (red curves in figure 12) is too high for some musical instruments such as the trumpet. Echo threshold curves for speech from Dietsch and Kraak (orange curves in figure 12) appear to better relate to what is perceived with such echo-critical music instruments.

This echo-analysis procedure was repeated for 3 different source positions on stage (soloist position, woodwind position and percussion position), and for the 1kHz and 2kHz octave bands (as diffraction effects depend on frequency). Two feedback reflections were detected as possibly being excessively distinct in a preliminary version of this analysis, which led to adjustments to the geometry at the rear of the parterre (concave wall) and in the upper wall-ceiling corner above the 2$^{nd}$ rear balcony (87° angle changed for a 90° angle between the rear wall and the ceiling, see figure 13). The analysis in figure 12, corresponding to the final, corrected version, gives confidence concerning the result that will be achieved. Reflections remain in the vicinity of the speech echo threshold by Dietsch and Kraak, and below the extended echo threshold from Barron, meaning they are likely to be audible without generating an excessively distinct echo.

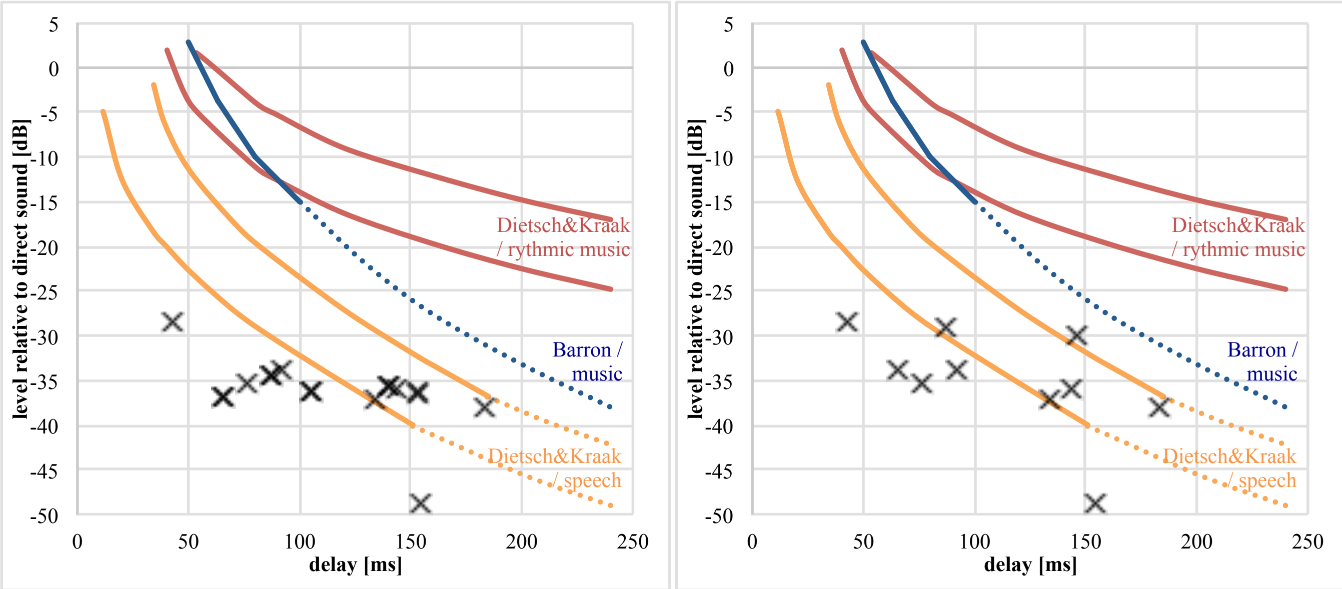


Figure 12: Echo graph for a source located at a soloist position on stage near the conductor, and for the 1kHz octave band. Each reflection is represented by a black cross corresponding to its relative level and delay with respect to direct sound at 1m distance to the source. Red and orange lines correspond to empirical echo thresholds found by Dietsch and Kraak respectively on a rhythmical music excerpt or a speech excerpt [25]. The blue line corresponds to the threshold for disturbing echo found by Barron with a music excerpt [10]. Dashed lines are regression lines extending the original experimental data to longer delays. On the left, a distinct cross represents each individual reflection, while on the right reflections arriving with very similar delays and directions are grouped and their level is aggregated.

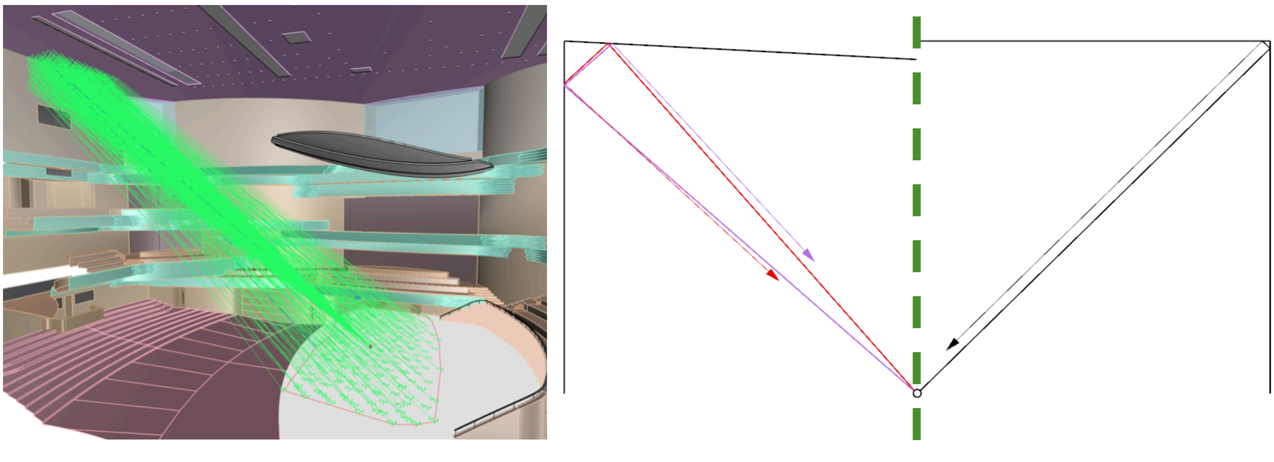

Figure 13: Left picture: Raytracing diagram showing the path for $2^{nd}$ order reflections off the corner between the rear wall and the ceiling. Right picture: 3D diagram showing the difference between a 90° rear corner reflection (in black, to the right of the source point) and twin reflections from a 87° rear corner (in red and purple, to the left). The main ceiling was initially angled at 3° to the horizontal right up to the rear wall, generating an angle of 87° between the two surfaces instead of the usual 90° corner. As a consequence, twin feedback reflections were generated instead of a single one, as two reflection paths exist for rays originating from and ending at the source: a first path in which sound waves first hit the ceiling, then the wall before returning to the source, and a second one in which sound waves first hit the rear wall, then the ceiling before returning the source. A 3dB level increase can be estimated when such twin reflections are generated, compared to the typical case of a 90° rear corner for which only one reflection path exist. In the final design the rear part of the ceiling was finally set to perfectly horizontal to avoid that 3dB level increase.

# 4 Discussion on last acoustic predictions before completion

At the time of writing, the Turku Fuuga music centre is taking shape on its building site and it is too early to judge the acoustic success of the concert hall. The latest available version of the Odeon model is dating from October 2023, while a final version is still in progress. Small changes have been implemented in the meantime, but they are not expected to have a strong impact on the general average values of predicted acoustic parameters. The Akukon team performed all Odeon simulations for this project: Sara Vehviläinen, Perttu Laukkanen and Henrik Möller.

Main parameter values are given in table 1 and are compared to the measurement results in the built Stavanger concert hall, from [5].

As can be observed, obtained values are generally very similar. It seems that Turku concert hall will sound even slightly stronger (with a G value that is 0.8 dB higher on average) and clearer (with a C80 value that is 0.9 dB higher on average) than the Stavanger concert hall. This corresponds perfectly to the wishes of the representatives of Turku Philharmonic Orchestra. It is worth highlighting that this increase in C80 compared to Stavanger is obtained while keeping the same high value of occupied reverberation time. The two halls also stand out for their very high average LF values.

Tapio Lokki and his team at Aalto University also used this Odeon model to generate auralizations of Turku concert hall as predicted by the model. Comparison with a calibrated Odeon model of Vienna Musikverein was available. The listening tests results are very promising, with a general preference for Turku that – in the context of these auralizations – was found to provide both clearer and more enveloping sound when compared to a similar seat in Vienna Musikverein.

In addition, the solid angle analysis was updated based on the latest version of the architectural 3D model (with non-faceted curved surfaces). A significant increase of efficient solid angle was obtained in comparison to the initial design discussed in paragraph 3.1, with a $\Omega_{eff}$ of 1.61 sr (13% of the entire space seen from the source, and +29% compared to the initial design). This increase of efficient solid angle implies a slight reduction of the late solid angle $\Omega_l$ that is now 3.96 sr (31% of the entire space seen from the source, and -5% compared to the initial design). This results in a predicted increase of average early-reflected strength ($G_{em}$) of 1.1dB and a corresponding decrease of average late strength ($G_{lm}$) of 0.2dB. Homogeneity was also drastically improved compared to the initial state, with an average increase of $G_{em}$ in balcony seats of 3.8dB. These results provide a good quantitative summary of the overall impact of several months of geometrical optimisation for the Turku concert hall, and illustrate the possibility of simultaneously achieving very clear acoustics with generous reverberation.

Table 1: Provisional Odeon simulation results in Turku concert hall compared to measurements results in the built Stavanger concert hall. Each parameter value is the average of all receiver position located more than 10m to the source, distributed evenly in each room. The acoustic configuration with maximum RT is considered in both cases (symphony orchestra setting, as both halls have variable acoustics). Parameters are defined, measured and frequency averaged according to ISO 3382.

| **Occupancy** | **Acoustic parameter** | **Turku concert hall Odeon simulation results** | **Stavanger concert hall Measurements** |
|---|---|---|---|
| Full audience | T30 (s) | 2.2 | 2.2 |
| Unoccupied | G (dB) | 5.0 | 4,2 |
| | G80-∞ (dB) | 2.3 | 1.9 |
| | G0-80 (dB) | 1.5 | 0.3 |
| | C80 (dB) | -0.7 | -1.6 |
| | LF (%) | 0.27 | 0.30 |

Figure 14: Architectural rendering of the main concert hall of Turku Fuuga music centre, in its latest version at the time of writing. © PES-Architects

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