ROOM ACOUSTIC DESIGN OF A 15 000-CAPACITY MULTI-PURPOSE ARENA

P Laukkanen Akukon Ltd., Helsinki, Finland
J Riionheimo Akukon Ltd., Helsinki, Finland
J Pätynen Akukon Ltd., Helsinki, Finland
H Penttinen Neural DSP Ltd., Helsinki Finland

1 INTRODUCTION

Nokia Arena is a 15 000-capacity multipurpose Arena located in Tampere, Finland. The Arena was designed and built on top of a major railway line between 2015 and 2022. Within the same project, a hotel and two mixed-use towers were built on the same deck. The Arena is used for many types of events such as ice hockey, commercial fairs, and various music events. This paper concentrates on the music use of the venue, which was the driving use scenario for most of the room acoustic design decisions during the project. So far, the feedback from the audience and mixing engineers has been positive when it comes to the room acoustics of the venue.

The paper presents the room acoustic design process of the multipurpose arena and the results of acoustic commissioning measurements of the finished Arena. Measurement results are compared to the design criteria as well as room acoustic measurements of similar international Arenas. Based on the measurement results, the relationship between subjective observations and objective measurements is discussed. Finally, the key lessons learned are summarized.

2 PRIOR RESEARCH ON ARENA ROOM ACOUSTICS

Arena room acoustics have been studied over the years based on room acoustic measurements, computer modeling, and subjective experience on achieved acoustics[2,3,4]. Early research has typically been limited to individual case studies of certain Arenas and individual conclusions based on one space. The first and presumably the largest study, where different venues have been compared to each other, is by Niels Adelman Larsen from 2005-2010[1]. Adelman Larsen's research includes measurements and assessment of room acoustics of 55 venues, from which around 15 are comparable to Nokia Arena, in terms of use profile and volume or capacity.

According to Adelman Larsen[1], the most important room acoustic criterion for large pop/rock venues is the reverberation time at low frequencies, T_{60} at 125 Hz octave band being the most important octave band. Other conclusions from Adelman Larsen[1] include that there should not be disturbing late reflections that can be heard as echoes. In his book, Adelman Larsen also discusses the importance of stage acoustics and how musicians should get sufficient feedback from the hall to be able to feel the same acoustic climate as their audience. Based on his research, Adelman Larsen gives a recommendation for reverberation time for large indoor venues as a function of room volume.

3 ACOUSTIC DESIGN OF THE NOKIA ARENA

3.1 Room acoustic considerations in the competition stage

The author gave acoustic design advice for the (winning) competition entry already before the project fully started. Alongside the sound insulation of the building envelope, the room acoustic characteristics of the roof build-up were identified as critical for the success of the acoustics of the Arena.

In terms of surface area, the roof/ceiling is the largest individual surface in indoor Arenas, and hence it is important to be able to integrate as much absorption into the ceiling as possible. *Figure 1* shows a roof build-up sketch drawn for the competition entry, where the designed room acoustic element was a perforated steel sheet with mineral wool backing.

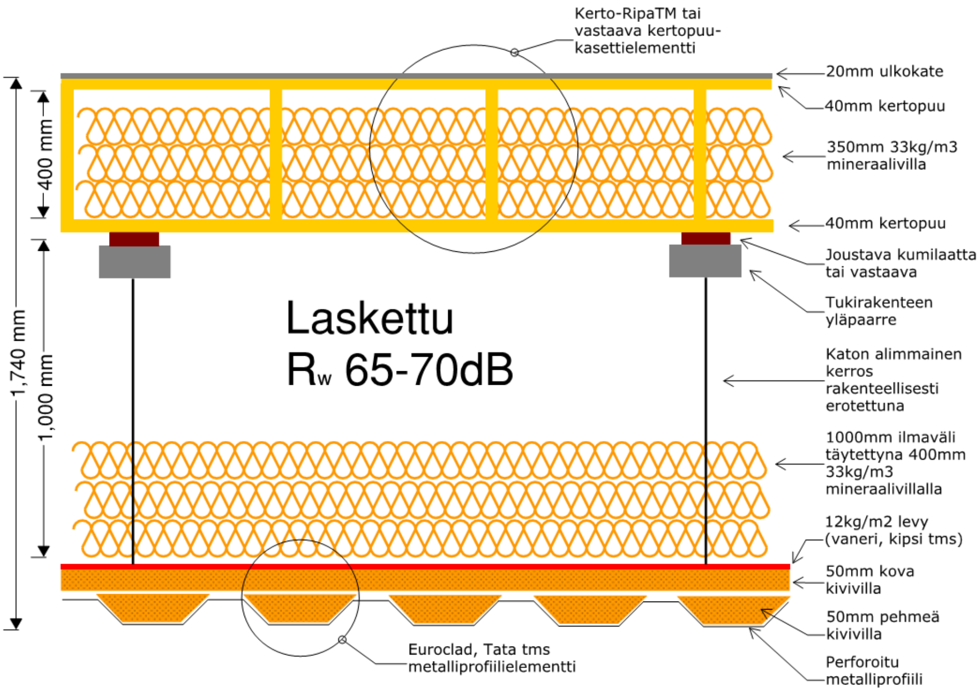

Figure 1: Roof build-up sketch drawn at the competition stage of the project.

3.2 Target criteria

As soon as the project concept design started, room acoustic criteria were set based on Adelman Larsen[1] recommendations. The reverberation time target was set to 2 seconds at mid frequencies and to 2,2 seconds at 125 Hz, respectively. These were based on Adelman Larsen's recommendation for 150 000 m^3 Arena. In addition to reverberation time targets, the brief specified that no individual audible echoes shall occur. *Figure 2* shows the reverberation time target of Nokia Arena, together with the measured reverberation time of O2 Hamburg (500 000 m^3, 16 000 capacity) and O2 London (400 000 m^3, 20 000 capacity)[1].

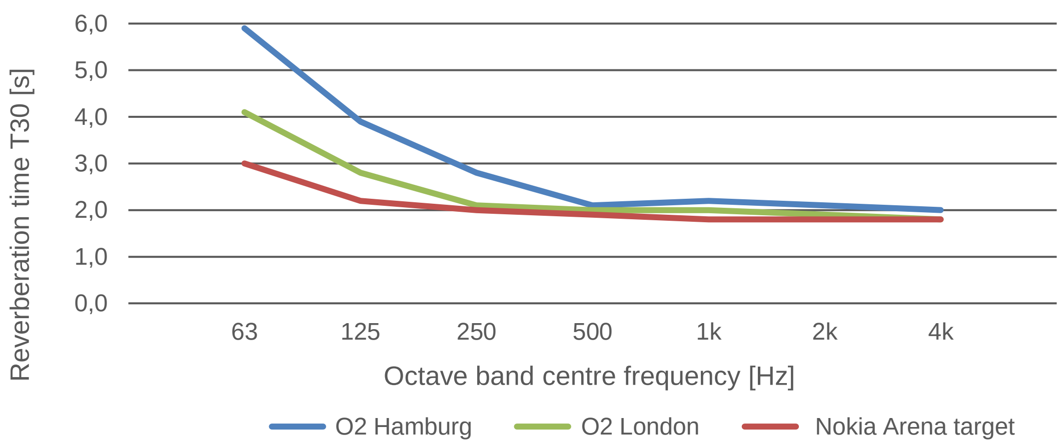

Figure 2: Reverberation time target in octave bands (red), together with measured reverberation time of two reference arenas.

3.3 Room acoustic modelling

Room acoustic Odeon model was built at an early stage of the design process. The key finding from the early Odeon modelling was, that the roof/ceiling itself won't be able to provide enough absorption at low frequencies, and additional surfaces had to be sought where low-frequency absorption could be integrated.

3.4 Roof/ceiling construction

Figure 3 shows the implemented final roof build-up from 2021. For building-physics-related reasons there was a limit in the mineral wool thickness that could be integrated into the underside of the roof element.

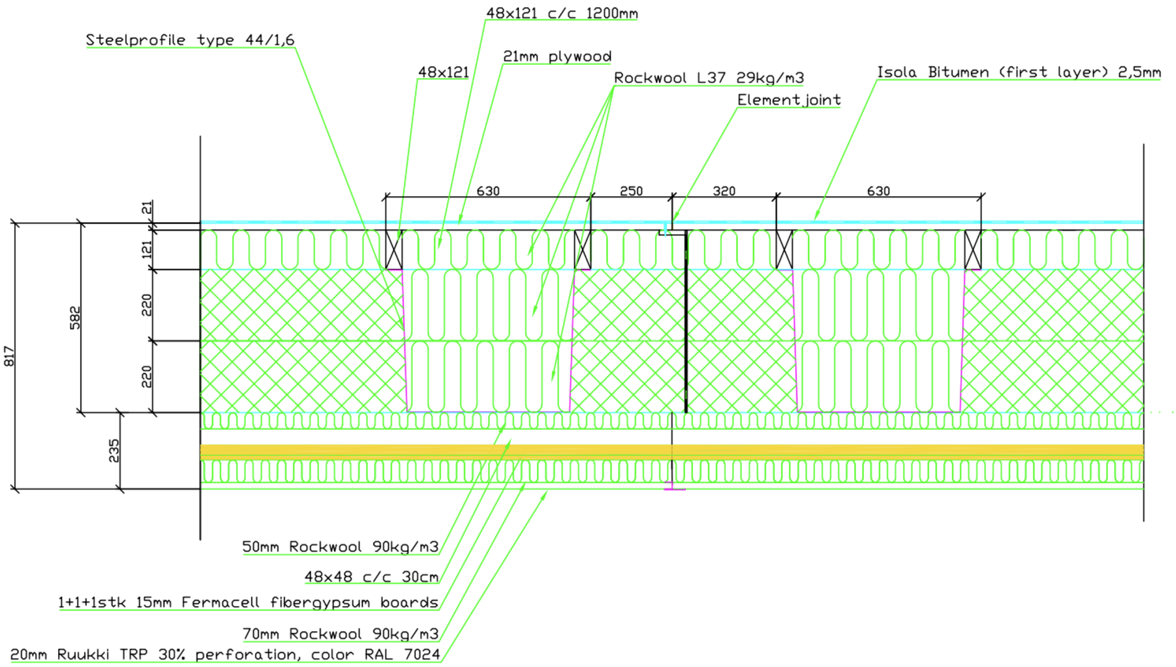

Figure 3: Final roof build-up section drawing

Figure 4: Sample roof element in a measurement laboratory

Figure 5: Sample roof element absorptive underside in a measurement laboratory

The absorption performance of the final roof build-up was measured in a reverberation chamber. Based on the absorption data of the final roof build-up, the amount of additional absorption was calculated, and integrated into the architectural design of the Arena. Multiple locations for added (low frequency) absorption were found. These are discussed in more detail in the next section.

3.5 Designed absorption surfaces

Figures 4-8 show the absorption surfaces with additional absorption. Surface (4) was not implemented in the end due to a low effect compared to price and installation challenges. Absorption surface number (7) was not implemented, as it was found architecturally difficult to fit together with the rear seat row. This was, however, identified as a big risk in causing/boosting a specular reflection that could be audible as an echo. This assumption was subsequently confirmed with audible reflections projected to some parts of the flat floor area. This effect is discussed in Chapter 4.

Based on the final Odeon modelling, the absorption surfaces that were included in the final design were not quite sufficient to meet the reverberation time criterion at low frequencies. This was accepted by the client as there was pressure on the budget towards the end of the project.

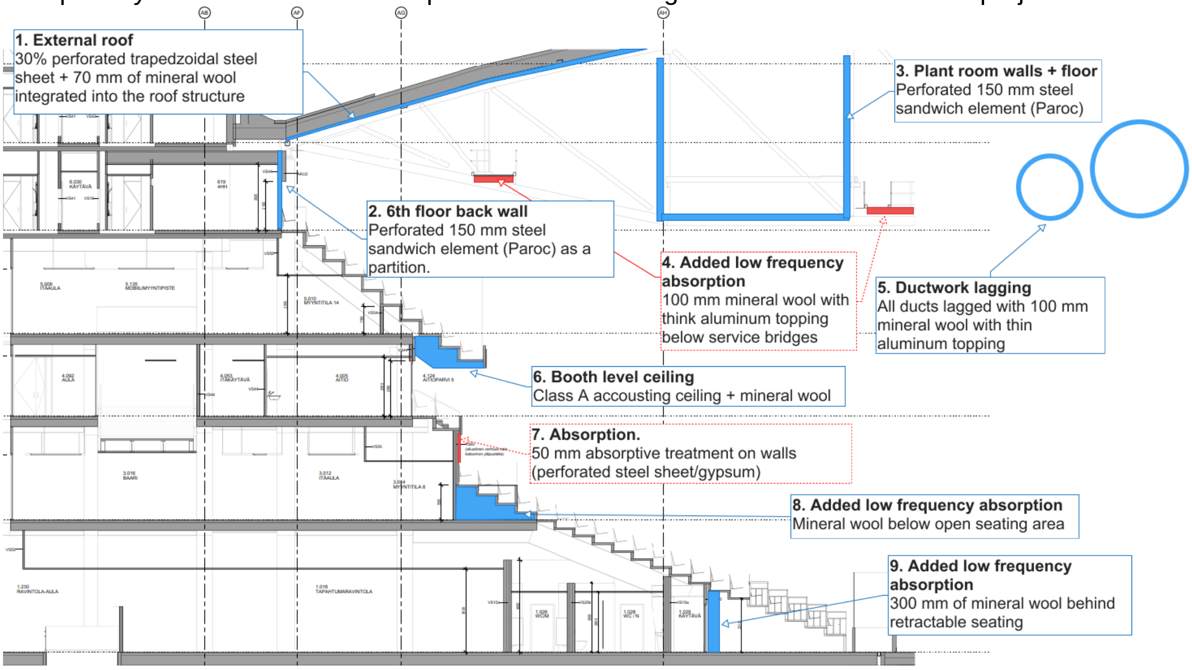

Figure 6: A summary of absorptive surfaces in the Arena. Red/dashed were not installed.

Figure 7: Absorption surfaces 2. and 6.

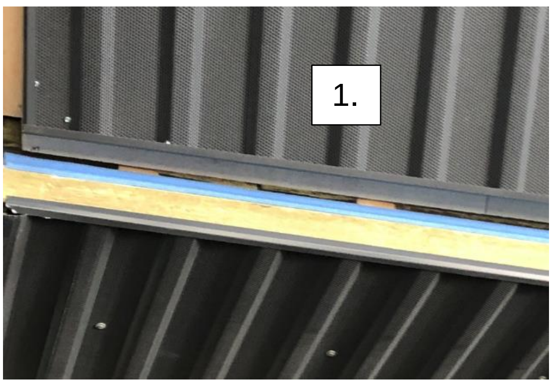

Figure 8: Absorption surface 1.

Figure 9: Absorption surface 9.

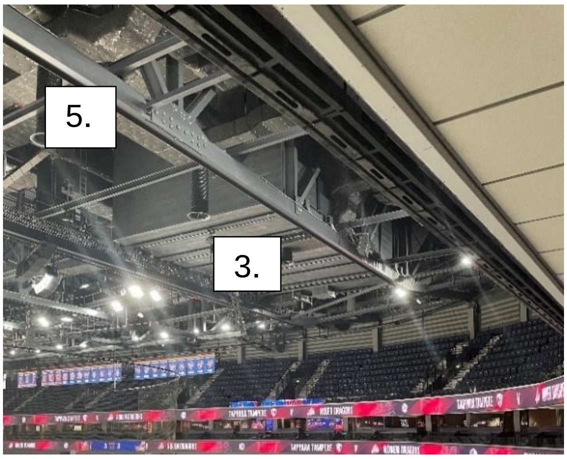

Figure 10: Absorption surfaces 3. and 5.

4 ACOUSTIC MEASUREMENTS

4.1 Measurement arrangements

The acoustic measurements presented in this paper were taken on 20th February 2023. Both monaural impulse responses and spatial impulse responses were recorded. All measurements were taken in an empty arena, with seats on a flat floor, as shown in Figure 11. A concert sound system consisting of D&B KSL8/12 line arrays and SL-SUB subwoofers was used as a sound source. Figure 12 shows a 3D rendering of the sound system.

Impulse responses were recorded using G.R.A.S 50VI 3D vector intensity probe which consists of three pairs of 40AI microphones arranged in co-centric orthogonal pairs with distance of 50 mm between the capsules. Microphone probe positions (R1-R7) are shown in Figure 11.

Results from monaural impulse response measurements (EDT, T20, T30, C50) were analyzed using Room EQ Wizard[6]. Spatial impulse responses and spatiotemporal plots were analyzed and plotted using the Spatial decomposition method (SDM)[7] on Matlab.

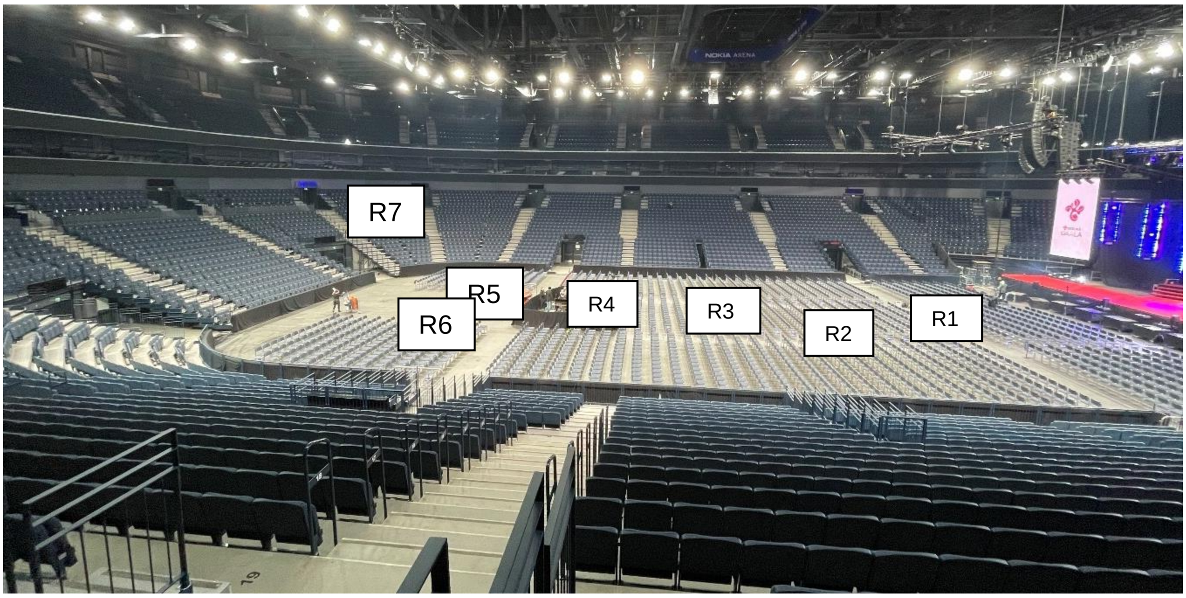

Figure 11: Arena during the acoustic measurements. R1-R7 are showing the locations of measurement microphone positions.

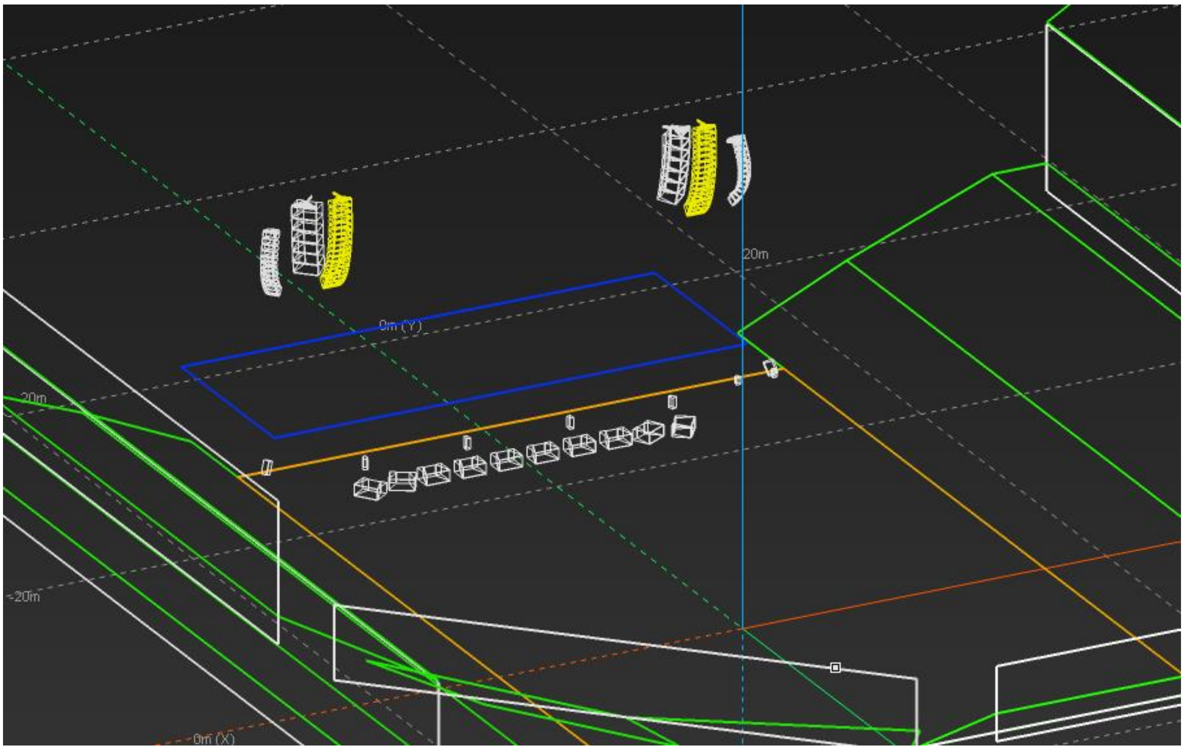

Figure 12: Sound system 3d-plot. Yellow denotes the main line-array speakers.

4.2 Measurement results

4.2.1 Reverberation time

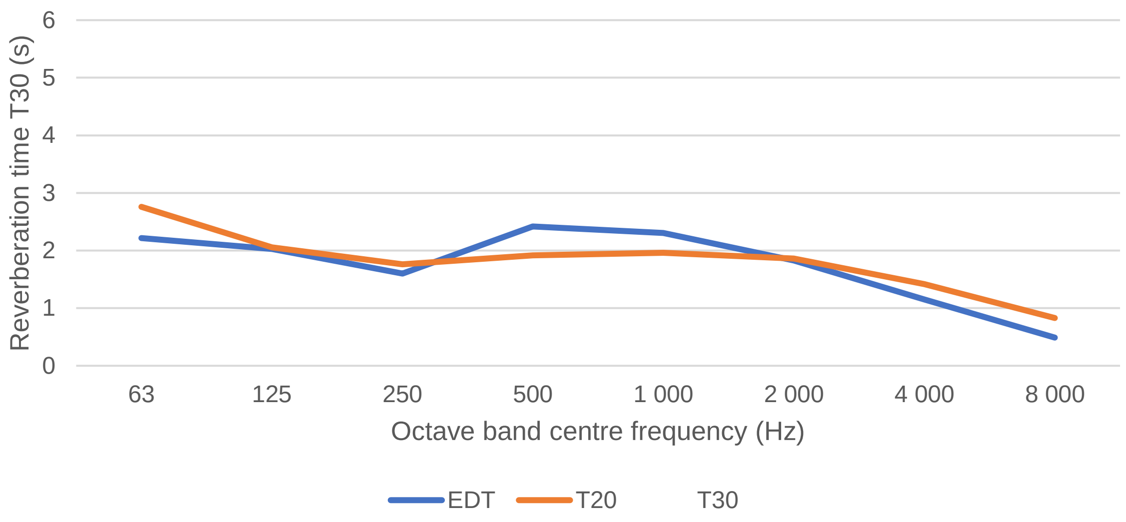

Figure 13: Measured reverberation time (spatial average).

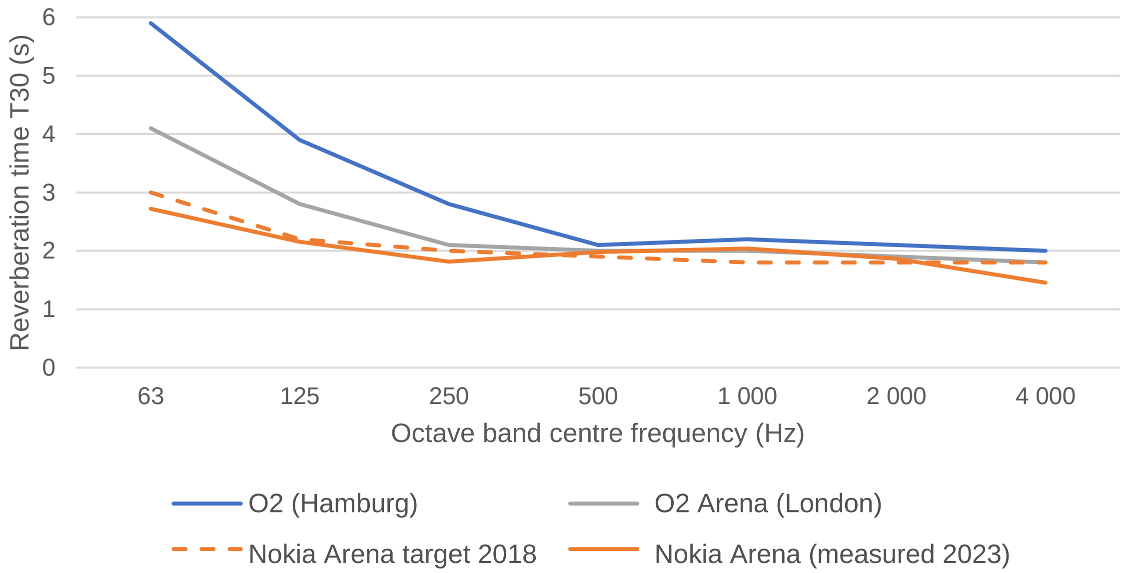

Figure 14: Measured and targeted reverberation time together with comparison to Hamburg and O2 London.

As can be seen in Figure 13, T20 and T30 are very similar, however, EDT is higher at mid-frequencies. This is likely a result of the first strong specular reflections which have more energy at mid-frequencies. It was also noticed that the shape of the EDT was very different at different measurement receiver positions.

Figure 14: Measured and targeted reverberation time together with comparison to Hamburg and O2 London. Figure 14 shows the measured reverberation time (T30) together with the target and comparison with two reference arenas. Remarkably, the measured reverberation time of Nokia

Arena was very close to the target in the end. The last Odeon modeling runs of the final design predicted longer reverberation time at low frequencies. The difference between the final modeled and measured reverberation time is illustrated in *Figure 15*.

The authors can think of three main reasons why the reverberation time turned out to be lower at low frequencies compared to what was predicted with Odeon for the final design.

Firstly, the external roof structure is likely to be more absorptive at low frequencies when it is acting as a large membrane, compared to the absorption of a 10 m^2 sample that was measured in a laboratory. Sound insulation measurements from the installed roof support this hypothesis, as the laboratory sound insulation performance of the roof build-up was significantly higher than what was measured on-site. Hence, the roof is leaking low frequencies more than what was predicted based on the laboratory measurement. This effect acts essentially as increased absorption inside the arena.

The second possible reason for the lower reverberation time is that the amount of absorption provided by the mechanical-, electrical- and AV installations, and other objects was not estimated correctly in the model.

The third obvious uncertainty comes from the fact the Odeon model did not include the stage construction and movable chairs on the flat floor that were present during the measurements. At least the movable chairs, however, are not considered to add a significant amount of absorption to frequencies below 125 Hz.

One can also question the accuracy of the reverberation time measurements conducted with a directional sound system, but at least according to Adelman Larsen[1], the difference between the RT measurements using an omnidirectional sound source and the sound system is negligible.

Regardless of the sources of the uncertainty, the low-frequency reverberation time turned out to spot-on meet the initial target.

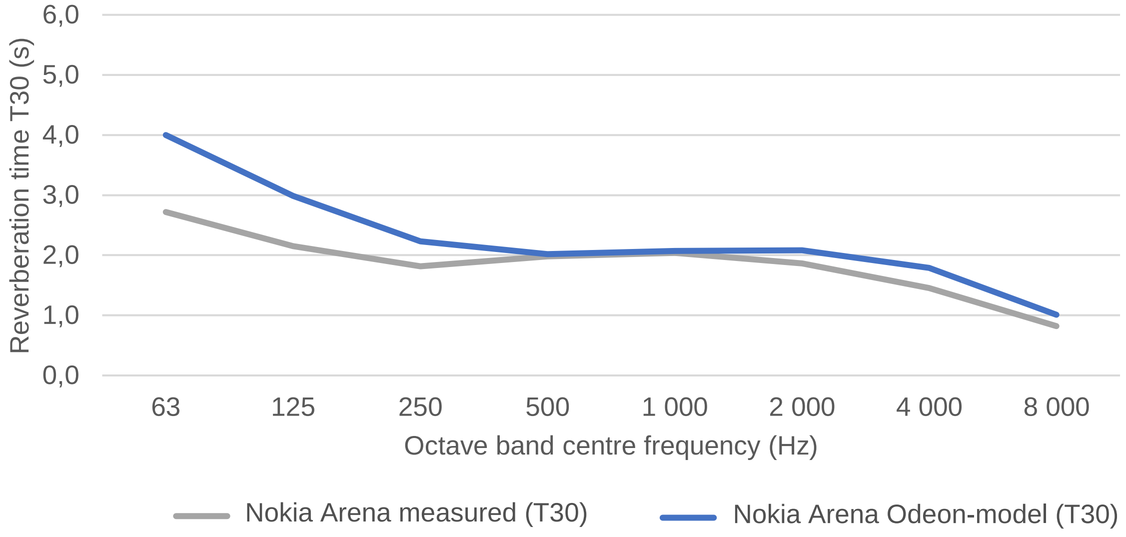

Figure 15: Measured vs. modeled reverberation time.

4.2.2 Spatial analysis

Based on a subjective listening to music events prior to the measurements, it was noticed that some specular reflections are audible in certain areas on the flat floor. However, during on-site listening, it was not immediately evident where these reflections originated from.

Therefore, a spatial decomposition method SDM[7] was used to track the direction of individual reflections. This method analyzes the spatial room impulse responses captured in-situ and performs spatio-temporal analysis by estimating the instantaneous direction of each discrete sample using the time difference between the capsules within short time windows. In other words, the analysis presents the sound field as pressure and direction of arriving sound at each sample. By integrating the sound energy with regard to the estimated direction of arrival beginning from a specific time until the end of the impulse response, the energy from a specific direction in a specified time interval can be plotted. The following plots have been generated from filtered impulse responses between 500 Hz and 4 kHz, to facilitate the tracking of discernible reflections.

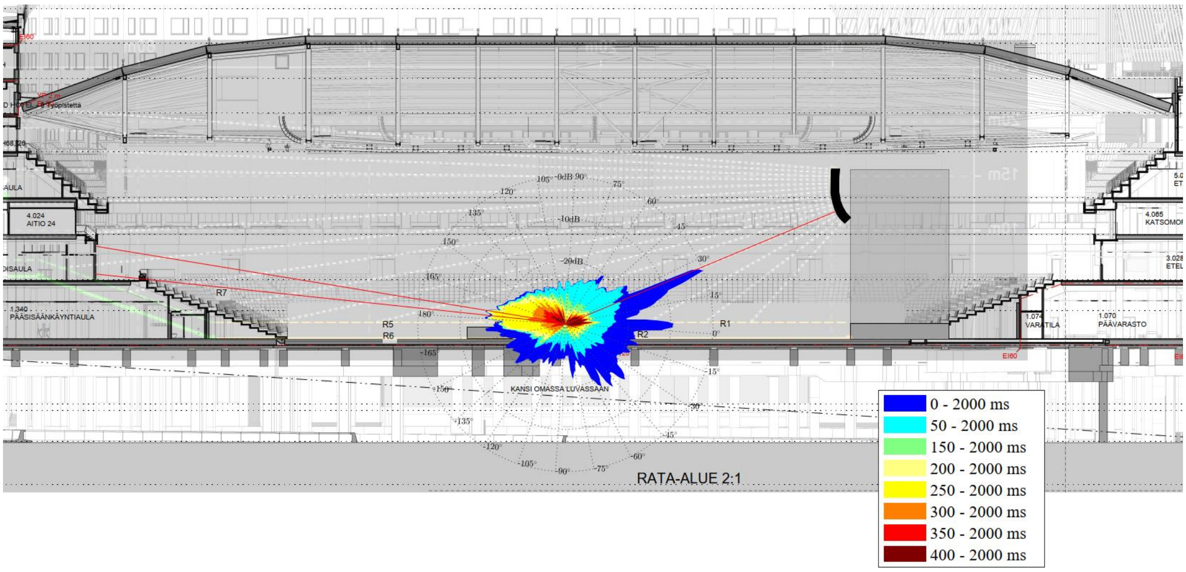

Figure 16: Spatio-temporal plot in the section of R3 receiver position

Figure 16 shows that a significant amount of energy is arriving between 200 and 300 ms after the direct sound from the back. The vertical angle of 6 degrees matches very well with the direction of the curved hard wall on the third floor. This is exactly the area where absorption was left out. A curved LCD screen above this hard surface is likely a contributor to the reflection. All other receiver positions on a flat floor show similar directions for the most significant reflection from the back. The same phenomenon can be seen also in a plan plot in *Figure 17*.

One other interesting observation from *Figure 17* is that there is a significant specular reflection arriving between 50 and 150 ms after the direct sound from around 62 degrees angle on both sides. This is caused by the same hard surfaces on the third-floor level reflecting the sound of a side-fill line array that is serving the side stands. This reflection is so early that it is not heard as an echo. It rather contributes to the spaciousness of the sound.

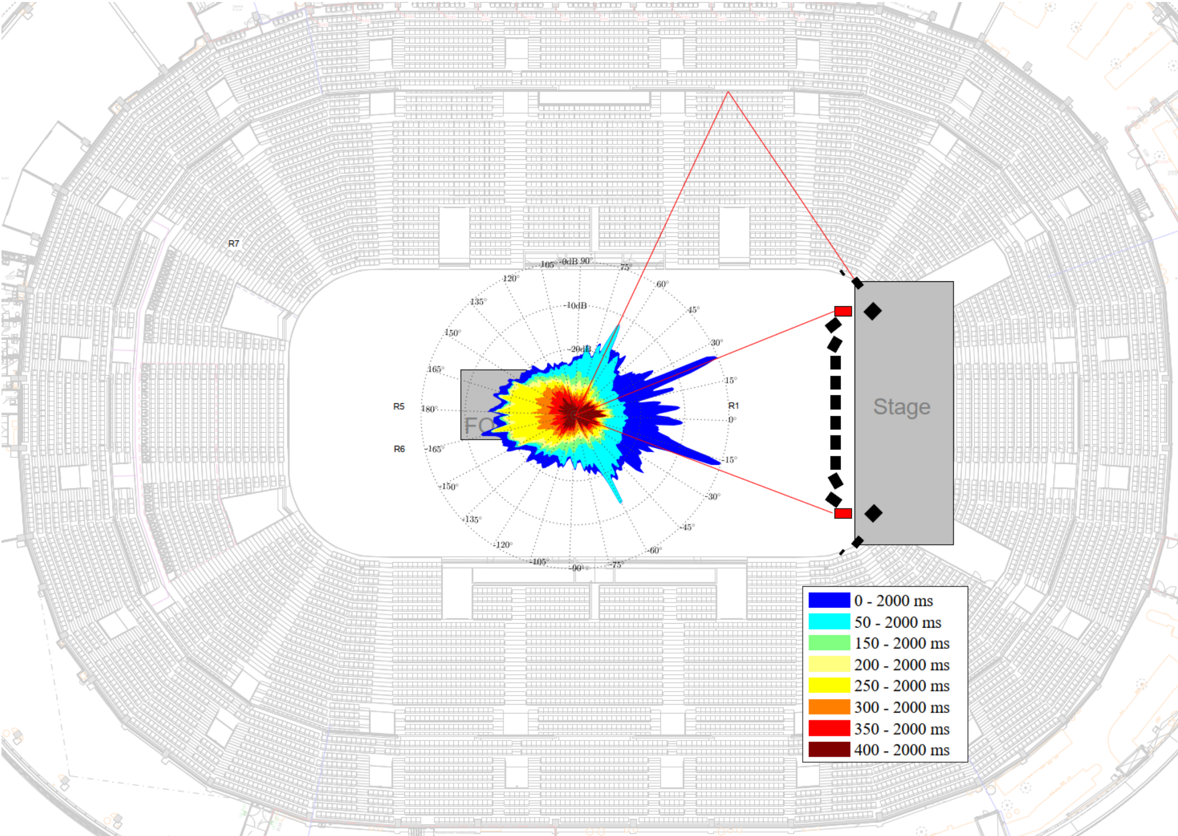

Figure 17: Spatio-temporal plot in the plan of R3 receiver position

5 OBSERVATIONS FROM SUBJECTIVE EVALUATION WITH MUSIC

After the measurements were taken on 20th February 2023, a subjective listening evaluation in an empty hall was conducted on the same day. Multiple pop/rock artists were running their sound check, and the authors were able to listen in different areas of the Arena. It was noticed that the rear wall reflection is audible around the center of the flat floor area and becomes less prominent when walking towards both the stage and the rear wall. This is logical, as at the front, the level difference between the direct sound and the reflection is larger. On the other hand, at the back, the time difference between the direct sound and the reflection gets smaller and hence the reflection integrates perceptually into the direct sound.

To more precisely compare the sound of different areas of the arena within a controlled environment, auralizations were rendered for an anechoic listening room. The estimated directions obtained from the SDM analysis were combined with the pressure signal and then distributed across a 45-loudspeaker setup in an anechoic chamber. With this method, different receiver positions and source material could be directly compared and evaluated.

The source material was various music pieces, pure vocals track, pure drum tracks, and some other test signals. The subjective listening of auralizations confirmed the conclusions derived from the on-site listening in an empty arena: 1. The rear wall reflection is most audible in the center of the Arena and is not considered disturbing when looking at the stage. 2. The rear wall reflection can be heard very clearly when the head is turned sideways.

The audience also affects the acoustics, and based on the limited number of live concerts, the authors' observation is that the occupied stalls attenuate the rear wall reflection even more. Hence in the full Arena, the rear wall reflection is even less disturbing. This is because the audience is physically masking part of the hard reflective rear wall.

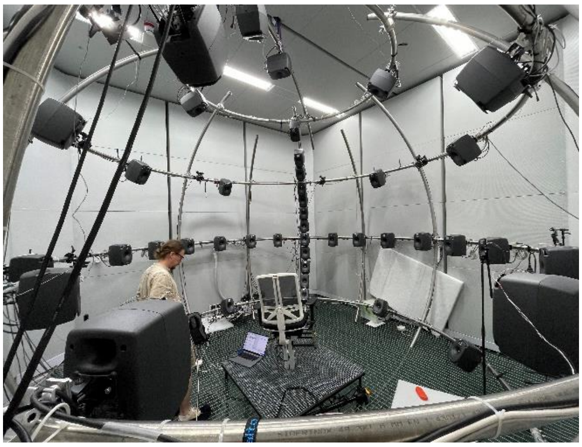

Figure 18: Auralization listening setup in an anechoic chamber.

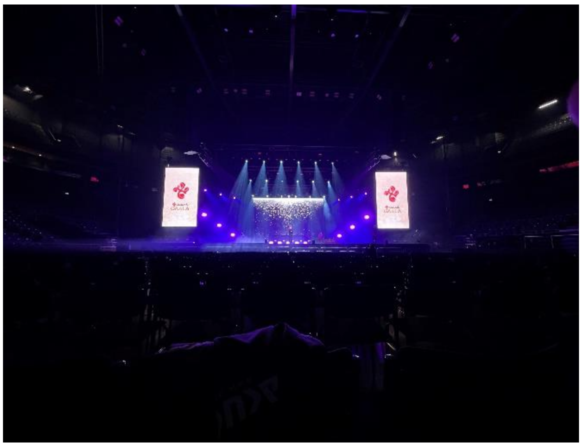

Figure 19: Sound check listening on a measurement day in an empty arena.

6 LESSONS LEARNED AND FUTURE WORK

There were two main lessons learned from the room acoustic design of the project. Firstly, based on the laboratory absorption measurements of the roof structure, and final reverberation time measurements of the Arena, it seems that the roof structure is absorbing low frequencies (< 250 Hz) significantly more than what the laboratory measurement of 10 m^2 sample build-up suggested. It is well-known fact that in most acoustic measurement laboratories the uncertainty of the results increases rapidly below 125 Hz octave band, which might explain part of this. Uncertainty of the Odeon modelling at low frequencies is obviously another possible source for an error. Regardless of these uncertainties, the authors think that there occurs also a physical phenomenon that makes the roof more absorptive when ~300 roof elements act as a large surface, compared to the 10 m^2 sample of two roof elements in a measurement laboratory. Perhaps the stiffness of the small roof area, compared to a very large roof area is different and causes the difference in the absorption characteristics. Or the roof trusses have some play on this. Anyway, this phenomenon is something that should be investigated further. The first step in this investigation would be to update the Odeon-model to represent exactly the measurement conditions and back calculate the absorption coefficient of the roof based on reverberation time measurements.

The second main lesson learned is that regardless of the effort made to investigate and optimize the surfaces to avoid specular reflections during the design stage, this wasn't 100% successful. The main reason for this is that the 3rd floor rear wall absorption (surface 7 in *Figure 6*) was not implemented against the acousticians' advice. Perhaps the importance of the rear wall absorption should have been emphasized more when finalizing the layout of the Arena, and more space should have been reserved for absorptive treatment so that there would not have been coordination issues later. Luckily, surface 7 discussed earlier is relatively easy to treat with absorption material afterwards, at least partly. This will be tested later this year with a mock-up installation.

One other remedial measure to soften the audibility of a rear wall reflection that the authors have been thinking of is to design small surfaces that can generate earlier reflections to mask the rear wall reflection in the time domain. A similar idea is sometimes used in performance spaces for classical music.

7 REFERENCES

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