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ROOM ACOUSTIC DESIGN FOR THE CONCERT HALLS

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EXECUTIVE SUMMARY

The concept design phase for the new concert hall in Turku has been fruitful and very promising in terms of acoustic quality. The main concert hall, especially, was developed to a level that promises to be world-class, both architecturally and acoustically. The acoustic design work on this large symphony hall has mainly focussed on 3 key subjects:

- Designing a stage environment with the right size and all the necessary features to accommodate all types and sizes of orchestras. The stage platform dimensions were adjusted to provide the best conditions for good cohesion and precision of the orchestra sound. The adequate nature, size and detailed shape of the reflective surfaces surrounding the stage was studied and defined. This notably includes the large canopy suspended above the stage, for which the height can be adjusted depending on the orchestra size and the specific needs of each musical work. First acoustic predictions (presented in a separate report) indicate an excellent general result, with some local points of vigilance that will require further work in the next design phase.
- Developing a sufficiently spacious acoustic volume for a long, rich and enveloping reverberant sound. The celling shape, especially, was adjusted to increase the total acoustic volume and bring more acoustic reverberation from above and behind the audience. The additional acoustic volumes (or “acoustic chimneys”) located behind the side balconies were also further developed with the aim of creating a more enveloping reverberant sound that will surround audience members from all directions. First acoustic predictions give extremely promising results, with a very strong and long reverberation, without compromising clarity. During the next detailed design phase, it is typical that the acoustic volume slightly diminishes, resulting also in a slight reduction of reverberation time. The current design allows for a sufficient safety margin to cope with these future developments.
- Checking and adjusting the position, size and detailed shape of all hard surfaces contributing to early acoustic reflections. These reflections are crucial to ensure a present and precise orchestra and soloist sound across the audience and to allow for a sense of proximity and engagement even at the farthest seats. Balcony front surfaces and adjacent wall surfaces were adjusted in their position, orientation and curvature to provide adequate amounts of early reflections to all audience areas and for all possible sound source positions on stage. First acoustic predictions results are once again extremely promising, displaying a very generous provision of early reflections that is able to offer a high level of acoustic clarity even in a very reverberant environment. Some inhomogeneity in the early reflection coverage was spotted in some areas of the parterre and the side balconies surrounding the stage. These will need to be further investigated in the next design phase.

Important design work was also delivered on the small hall, with the aim of creating a space that would be acoustically perfectly adapted to the two main purposes of the hall: chamber music concerts and orchestra rehearsals, without requiring excessively complex and expensive space modularity. The proposed design is promising as well, as clever solutions were developed to cope with the sometimes-conflicting needs of these two main uses. It must however be stated that a smart re- evaluation of the main purpose(s) of this small hall could lead to a simpler and less expensive design.

YHTEENVETO SUOMEKSI

Turun Musiikkitalon hankesuunnitteluvaihe on ollut antoisa ja akustisen laadun kannalta erittäin lupaava. Ison konserttisalin suunnitelmat on kehitetty tasolle, joka mahdollistaa sekä maailmanluokan arkkitehtuurin, että maailmanluokan akustiikan. Ison konserttisalin akustinen suunnittelu on keskittynyt pääasiassa kolmeen pääosa-alueeseen:

- Lavan ja lavan ympäristön suunnittelu, jonka tarkoituksena oli varmistaa lava-alueen akustinen ja toiminnallinen laatu kaikentyyppisille ja -kokoisille orkestereille. Lava-alueen mittasuhteet määriteltiin tarjoamaan parhaat olosuhteet orkesterin keskinäiselle kuulemiselle. Lavaa ympäröivien heijastavien pintojen paikat ja muodot määriteltiin yhdessä arkkitehdin kanssa. Näihin pintoihin kuuluu erityisesti lavan yläpuolelle suunniteltu orkesteriheijastin, jonka korkeutta voidaan säätää orkesterin koon ja kunkin musiikkiteoksen erityistarpeiden mukaan. Akustiset mallinnustulokset (raportoitu raportissa *AKU-201288-007 Turun Musiikkitalo 0002241 – konserttisalin akustinen malli*) osoittavat lava-alueen akustiikan toimivan yleisellä tasolla erinomaisesti. Mallinnuksen perusteella kuitenkin havaittiin myös paikallisia alueita, jotka tarvitsevat jatkokehitystä. Näitä tullaan tutkimaan tarkemmin ja kehittämään jatkosuunnittelussa.
- Riittävän akustisen tilavuuden varmistaminen. Konserttisalin riittävä tilavuus on yksi tärkeimmistä kriteereistä riittävän pitkän ja täyteläisen jälkikaiunnan saavuttamisessa. Salin kattopinnan vähimmäiskorkeus määriteltiin tarkasti, jotta salin akustinen tilavuus saatiin riittävän suureksi, ja mahdollistettiin kaiunnan muodostuminen yleisön yläpuolelle ja taakse. Lisätilavuutta suunniteltiin niin ikään parvekkeiden taakse. Nämä ’akustiset savupiiput’ mahdollistavat ympäröivän jälkikaiunnan muodostumisen parville. Ensimmäiset akustiset mallinnustulokset ovat olleet lupaavia. Tärkeimpinä tuloksia mainittakoon riittävän pitkä ja voimakas jälkikaiunta, kuitenkaan selvyydestä tinkimättä. Toteutussuunnitteluvaiheessa on tyypillistä, että salin akustinen tilavuus hieman pienenee, joka lyhentää jälkikaiuntaa hieman. Tämän hetken suunnitelmissa on juuri oikea määrä varaa tilavuuden pienentymiselle.
- Varhaisten sivuttaisten heijastusten varmistaminen. Varhaisia sivuttaisia heijastuksia tarjoavien pintojen sijaintien, koon ja muotojen optimointiin käytettiin hankesuunnitteluvaiheessa paljon aikaa. Varhaiset sivuttaiset heijastukset ovat ehdottoman tärkeitä varmistamaan, että orkesterin ja solistin äänet kuuluvat koko yleisöalueelle selkeästi ja ”intiimisti”, sekä aikaansaamaan läheiseltä tuntuvan ja kuuntelijaa ympäröivän äänikentän jopa kauimmille yleisöpaikoille. Parvekkeiden etupintojen ja viereisten seinäpintojen paikkaa, suuntaa ja kaarevuutta säädettiin niin, että ne tarjoavat riittävästi varhaisia heijastuksia kaikkialle yleisöön kaikista äänilähdepisteistä lavalla. Ensimmäiset ennusteet akustisista olosuhteista vaikuttavat erittäin lupaavilta ja osoittavat, että saliin on mahdollista aikaansaada suuri määrä aikaisia heijastuksia, jotka tuottavat korkeatasoisen akustisen selvyyden erittäin kaiuntaisesta ympäristöstä huolimatta. Joitakin epäjohdonmukaisia tuloksia varhaisten heijastuksien kattavuudessa havaittiin joillakin permannon alueilla ja sivuparvekkeilla lavan ympärillä. Nämä tullaan tutkimaan tarkemmin seuraavassa suunnitteluvaiheessa.

Tärkeä suunnittelutyö tehtiin myös pienen salin osalta, jossa tavoitteena oli luoda tila, joka on akustisesti sopiva kahdelle pääkäyttötarkoitukselleen: kamarimusiikin konsertit ja orkesterin harjoitukset, vaatimatta liian monimutkaista ja kalliisti muotoiltua tilaa. Ehdotettu suunnitelma on myös lupaava, sillä näitä kahta, osin ristiriitaista pääkäyttötarkoitusta varten on kehitetty ovela ratkaisu. Täytyy kuitenkin painottaa, että salin pääkäyttötarkoitusten harkiten tehty uudelleenanalysointi voisi johtaa yksinkertaisempaan ja halvempaan ratkaisuun.

1 INTRODUCTION

The main concert hall in the new Turku Music Centre (Turun musiikkitalo)– with a planned capacity of approximately 1,400 seats – is the heart of the project. In addition to its main symphonic use, the concert hall will be acoustically flexible, providing good acoustic conditions also for recitals, chamber music and semi-staged opera, as well as uses incorporating amplified sound, video projection and new media, such as jazz, world music and spatially and electronically manipulated contemporary music. It is clear however that the main purpose of the concert hall remains symphony orchestra concerts, and that acoustic design is focussed on providing excellence for that core function. The secondary uses are also taken into considerations in the design, but whenever a conflict is identified, acoustic quality for symphony orchestra concerts always takes precedence.

This report describes the design work delivered during the concept design phase in this pursuit of acoustic excellence.

The document is structured as follows:

- A chapter detailing the work carried out on the main concert hall acoustic design. All aspects of the design are covered, including the stage platform design, the acoustic volume design, the early reflection design, and the variable acoustic design. Adjustments made and decisions taken are always explained. Specifications for building materials are also provided, and a summary of the remaining work to be done concludes that chapter.
- A shorter chapter explaining the work carried out on the small hall. This chapter is currently less detailed than for the main concert hall, as strategic orientation regarding the main intended purpose of this small hall is still an important matter. The main design decisions taken are still described and explained. They could be further detailed once the strategic orientation for this hall is confirmed.

2 MAIN CONCERT HALL / SALI

2.1 Stage platform design

The design of the stage platform of the main concert hall has been an important focus of this design phase, in order to combine all possible requirements and constraints into one optimal stage design. Regarding acoustics, the stage design is important in several ways. First, it is the place of production of the sound and can therefore greatly influence the sound quality. But in addition to that direct acoustic influence, providing satisfactory physical and listening comfort to orchestra musicians also significantly impacts on the cohesion, precision and musicality of the orchestra sound. Good listening conditions for orchestra musicians include the necessity to hear precisely the sound of one’s own instrument, but also the sound of others in the same instrument group or across the stage, as well as the necessity to receive a proper acoustic feedback from the concert hall. Apart from these important acoustic needs, many practical constraints have to be incorporated to the stage design: providing sufficient space to each musician without spreading the orchestra excessively, integrating sufficient flexibility to accommodate various orchestra sizes, accommodating adequate stage entrance paths, insuring thermal comfort and humidity control… Several meetings were organized to better understand and take care of the specific needs of all orchestra musicians. Several versions of the stage layout were suggested, studied, compared to other existing orchestra stages and adjusted until resulting in the finally proposed version, which accurately fulfils all needs and balances conflicting requirements.

The general dimensions of the proposed stage platform are large, typical of a concert hall fitted to accommodate the largest international touring orchestras. As can be seen from the table below, it is much larger than the stage platforms of Berlin Philharmonie and Stavanger concert hall. Both Berlin and Stavanger stages are known to be excellent but tight stages. It is also much larger than Luzern and Lahti stages without their stage extensions. Indeed, the proposed stage in Turku is of similar size as the Lahti stage with its stage extension and Luzern stage with is largest stage extension. And this is not even counting the possible stage extension proposed in Turku. This confirms that even without a stage extension, the proposed stage is large enough to accommodate the largest international orchestras.

As can also be seen from the table below, the width of usable stage floor area was limited to a similar value as in Stavanger and Luzern concert hall. The large total area is obtained by opting for a large stage depth, but not by increasing the width. This is made on purpose as limiting the stage width improves listening conditions across the orchestra as well as lateral reflections and spaciousness for the audience. The stage depth of 13,4m is on the large side. It implies a slight delay of the sound coming from the percussions compared to the sound coming from the strings as heard from the audience or the conductor position (about 35ms as a maximum). Such a delay is typically something that the percussionists can still easily compensate for. When adding the stage extension, the stage depth is further increased to 15,9m, which potentially increases that delay to more than 40ms, which will make the compensation process more difficult. Of course, the choir singers and the organist would need to compensate for even larger delays. These considerations demonstrate that it is not desirable to further increase the stage size. Any further increase of stage depth or stage width would be at the expense of acoustic quality and ease of ensemble playing.

Stage dimensions	Depth (m)	Width (m)	Usable floor area (m²)	Stage extention area and depth	Total available floor area and depth
Berlin Philharmonie	11,40	16,30	172	-	172m²
Luzern KKL	11,30	18,10	178	40m² (2,2m)	218m² (13,5m depth)
Lahti	12,45	20,90	140	60m² (2m)	209m² (14,45m depth)
Stavanger	11,90	18,20	184	-	184m²
Turku proposed stage	13,40	18,20	211	46m² (2,5m)	211m² (13,4m depth) 257m² (15,9m depth)

The large floor area is proposed to be equipped with motorized stage risers to allow for an easy to operate flexibility and adaptation to the various possible orchestra sizes, without any compromise on the quality of the stage floor. The shape and exact size of each motorised platform is however not flexible and need to be designed in accordance to the specific needs of each orchestra groups. To go into further details of the stage design, the diagrams below allow for a comparison of the proposed platforms for Turku new concert hall, with those of existing international symphony halls.

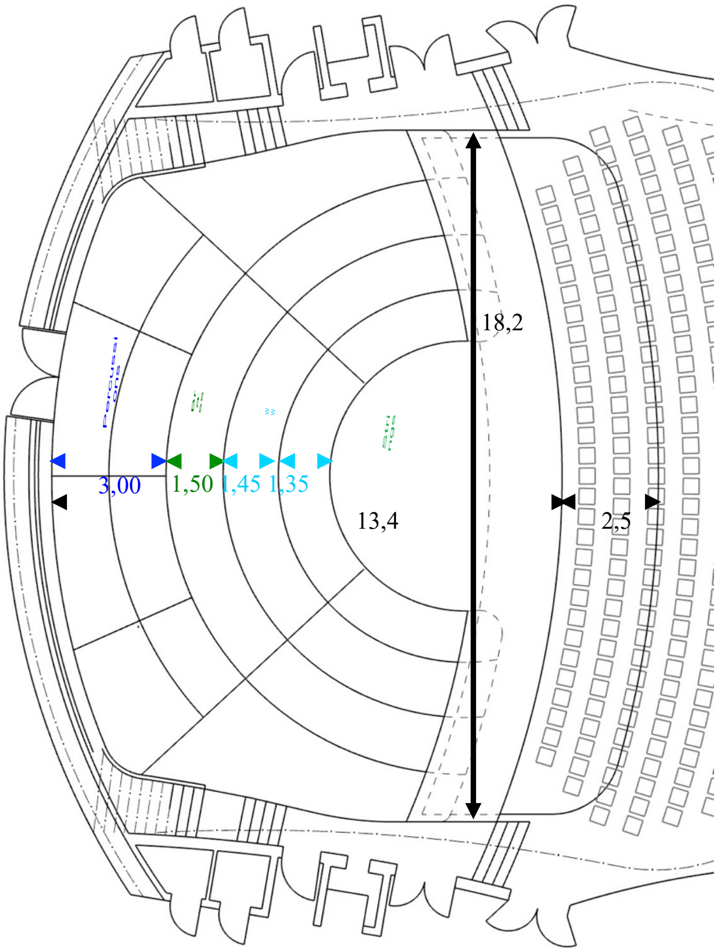

Figure 1: Proposed stage layout for Turku

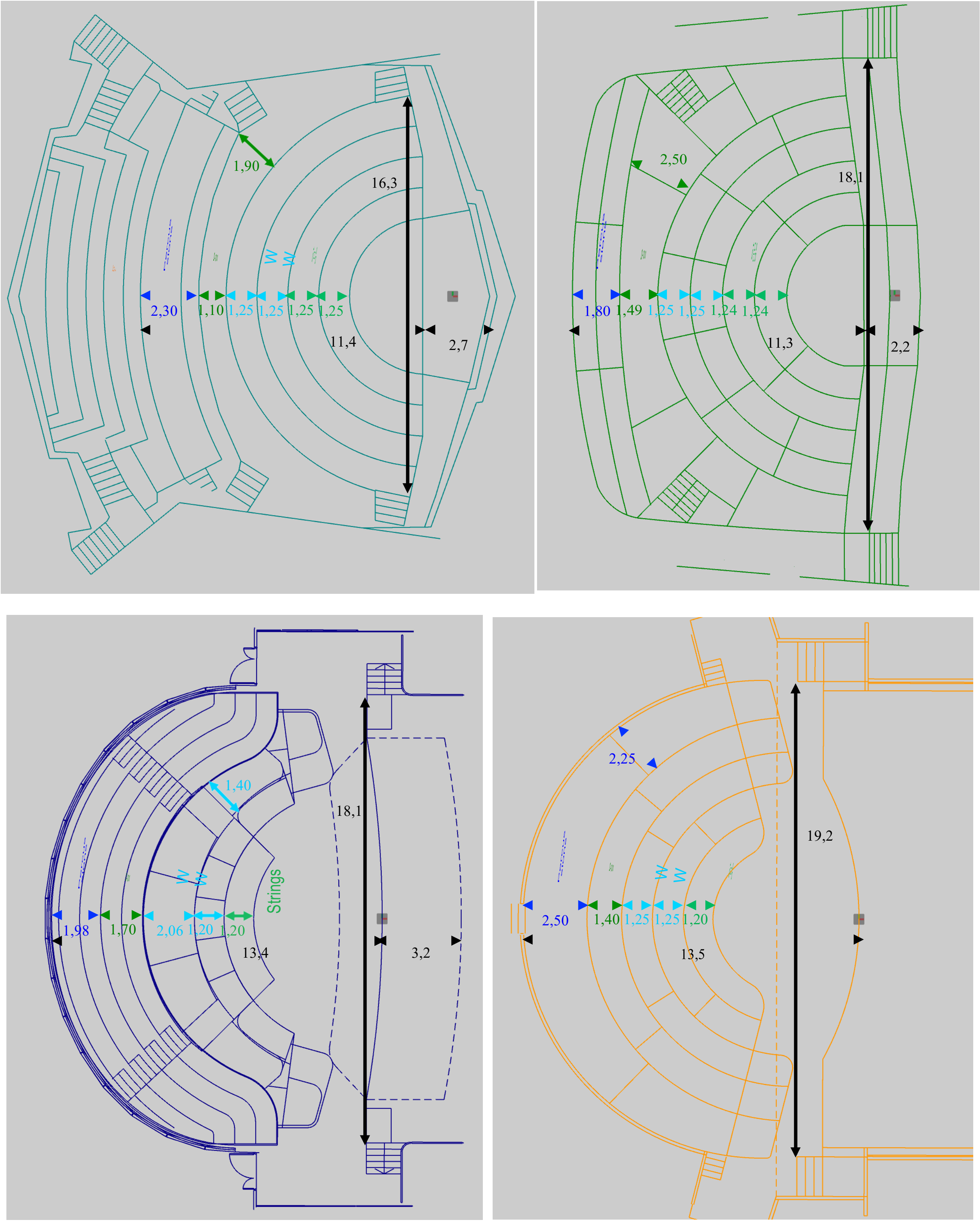

Figure 2: Stage layouts in existing concert halls. Top left: Berlin Philharmonie; top right: Luzern KKL; bottom left: The Sage Gateshead; bottom right: Birmingham Symphony Hall.

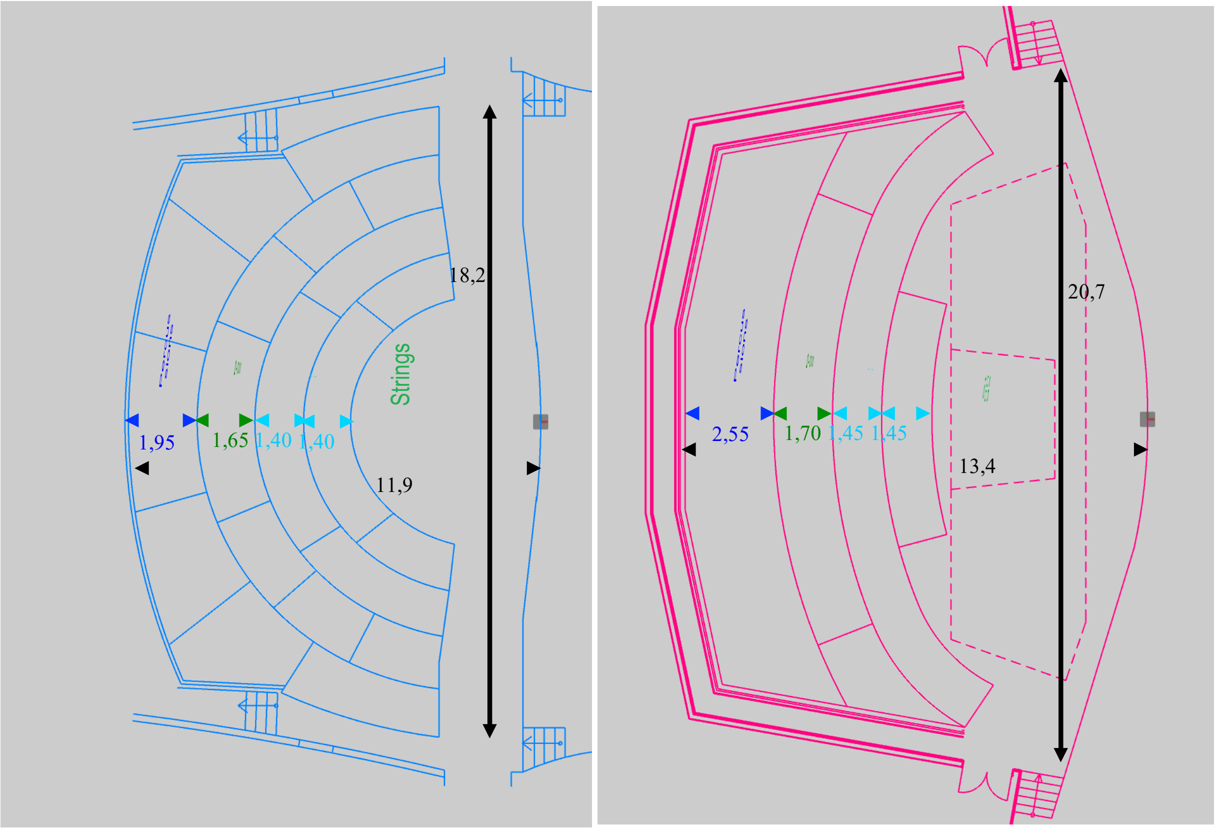

Figure 3: Stage layouts in existing concert halls. Left: Stavanger Concert hall; right: Lille Nouveau Siècle Concert Hall

These diagrams and their comparison illustrates that the proposed platform dimensions are comfortable in size without being excessive. The rear two platforms accommodating percussion instruments are significantly larger than in any of the compared concert halls, and most of the existing ones, with a total depth of 3m. It was decided to subdivide that zone in two platforms in order to provide more flexibility in orchestra arrangements in cases where a smaller zone is needed for percussion instruments.

Other aspects regarding the stage acoustic design, and acoustic conditions for the musicians on stage are further developed in the rest of this report. This includes subjects such as stage floor specifications, early reflection design towards the stage, acoustically absorptive curtains at the back of the stage and rehearsal curtain to compensate for the absence of audience.

A stage pit is also accommodated in front and below the stage platform, as required in the program. The 2.5m deep stage extension displayed in Figure *1* can be set either at stage level (stage extension mode), at the level of the first rows of audience ("normal" mode, accommodating maximal audience), or lowered even further to create an orchestra pit ("pit mode"). This platform having an area of approximately 45m^2, it is sufficient in itself when only a few musicians have to be accommodated. Accommodating a large orchestra in the pit requires using in addition some of the pit area that is encased under the stage platform. This encased zone allows for more space and larger orchestras, but it also comes with significant shortcomings: instruments located in that zone have a somewhat muffled sound compared to those located in the open zone, and musicians located in the encased zone very often suffer from excessive sound levels which can occasionally cause them hearing damage. For these reasons, it is often advised to limit the encased pit area to a maxim of 30% of the total area. That ratio can be increased to 50% or even 60% in specific cases, when an encased orchestra pit is wanted in full knowledge of the facts. In the case of Turku concert hall, applying the 30% ratio would result in a total pit depth of 3.75m, and a total pit area of 67,5m^2, which would be large enough to accommodate orchestras of up to 30 musicians on average (depending on which instruments are to be accommodated). Accommodating larger orchestras would require a larger encased area, with the associated shortcomings that need to be accepted, and also with an associated significant extra cost.

In addition, it must be understood that creating a large enough orchestra pit will not be sufficient to transform the concert hall into an opera hall. Opera productions also require specific theatre technical installations, including abundant motorization above the stage and lighting positions above the audience, that are in conflict with the needs of a symphony hall. In that context, our opinion is that the exact needs associated to the orchestra pit asked in the brief would need to be further thought of and clarified.

2.2 Acoustic volume and reverberation

Several actions were undertaken since the initial competition phase design in order to optimize the acoustic volume of the hall and its distribution around the audience and the musicians.

Having sufficient acoustic volume is key to allowing a sufficiently long and rich reverberation to develop in the concert hall. It is also key to avoid acoustic saturation in the loud musical passages and for the largest orchestras. The volume of the main hall is currently estimated to be around 20’000 m^3, which is within the ideal range defined in the acoustic brief (between 18’000 and 20’000 m^3). Acoustic predictions using Odeon simulation software (see separate acoustic report on that matter) result in an obtained reverberation time of 2.4s on average, in fully occupied conditions. This demonstrates the potential to develop this concert hall into one of exceptionally rich and strong acoustics. Some acoustic variability will however be advisable in order to slightly reduce the reverberation time and the risks of acoustic saturation, depending on the musical works.

In addition, at this stage of the design, architectural finishes have not all been precisely defined in their nature and thickness. It is usual that the acoustic volume of a concert hall slightly reduces, as the design gets more and more detailed, resulting also in a slight reduction of reverberation time compared to initial estimations. In that respect, achieving such a long reverberation time, slightly above the range defined in the acoustic brief (between 2.0 and 2.3s), is in fact an excellent result. It leaves a sufficient margin for future development of the architectural design. And it also offers the opportunity to tune the acoustics of the finally built hall from the loudest and most demonstrative acoustics to more subtle settings, depending on musical expectations.

But the total acoustic volume is not the only important aspect. Its distribution around the audience and the stage is key to spaciousness, the feeling of being surrounded and fully enveloped by reverberant sound. Acoustic reverberation develops predominantly in zones of the concert hall with ample space and little absorption. The proposed design shares with traditional shoebox concert hall a configuration where most of the acoustic absorption is located in the lower half of the volume. No audience nor acoustic treatment is located in the upper half of the concert hall, which allows for ample reverberation to develop above the audience and the stage. In order to move the “acoustic center” of the room towards the main audience and favour an acoustic halo surrounding the audience rather than a fog around the orchestra, the main ceiling was slightly angled to provide a maximal free height at the rear of the parterre. Its convex lens shape will also favour the projection of reverberant sound towards the periphery of the upper volume, improving the sense of acoustic envelopment that this acoustic halo will provide. In addition, vertical void spaces have now been delimited behind all of the side balconies, connecting the upper reverberant volume to the lower half of the space where the audience is located, creating “acoustic chimneys” for the reverberant sound to travel around the audience and reach the listeners from all possible directions.

2.3 Variable acoustics

Variable acoustic devices are required to be included into the design of the main concert hall. The primary goal of these devices is not to modify the acoustics of the symphony hall and make it more suitable to other uses such as amplified pop concerts or conferences. Their primary goal is to allow for the necessary acoustic adjustments for classical music.

Three type of variable acoustic devices, with three different acoustic goals, are planned:

- Retractable acoustic curtains around the stage platform. These curtains are installed on curtain tracks and can be deployed along the stage rear wall and the rear part of the stage sidewalls. The role of these curtains is to allow for fine-tuning of the orchestra balance. They can be deployed locally to avoid excessive loudness of some instruments located near these walls. A sound transparent architectural surface, such as an open wood lattice (50% openings) is planned to cover these walls and hide these curtains so that they can be installed when and where acoustically needed with no consequence on the visual aspect of the stage environment. The door located inside that stage back wall also needs to be covered with that curtain and sound transparent surface. This will require to build a door or removable zone in the sound transparent surface in addition to the real acoustic door. These curtains cannot simply be pulled manually, as they are not accessible behind the sound transparent surface. A manual (curtain rope) or motorized mechanism therefore has to be provided. These curtains are planned with a total length about 20m and a height of about 2.5m, representing a total area of about 50m^2. They do not need to be stored in curtain pockets.
- One large rehearsal curtain that can store above the main ceiling of the concert hall, hidden by a motorized hatch. It deploys vertically in the middle of the volume, in front of the rear balconies. The role of this curtain is to lower the reverberation time during rehearsals, as the hall without an audience will have a longer reverberation time. The minimum size of that rehearsal curtain is 260m^2 (13m width x 20m height, or slightly less height, counting on both sides of the curtain being visible to sound). The action of these curtains has to be motorized.
- Several retractable acoustic curtains located in front of the outer sidewalls, both in the “acoustic chimneys” behind the side balconies, and in the upper volume between the technical gallery level and the main ceiling. The role of these curtains is to tune the acoustic reverberation both during rehearsals and concerts. As discussed in chapter 2.2, a long maximum reverberation time is aimed at for Turku concert hall, which will be perfectly fitted to some of the repertoire (choirs, baroque orchestral music, organ…) and may sound excessively rich and loud some other repertoires (very large symphony orchestras, modern and contemporary music…). These curtains will need to store in fully closed curtain boxes integrated either to the walls (in the case of horizontally sliding curtains) or to the ceiling (in the case of vertically deploying curtains). The exact nature and location of these curtains still remains to be developed in the next design phase. A minimum quantity of 400 to 500m^2 (depending on the nature of these curtains and their acoustic properties) is however required to obtain a sufficiently wide range of tunability.

Acoustic curtains can be made out of different fabrics. Heavy velour and wool serge are the most effective at absorbing sound. Heavy velour has to be chosen with a mass of 500 g/m^2, and needs to be pleated by installing an area of fabric that is twice the wall area to be covered. This is our suggested solution for the retractable acoustic curtains located around the stage platform. Wool serge has to be chosen with a mass of 500 g/m^2 as well. It does not need to be pleated and can be installed on the flat. In that case, a double layer of fabric (with an air gap in between) is however required to reach sufficient acoustic absorption. This is our suggested solution for the rehearsal curtain. Similar solutions can be used for the acoustic tuning retractable curtains, but other fabric can also be considered, such as semi-transparent fabrics that might be interesting especially when installed in front of the large glass walls in the upper part of the hall. Semi-transparent fabrics are generally slightly less absorptive, and therefore require to be installed with a larger quantity to reach the same acoustic effect of reverberation (up to +50% depending on the fabric and its installation).

In case the chosen fabric would need to receive a specific fire treatment, this treatment should not impair its acoustic properties, and will need to be approved acoustically based on acoustic measurement results.

2.4 Acoustic design for early reflections

Long and rich reverberation cannot come at the cost of precision and musical clarity. The acoustic presence of the room, through its enveloping reverberation, has to be balanced by sufficient presence and physicality of the sound sources. That is where early reflections are crucial. Every seat in the audience needs to receive not only the direct sound wave traveling from the stage, but also several slightly delayed copies of it, generated by nearby reflective surfaces. When the delay and strength of the reflection is appropriate, its energy effectively adds up to that of the direct sound wave and makes it sound stronger. When the direction of arrival of the reflection is appropriate, it widens the spatial perception of the sound source and makes it sound bigger. With an appropriate amount of such reflections, audience members feel physically connected with the musicians on stage, enhancing the feeling of proximity and engagement. Early reflections are similarly useful for musicians on stage as they influence their ability to hear precisely their own sound and the sound of fellow musicians across the stage.

The following paragraphs focus on the design work that has been produced in order to generate a homogeneous and generous coverage of such early reflections to all audience areas, as well as towards the musicians on stage.

2.4.1 Balcony fronts and sidewalls

Balcony front and sidewall surfaces, when properly located and angled in space, can generate the most useful early reflections: those that arrive at the audience ears from a lateral direction. This has therefore been the main design effort during this phase, to adjust the detailed shape of the concert hall in order to ensure a homogeneous coverage of the entire audience with such early lateral reflections.

Following a study trip to Kristiansand and Stavanger concert halls, one of the first design moves for this phase has been to compare the general width of the competition design for Turku concert hall with that of Stavanger concert hall. Stavanger concert hall is considered as an appropriate example of what is wished for in Turku in terms of early lateral reflections. That comparison (see Figure *4*) resulted in a decision to slightly reduce the stage width, and more significantly the width of the front part of the parterre. By reducing the width, early lateral reflections to the stage and the audience are made to arrive quicker and stronger at listeners' ears. In addition, lateral seats in the front part of the parterre are not very good seats both in terms of sightlines (looking towards the back of the musicians) and in terms of orchestra balance (instruments located closer are inevitably heard stronger than those on the other side of the room), it was therefore proposed to delete these side seats by reducing the parterre width and placing the corridors and stairs along the sidewalls. The room width was also slightly reduced at balcony levels by moving side balconies forward.

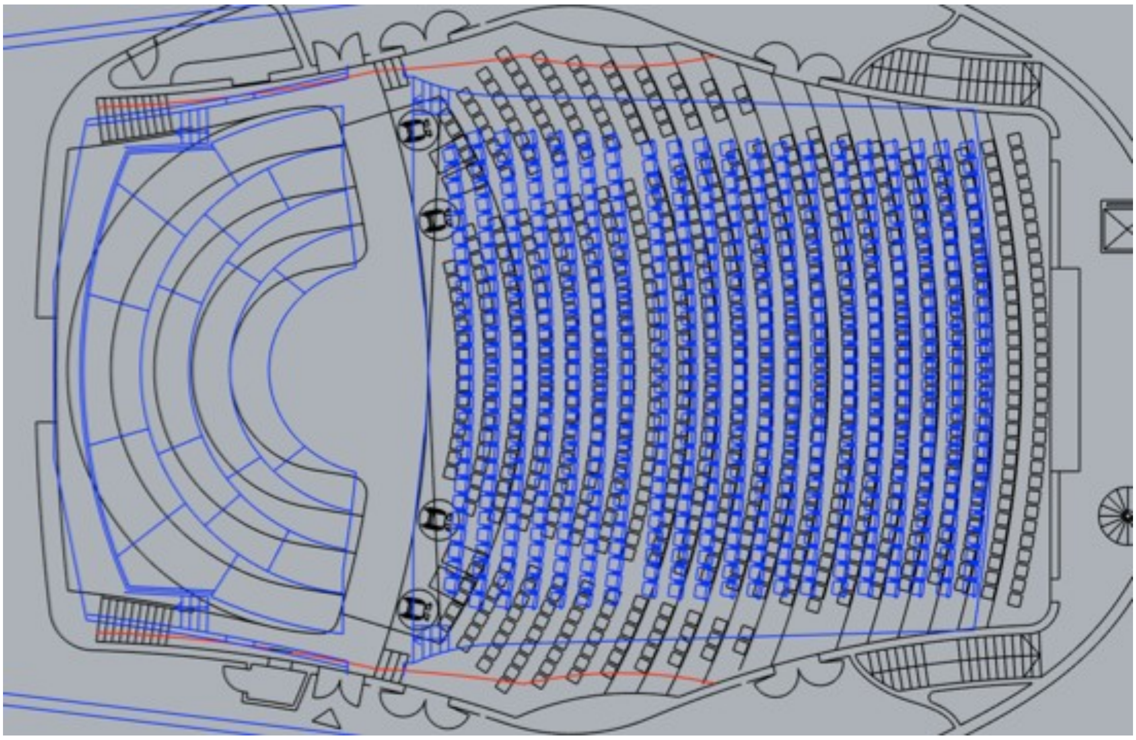

Figure 4: Overlay of the main floor plan of Turku concert hall (competition phase, in black) and Stavanger concert hall (as built, in blue). Red lines are a proposal to reduce the width on stage and in the front part of the parterre. This proposal was later adjusted and properly integrated to the design. (Note: The stage layout displayed here is not the finally chosen stage layout, the stage was later significantly increased in size).

The second step of acoustic design has been to analyse the acoustic effect of each balcony front and sidewall surface individually and to propose some modifications of these surfaces in order to properly orient lateral reflections to all audience areas, with appropriate homogeneity for all possible sound sources position on stage.

The size of each acoustically efficient surface was checked in order to make sure that it will reflect not only the high frequencies (high pitch tones) but equally the mid and a significant part of lower spectrum (low pitch tones). All acoustically efficient surfaces must have their smaller dimension bigger than 1m. This value can exceptionally go down to a strict minimum 90cm for a few surfaces where making them bigger will have serious side effects.

Acoustically efficient balcony fronts and sidewalls were already convexly curved in plan in the competition design. This curvature helps spreading the reflected sound to wider areas of audience while making the sound of those early reflections slightly mellower / less sharp. However, geometrical acoustic analysis performed during this phase showed that this curvature in plan was not sufficient to allow for homogeneous reflection coverage. Some zone of audience would receive proper early reflections originating from some locations of sound sources on stage but not others, resulting in unbalanced orchestra sound. In order to correct that issue, a slight convex curvature of these surfaces in in section (in a vertical plane) was added. This results in double curved surfaces as depicted in Figure *5*.

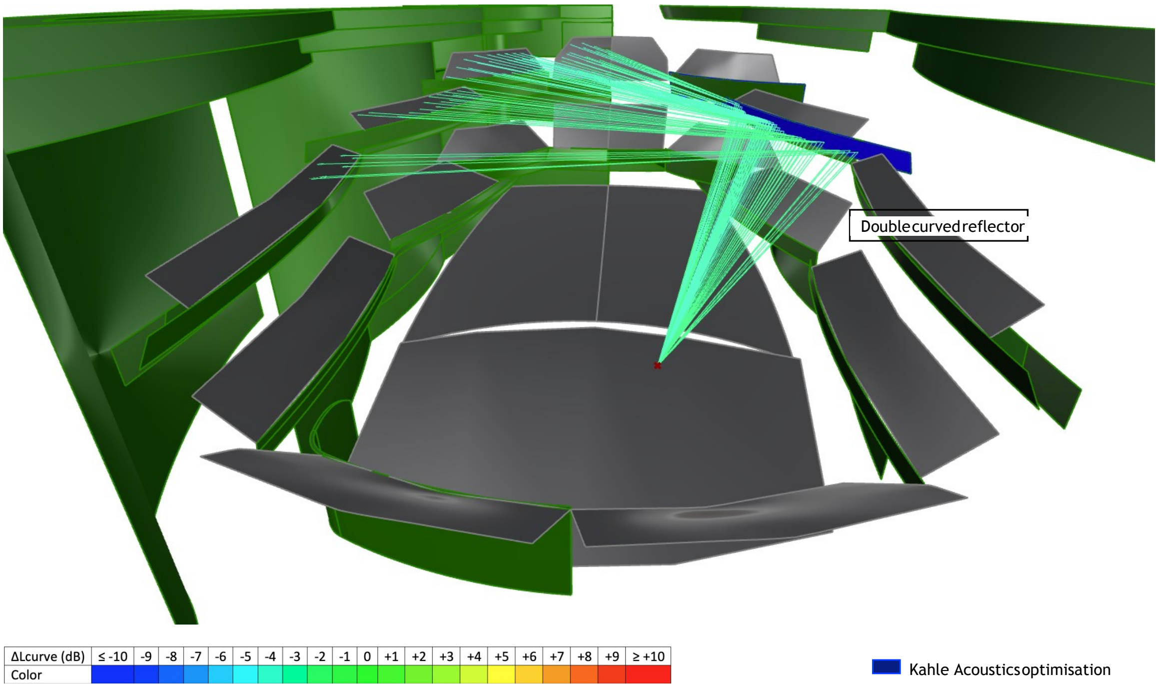

Figure 5: Raytracing diagram displaying the acoustic reflections generated from a balcony front surface after a sight curvature in section was added. The color of each ray informs on the acoustic strength of the generated reflection: green rays are as strong as if the reflection was on a purely flat surface while cyan rays are slightly softer due to the geometrical spreading caused by convex curvature. That softening effect is kept always above the -4dB tag in order to keep sufficiently strong reflections.

Other geometrical optimisations included:

- Adjustments to the tilt angle of each balcony front surface for a more homogeneous coverage of reflections.
- Introduction of slight “twist” to some efficient surfaces, for which the tilt angle is made to vary along the length of the surface in order to adjust to direction of early reflections.
- Modifications to the rear corners of the technical gallery balcony fronts, in order to avoid late echoes towards the stage and let early lateral reflections from the upper corners of the hall reach the balconies, as displayed in Figure *6* and Figure *7*.

The current level of geometric optimisation of the concert hall can now be considered as excellent. Further verifications and slight adjustments are still planned for the next phase(s), but the global architectural design has already proven to be exceptionally efficient and promising in terms of acoustic quality. Required adjustments to the initial competition phase design were limited to the small details only, and were always relatively easy to integrate to the architectural design. This demonstrates that the base project is particularly healthy and resilient. Early lateral reflections being considered as key to acoustic excellence, it can be safely stated that this concert hall design is on the right track towards success.

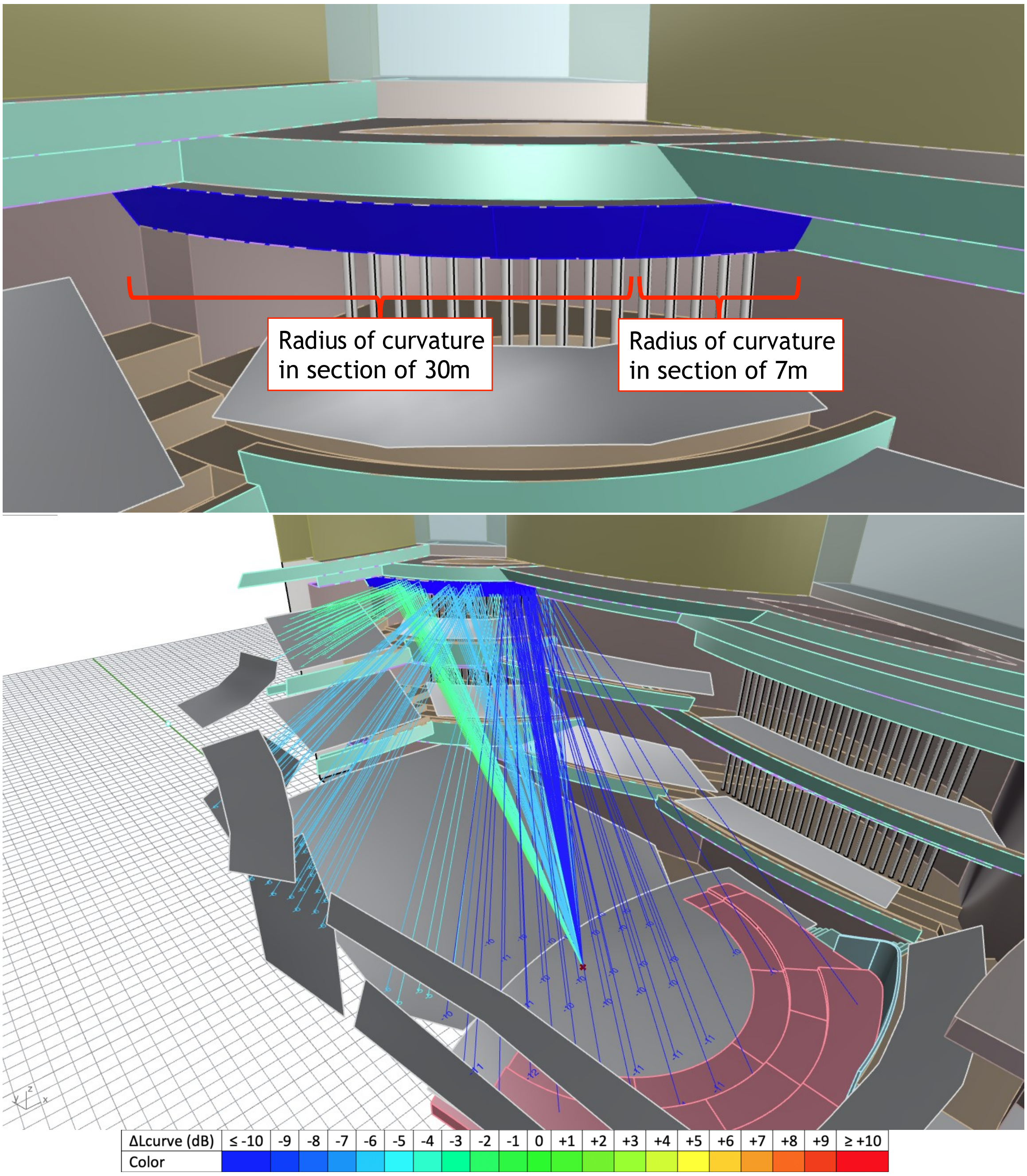

Figure 6: Suggested and implemented "surface morphing" of the rear corners of the technical gallery balcony front. A varying radius of curvature in section of that surface, as displayed in the upper picture, helps generating much softer reflections towards the stage while keeping strong lateral reflections towards the top balcony seats, as displayed in the lower picture. Acoustic reflections generated off that surface and oriented back to the stage are arriving excessively late and would damage sound clarity if they were too strong. The strong convex curvature added to that zone of the surface reduces the strength of these reflections by about 10dB. At the same time, the rest of the surface has a much more subtle curvature in section, and thus generates strong and efficient reflections towards the top balcony

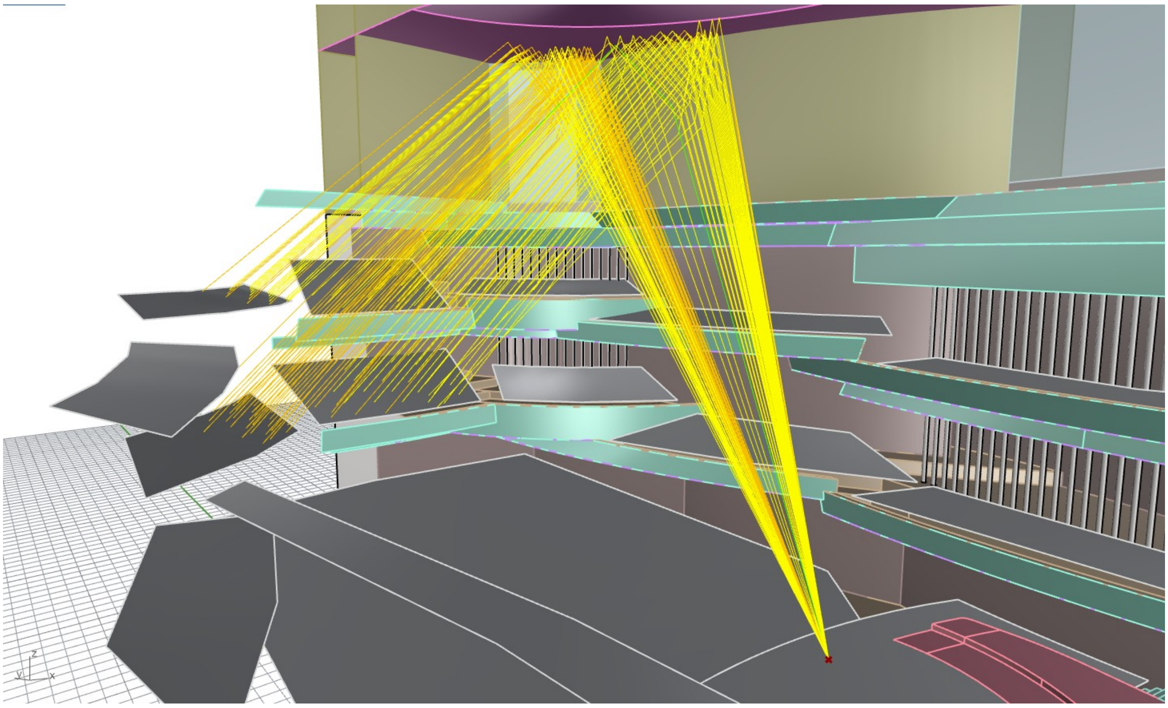

Figure 7: The top rear corners of the hall, where the upper sidewalls meet the periphery of the ceiling, generate very useful lateral reflections to the rear balconies. In the earlier versions of the design, the rear corners of the technical gallery (surfaces discussed in Figure 6) were hindering a significant part of these reflections. The implemented correction consisted in pushing these surfaces back so that acoustic rays from the upper corners of the hall are able to reach all audience seats without being blocked by the technical gallery. The very good acoustic coverage finally obtained is displayed on this raytracing diagram.

2.4.2 Canopy

In modern concert halls, suspended reflectors above the stage platform are generally acoustically required. On the one hand, the ceiling height of a concert hall has to be large enough to reach sufficient acoustic volume for ample reverberation, with values typically around 20 or 21m. But on the other hand such a ceiling height would generate late acoustic reflections back to the stage and the parterre, which would be detrimental to listening precision. Good listening conditions for musicians on stage requires, on the contrary, that ceiling reflections arrive early enough to not be perceived as echoes. Suspending acoustic reflectors at an intermediate height is the solution to meet these two conflicting needs simultaneously.

Several solutions and design options exist for such canopy reflectors, a catalogue of which can be seen in the concert halls built in the last 30 years. For Turku concert hall, it was chosen to design the canopy as a single object incorporating all the necessary technical equipment, stage lighting being first in the list. The size (slightly above 136m^2) and position of that canopy reflector was defined so as to allow for homogenous coverage of ceiling reflections to the stage, the parterre and the choir balcony, for all source positions on stage. The precise shaping of that surface was then defined as depicted in Figure 8, with the goal to generate stronger reflections from sources located in the front part of the stage, and weaker reflections from brass and percussion instruments located at the back of the stage. This is obtained by morphing the canopy surface with a varying radius of curvature along its long section. Similarly, the radius of curvature of the surface varies in short section in order to provide strong reflections towards the stage and the parterre, but also spread weaker reflections towards side balcony seats.

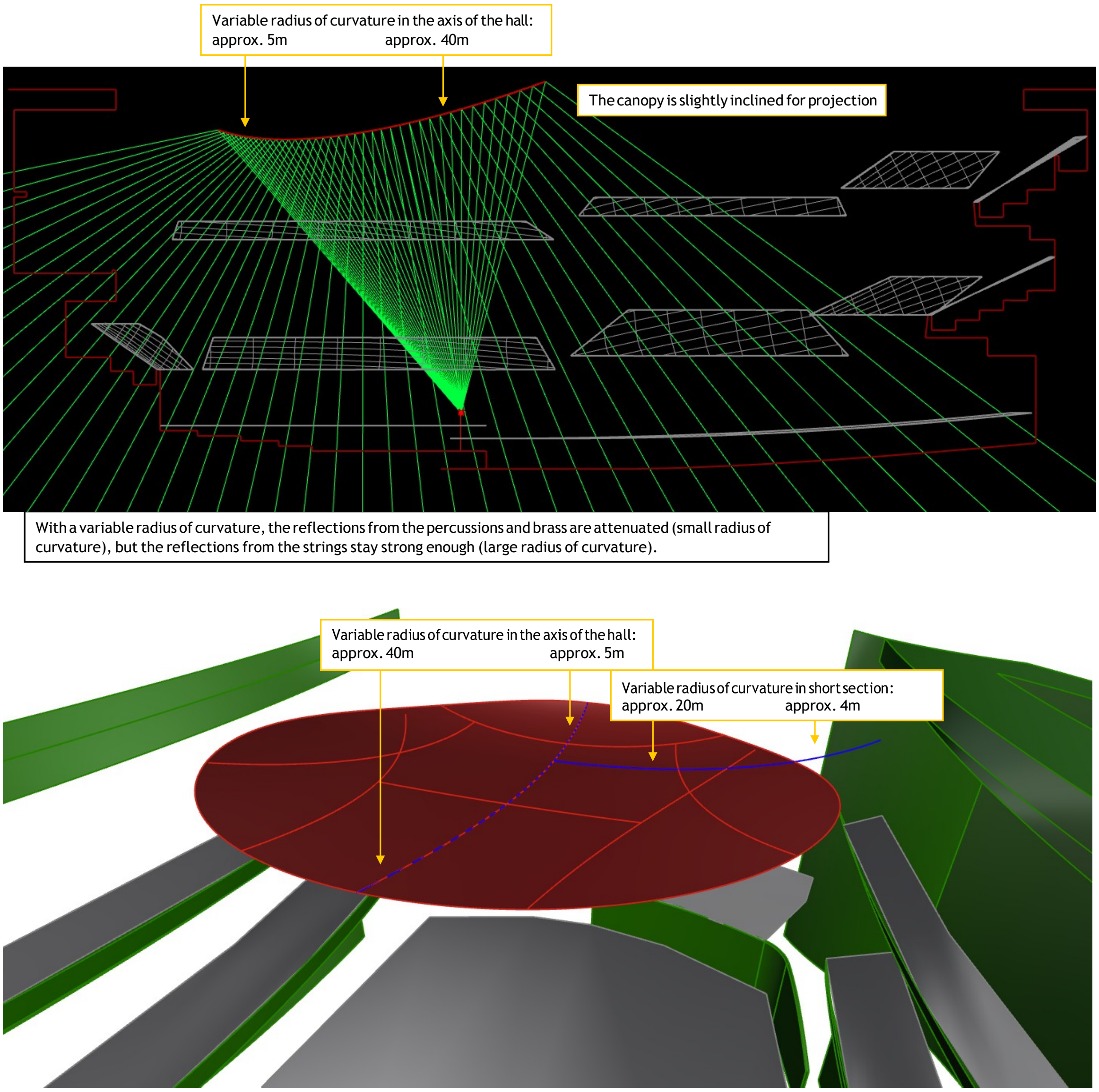

Figure 8: Acoustic specifications for the shape of the canopy reflectors

This canopy reflector is meant to be tuneable in height, so as to adjust the acoustic quality on stage depending on the orchestra size and all potential musical demands (a low canopy reflector generates a clearer but also stronger and denser sound quality, while a high canopy setting favours an open and airy sound quality). Typical heights for such single-object canopies is between 13 and 15m above stage floor, with some rare examples of lower settings for chamber music or recitals. Most height adjustments of this canopy (outside maintenance situation) are therefore expected to be within that 13 to 15m range. Changing from one setting to another needs to be fully motorized and automated from a movable console on stage, with real-time feedback information to the operating person on the current position in height.

It is also required that the angle of inclination of the canopy in long section can be tuned with a minimum range of -5° to +10° with respect to the currently designed orientation. The process for adjusting that angle does not need to be as automated and fast as for the height. It is most probable that the appropriate angle will be set during the first season, after a few test rehearsals and concerts, and will very rarely need to be changed again after that.

2.4.3 Main ceiling

The main ceiling of the concert hall must meet 3 distinct acoustic needs:

- First, its average or global height must be set at an appropriate value, generating sufficient acoustic volume and a sufficiently large "empty space" in the top part of the hall where reverberation can develop.
- Second, its general shape and orientation must favour the development of enveloping reverberation for the audience members, and avoid holding reverberation around the stage.
- Finally, the more precise shape of the ceiling located above the middle of the parterre and the rear balconies must provide first order early reflections to the balcony seats, and the periphery of the ceiling must also provide second order lateral reflections to these balconies.

For Turku concert hall, the main central part of the ceiling is currently designed with convex inversed-bowl shape, with a large radius of curvature (>80m). The lower point is set above the front part of the stage (near the conductor and soloist position), at a height of 20.8m above stage floor. It then increases slightly towards the choir balcony (maximum height of 21.3m above stage floor) and more significantly towards the rear balconies (maximum height of 22.3m above stage floor). This shape perfectly meets the first two acoustic needs listed above, with sufficient height and good projection of late reverberation away from the surroundings of the stage. It also partly meets the third need listed as it generates appropriate first order reflections towards balcony seats.

The periphery of the ceiling had however to be treated as a separate subject, in order to optimize the coverage of second-order lateral reflections from the corner between the ceiling and the top sidewalls. In the current stage, it is designed as a flat and slightly inclined ring, with a width of about 4m on average (covering a zone at a distance to the top sidewalls varying from 2.3 to 7m). That shape was checked and has proven to be efficient in generating the wanted lateral reflections towards the balcony seats, as was shown in Figure 7. However, other possible options be investigated during the next design phase and could result in a more complex geometry of that ring.

2.5 Acoustic requirements regarding building materials

All surfaces in the concert hall need to be acoustically fully reflective, with the exception of variable acoustic curtains discussed in 2.3, and audience chairs.

Fully reflective surfaces can be made out of several materials, as long as they are hard and heavy enough. However, it is intended that most architectural finishes in Turku concert hall will be wood. Some surfaces can also be in plaster, concrete, glass, synthetic resin / acrylic, as long as wood remains the material covering the majority of the surfaces.

Wall and ceiling finishes in wood have the best acoustic behaviour when the mass and rigidity of construction provide them with sufficient inertia to vibrations. A surface density of generally minimum 35 kg/m^2 is required, which corresponds to approximately 60mm thickness of relatively dense wood.

The same result can be obtained either with massive wood, or by gluing together several thinner layers of wood, or building sandwich constructions with an outer layer of wood and a core made out of a denser material such as Fermacell. However, panels made out several layers glued together have to be factory-made and not made on site, as each layer has to be continuously glued to the next one with no air trapped in between, in order to obtain the required inertia to vibrations. This requirement can perhaps still be met by on-site construction in the case of flat panels, but factory construction is surely required for curved panels, which is almost always the case in this project. Heavy wood panels have to be fixed to a sufficiently rigid sub-structure. This substructure should ideally equally be made out of wood, but a steel sub construction is acceptable as well, as long as it is stiff enough.

Three different cases have to be distinguished regarding wood floors. A fully acceptable first type of construction consists in wood planks continuously glued to a properly levelled concrete slab. This type of wood floor is perfectly suited to corridors, staircases, and any floor surfaces that will not be fitted with audience chairs. A second type of construction is acoustically preferred for all floors on which audience chairs are to be fixed, both on the main floor and in the balconies. In this second type of construction, a void space is created under the wood floor. A wood or metal structure is built to hold the wood planks with no acoustic absorption nor vibration isolation added. The floor surface has to be sufficiently heavy with a surface density of 30 to 40kg/m^2. This can be obtained either with very thick wood planks (60-80mm thickness) or by gluing thinner wood planks to high density flooring boards. It is fully acceptable that some seats are fixed to a wood floor glued on concrete (1st type of construction), as long as this remains the exception. The goal of that second construction type is to allow for vibrations in the floor to transmit to the chairs and be perceived in the body of audience members, contributing to their acoustic perception especially for low frequencies. The third wood floor construction type is the stage floor. It is similar to the second construction type, but with more precise and stringent acoustic specifications. The stage floor has to be made fully out of wood (no high density flooring boards permitted) in different thicknesses: 25mm thickness (approx. 13 kg/m^2, between 25mm and 42mm thickness depending on point load requirements) is ideal for most of the stage area, as it will allow for a richer resonance of music instruments in contact with the stage floor such as cello and double bass; while 45 to 80mm wood (approx. 25 kg/m^2) is preferred for the floor of the risers located at the back of the stage, meant to accommodate brass and percussion instruments. The wood type and quality for the stage floor also needs to be chosen carefully, with appropriate balance between the relative softness and a sufficient density and rigidity. A pine species of sufficient hardness such as Oregon pine is traditional choice, but other alternatives also proved to be fully valid, for example ash.

As for the surface treatment, all wood surfaces should preferably by oiled rather than varnished in order to keep unaltered the natural micro-porosity of wood. Matt surface treatments are to be preferred over shiny ones.

Wall and ceiling finishes made out of plaster can either be plastered concrete or gypsum boards fixed to a substructure. The first case naturally provides all the mass and inertia required. In the second case, the requirements are similar to those for wood surfaces. A surface density of minimum 35 kg/m^2 is required, corresponding to 4 layers of standard gypsum boards, 3 layers of 12.5mm thick high- density boards, or 2 layers of 25mm thick gypsum boards. As a sub-structure, standard metal studs are to be avoided, as it is not providing sufficient stiffness and inertia. Special studs made out of 2mm thick steel (such as in Knauf cocoon system) can be considered. A wood sub-structure is also fully acceptable acoustically.

Glass surfaces will also need to be sufficiently heavy and stiff to get the appropriate acoustic behaviour. Small windows can be equipped with 8mm thick glass pane or 44.1-laminated glass (20 kg/m^2 surface density, on the concert hall side in the case of double glazing), as long as their combined area does not exceed 80m^2. Large glass walls will need thicker glazing such as 66.1- laminated glass on the concert hall side in order to reach a surface density of 30 kg/m^2. It should also be noted that these large glass walls were initially advised to be convexly curved in order to avoid excessively sharp sounding acoustic reflections. They were changed to flat glass panes with the aim of avoiding excessively expensive construction. The potential necessity of countermeasures to avoid any acoustic defect is still being studied and will be addressed in the next design phase.

The canopy is currently planned to be built out of translucent acrylic. It is typically difficult to get sufficient surface density (similar to wood or plaster finishes) from such material. Such synthetic materials can however be built with very high stiffness (much stiffer than wood or plaster), and a sufficient amount of internal vibration dampening that will avoid an excessively resonant behaviour (as can be found in steel plates or glass). With such a material, which will still need to be chosen with special care, a minimum surface density of 20 kg/m^2 can be considered as sufficient, corresponding to a thickness of about 15-20 mm.

Rough or painted concrete can also be considered for some of the wall and floor finishes. This should however be limited to surfaces not directly accessible to musicians and audience members, such as the floor of the technical gallery and some of the upper walls around it. The organ niche should also be built with heavy concrete walls, either painted or plastered.

Audience chairs will be the major source of acoustic absorption in the unoccupied concert hall. Their detailed design should aim at limiting the acoustic difference in the behaviour of seat when it is empty, compared to when an audience member occupies it. But limiting that difference must not come at the cost of excessive acoustic absorption, which would restrict the acoustic potential of the hall in terms of perceived loudness and reverberation. Important acoustic aspects regarding the seat design include the following: thickness of foam(s) for seat back and seat bottom, properties of the fabric covering the foam, height of seat backs, finishes for the under face of seat bottoms, finishes for the armrests, etc. Details on this matter will be provided during the next phase.

Behind the side balcony seats, series of metal tubes are installed to create semi-open surfaces mimicking organ tubes. Any specific vibration or resonance of these tubes is to be avoided. They will need to be built in at least 1mm thick steel or other metal of similar density (extra thickness would be required for lighter metals, such as 2.5mm in the case of aluminium). In the case of hollow tubes, no openings will be allowed towards the interior of the concert halls, and it is advised to install airtight plugs (in cork, neoprene or other soft material) at both end of each tube. If the tubes are used as pipe for air circulation and supply to the balconies, such plugs are of course not possible, but the necessity for the tubes to be airtight is even stronger: each tube is only allowed to open towards a ventilation duct or plenum. The semi-open surface created by the arrangement of metal tubes will need to be transparent to sound, with minimized transmission loss and residual acoustic absorption. For this reason, air gaps between the tubes will need to occupy at least 66% of the total surface (one third of tubes, two thirds of gaps).

In the case where the construction of an organ would not be planned in due time for its façade to be present for the first season of concerts, special acoustic treatments would be required in order to temporarily replace the organ and its influence on the acoustics of the concert hall. An organ façade acts as a highly diffusive and partly absorptive acoustic treatment. This acoustic behaviour can and must be mimicked with other architectural finishes if an organ is not immediately planned. If necessary, details on this matter will be provided during the next design phase.

2.6 Further work planed on the main concert hall

As promising as the current design can be, further acoustic design work is without doubt needed to further develop this great potential into a great acoustic success.

First computer simulations using Odeon software have provided very positive results, but have also highlighted some potential weak points that will need to be investigated and solved. In that respect, the goal for next phase will be:

- To improve the homogeneity of early reflection coverage in the parterre where, depending on the source position on stage, some seats currently appear very abundantly covered while others appear comparably weaker.
- To also improve the homogeneity of early reflection coverage on stage. Computer simulations for acoustic conditions on stage (acoustic parameter ST1) are currently inconclusive, with an unexpected inhomogeneity, the cause of which will need to be further investigated.
- To further improve the acoustic conditions in the choir balcony where more early reflections to and from the front part of the stage would be suitable. Specific design work on the organ wall and the connection of the side balconies to the organ wall will need to be conducted.
- To check and ideally further improve acoustic clarity for the side balcony seats located near the stage.

On all those listed subjects, it will need to be systematically questioned whether the currently non- ideal local results obtained can be explained by aspects of the current design, or whether artefacts and limitations of the computer simulations are at least partly responsible. Other methods could potentially be useful for that purpose, be it alternative computer simulation algorithms or scale model acoustic measurements.

In addition, more detailed design work is still required on the following aspects of the design:

- Shape optimisation for the periphery of the ceiling and the upper glass walls, as discussed in 2.4.3 and 2.5.
- Geometrical analysis and detailed shaping of the portions of outer concave walls that are visible to sound in between balconies. Any harmful focusing from these surfaces must be avoided.
- More detailed work on the definition and integration of variable acoustic curtains.
- More detailed work on the definition of architectural finishes and on the design of the seats.
- Final check of the detailed shape, size and orientation of each acoustically efficient surface.

3 SMALL HALL / KAMARI

The main purposes of the small hall, as currently defined by client representatives, is (in decreasing order of importance):

1. Chamber music concerts.
2. Orchestra rehearsals.
3. Other uses such as educational uses, conferences and events with amplified sound.

It was made clear that this third and last type of use is to be of much lower importance in the architectural and acoustic design of that space, orchestra rehearsals and especially chamber music concerts being top priority.

However, chamber music concerts and full symphony orchestra rehearsal have very different and partly conflicting acoustic needs. Three specific aspects best illustrate that acoustic conflict:

- Chamber music concerts need a room that will very effectively convey sound from one small zone where the sound sources are located (the stage of the chamber music hall is small) to all of the audience. Loudness must be high so that even recitals of relatively quiet instruments can “fill the space” with sound. On the contrary, full symphony orchestra rehearsals in a space that is much smaller than the main concert hall (the volume of the small hall is currently less than a quarter of that of the main hall) requires the acoustic loudness to be specifically controlled. Excessively loud acoustics in an orchestra rehearsal hall makes the musical work difficult, as all musicians need to restrain their musical dynamics or suffer from high and harmful sound levels.
- The width of a chamber music hall is ideally limited to about 12 to 15m. This is both for acoustic and practical reasons. Regarding acoustics, a limited width helps in providing strong early reflections that will support the sound of a soloist or small group of instruments. As for practicalities, audience of chamber music concerts want to be seated in front of the musicians and not to their side. And as chamber orchestra musicians seat together in a limited area, an excessively wide hall would generate many side seats of poorer quality. On the contrary a rehearsal hall fit to accommodate a full symphony orchestra needs a width of at least 19m, and ideally 20 to 21m. If not, the orchestra will not be able to seat in the same arrangement as in the concert stage, and additional musical work will be needed when the orchestra arrives on stage, requiring re-evaluation of aspects that had been previously worked on in the rehearsal hall.
- A high degree of acoustic optimisation is generally favoured in chamber music halls, with early reflections specifically designed to improve acoustic clarity and perceived proximity to the stage. On the contrary, sound sources in an orchestra rehearsal hall are spread throughout the main floor. Some specific early reflections for cross communication within the orchestra need to be provided, but one side of the room (where the chamber music stage is) should not be excessively favoured by early reflections compared to the rest of it.

The currently design is an attempt to resolve each of these contradictions.

- Regarding loudness, a large acoustic volume is provided, ideally fitted for orchestra rehearsals of up to 80 musicians. Such a volume can also be fitted for chamber music concerts as long as the acoustics are sufficiently reverberant and early reflections are provided in a sufficient amount. This means that variable acoustics are absolutely required in order to lower reverberation and loudness for orchestra rehearsals. This is especially true as the chamber music mode of the hall includes an audience tier with acoustically absorbing seats and audience, while the rehearsal mode of the hall does not include that source of acoustic absorption. Variable acoustics are first needed to compensate for the influence of the retractable tier and the audience, and more variables acoustics are then needed to effectively make the acoustics significantly less loud for orchestra rehearsals than for chamber music concerts.

- Regarding the width, the small hall is designed so that it can be used in two different directions. It is a box of about 14.4m (in between pillars) by 19.3m. 14.4m is a very adequate width for chamber music concerts, while 19.3m is better fitted to large symphony orchestra rehearsals. This implies that the retractable tier has to be stored each time that the small hall needs to be changed from chamber music concert to orchestra rehearsal mode, so that the orientation of the room can be turned by 90° and the orchestra can occupy the entire floor. It also means that if a podium is planned to be used as a stage in the chamber music mode (which is not the case in the current design), that podium would also need to be dismounted and stored each time that an orchestra rehearsal needs to take place. However, it should also be noted that rehearsals of smaller orchestras can also take place in the chamber music mode, as long as the intended orchestra layout does not require a width larger than 14m. Group rehearsals of the Turku Philharmonic, as well as some of the classic repertoire could indeed take place in the chamber music mode, with just the loose seats to be removed.
- Regarding early reflections, the design work is still partly in progress. The orchestra rehearsal mode has a strong impact on what would otherwise have been specifically optimized for chamber music. As a starting point, the room must remain symmetrical in orchestra rehearsal mode, so that one side of the orchestra is not made to sound louder than the other. This limits the possibilities to favour projection from the stage to the audience in the chamber music mode. This imposed symmetry is, however, put to good use in the design for the shape of the pillars and ceiling reflectors. In addition, two of the ceiling reflectors are motorized and adjustable so that they can be lowered in chamber music mode. Additional early lateral reflections would be beneficial in chamber music mode, but would require additional reflective surfaces that are currently only at the proposal stage.

Solving each of these acoustic conflicts is essential but makes the design of this small hall more complicated and more expensive. It must be stated here that a smart re-evaluation of the main purpose(s) of this small hall could lead to a simpler and less expensive design.