# Room Acoustic Modelling Techniques: A Comparison of a Scale Model and a Computer Model for a New Opera Theatre

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## ABSTRACT
Today most acoustic consultants are using room acoustic computer models as a basis for their acoustic design. However, room acoustic scale modelling is still being used for the design in some major projects, although the costs and the time needed are significantly larger than those related to computer modelling. Both techniques were used by the author in a project for a new opera theatre; first the acoustical design was based on computer simulations using the Odeon software, and next a 1:20 scale model was built and tested. In the paper the results obtained with the two different modelling techniques are compared, and in general a satisfactory agreement has been found. The advantages and drawbacks related to each of the modelling techniques are discussed.


## 1. INTRODUCTION
There is a long tradition for the use of models in the acoustic design of concert halls and opera theatres. The technique of using physical scale models have been developed over the last 100 years (Rindel, 2002), and the room acoustical parameters, which are today well established as in ISO 3382:1997, were first of all developed for the use in scale models. Starting around 1970 computer models have been developed as a faster and cheaper alternative to the scale models. However, it is not unusual that both modelling methods are used for the same project; some acoustic consultants may not trust the newer computer modelling technique, but on the other hand there are important information to gather from the computer modelling that cannot be obtained with the scale modelling technique.

This aim of this paper is to compare the two modelling tools and to discuss the advantages and disadvantages of each method. The comparison is based on the acoustical design of a new opera theatre, namely Ankara Congress and Cultural Centre–The Opera House, Turkey, a project by architect Özgür Ecevit, Turkey, and acoustics by Jordan Akustik, Denmark, and the author. The opera is of the horse-shoe type with three balconies and approximately 1400 seats. The design and acoustical investigations were made in 2001, but for economical and political reasons the project has not yet been built.

## 2. COMPUTER MODEL

### 2.1. Room Model

The ODEON room acoustics program has been used in version 5.0 to document the auditorium design. The following is the final phase III, i.e. the design has been modified in various ways as a result of two earlier phases of computer model investigations. The materials used are those agreed with the architect. The recordings are based on a fully occupied auditorium.

Changes in the design since Phase II are mainly a new proscenium frame and changes to the lighthouse on top of the auditorium. In addition the sound absorption of the materials for wall and ceiling linings has been adjusted in order to optimise the reverberation time. The sound diffusing properties have also been adjusted in accordance with recommendations from the previous design phases.

The room model for the computer simulations is shown in Fig. 1 and 2. Only the active part of the stage is modelled, i.e. some typical stage setting is assumed. The

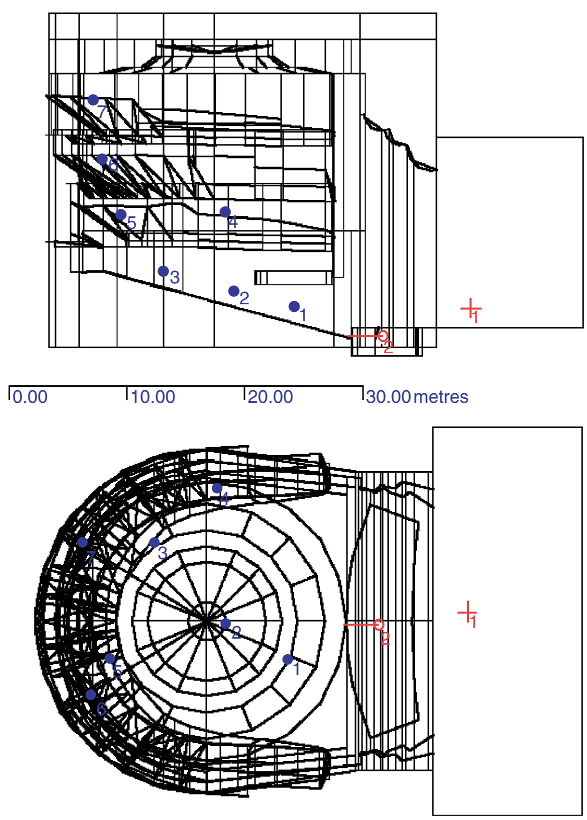


Figure 1. Section and plan of the digital model. The two source positions and the seven receiver positions are marked.

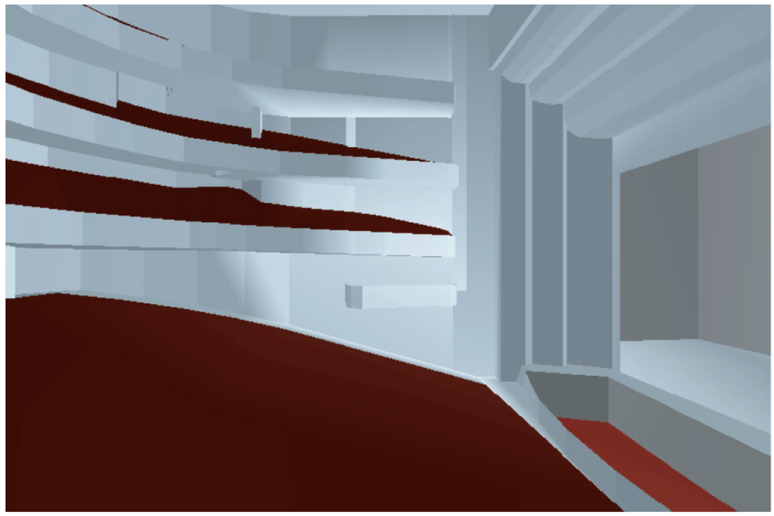

Figure 2. View into the computer model. Surface colours represent the different sound absorption characteristics.

investigations are all based on a fully occupied auditorium and the absorption data for the occupied seats are taken from (Beranek & Hidaka, 1998) group 2, audience on medium upholstered seats.

Two source position were used, one on the stage and another one in the pit, both chosen as omni-directional. Seven receivers were chosen, three on the main floor, two on the first balcony and one on each of the other balconies.

### 2.2. Room Acoustic Parameters

The calculated acoustic parameters are defined in the international standard ISO 3382:1997. The recommended range of each parameter for grand opera with full audience occupation is summarised in Table 1 together with the just noticeable difference for each parameter. 1

**Table 1. The acoustic parameters, their recommended range for grand opera and JND.**

| Parameter | Recommended range | Just noticeable difference |
|---|---|---|
| $T_{30}$ | 1.5 to 2.2 s | 5% |
| EDT | 1.5 to 2.2 s | 5% |
| G | −2 to + 6 dB | 1 dB |
| $C_{80}$ | −2 to + 4 dB | 1 dB |
| LF | 0.2 to 0.4 | 0.05 |

## 3. CALCULATION RESULTS

### 3.1. Spatially Averaged Results

In the following figures 3–7 are shown the frequency dependency of the calculated acoustic parameters. The curves show the average over the seven receiver positions, but separately for the two source positions, on the stage and in the pit.

#### *3.1.1. Reverberation Time ($T_{30}$)*

The reverberation time is shown in Fig. 3. It is almost independent of the frequency and around 1.7 s. This is in the optimum range for an opera house. There is no significant difference between the two source positions, which is good.

#### *3.1.2. Early Decay Time (EDT)*

The EDT is shown in Fig. 4. It is a little shorter than $T_{30}$, which is normal. EDT is longer with the source in the pit, which is due to sound reflections in the pit.

#### *3.1.3. Strength (G)*

The relative sound pressure level or Strength is shown in Fig. 5. With the source on the stage the mean value is around 0 dB with only small frequency dependency. This is good and in the optimum range for an opera house. With the source in the pit the strength is a little lower (less than 1 dB) at the high frequencies, and below 1 kHz there is practically no difference between the two source positions. This indicates a good balance between stage and pit.

#### *3.1.4. Clarity ($C_{80}$)*

As shown in Fig. 6 the Clarity with the source on the stage is 2–3 dB higher than with the source in the pit. This is a significant difference and it means that the sound from

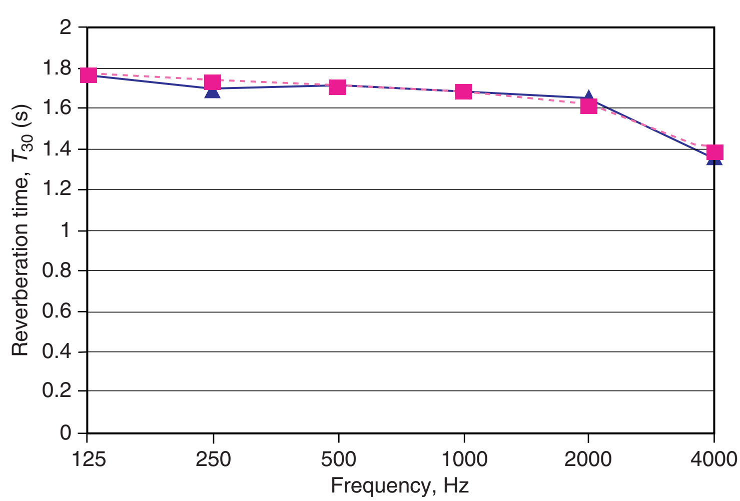


Figure 3. Average reverberation time. Blue triangles: Source on stage. Red squares: Source in pit.

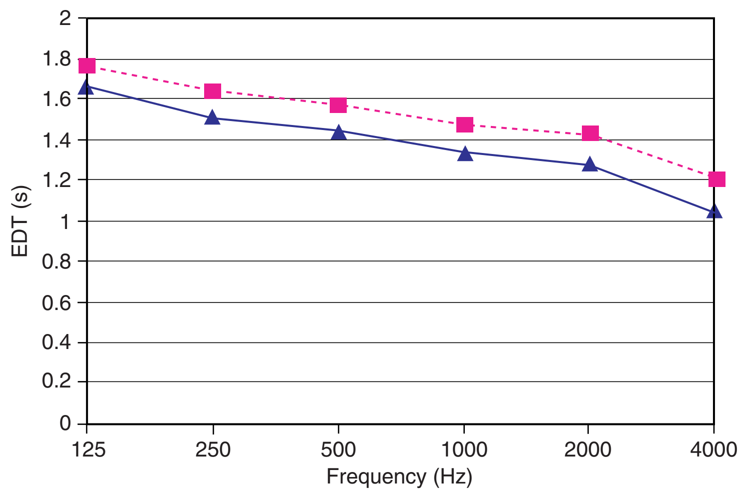


Figure 4. Average EDT. Blue triangles: Source on stage. Red squares: Source in pit.

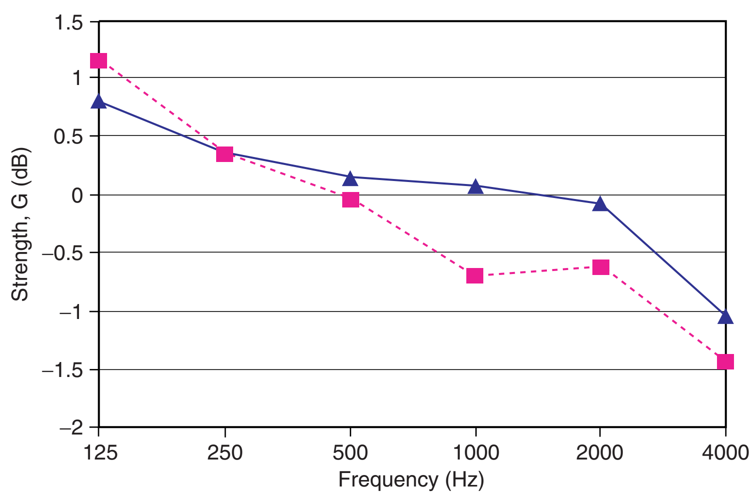


Figure 5. Average Strength, G. Blue triangles: Source on stage. Red squares: Source in pit.

the stage is heard more clearly than the sound from the pit, which is normal in an opera house. The Clarity is in the optimum range.

*3.1.5. Lateral Energy Fraction (LF)*

The lateral energy fraction is shown in Fig. 7. The frequency variation is negligible, but with the source in the pit the values are a little higher than with the source on the stage. This can be explained from the lack of direct sound from the pit to the audience. The values are in the optimum range.

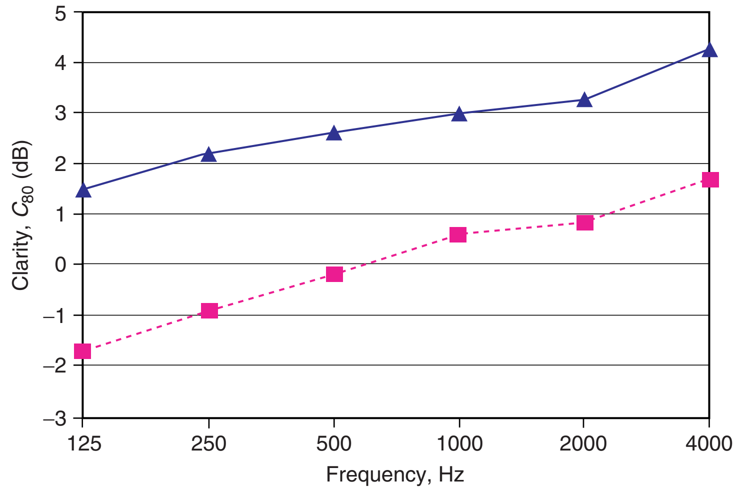


Figure 6. Average Clarity, $C_{80}$. Blue triangles: Source on stage. Red squares: Source in pit.

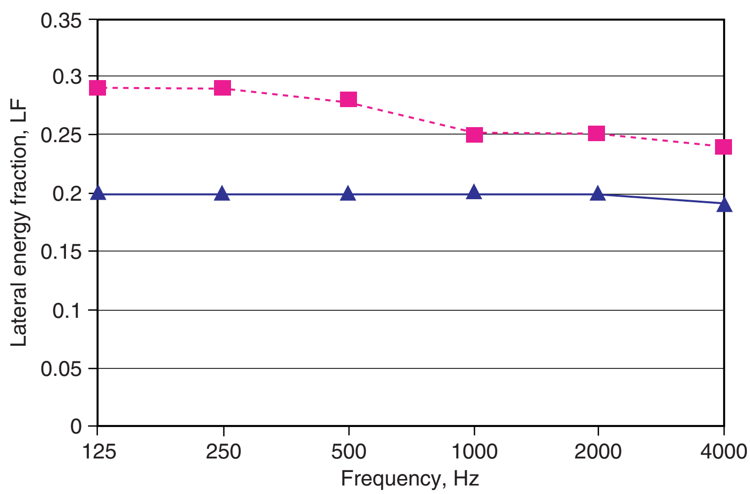


Figure 7. Average lateral energy fraction, LF. Blue triangles: Source on stage. Red squares: Source in pit.

### 3.2. Variation of Results Within the Auditorium

In the following is shown the spatial distribution of the acoustic parameters at 1 kHz octave band. Each parameter is shown with the source on the stage. More than 2000 receivers have been used in a grid with the size 0.75 m.

It should be noted that some receiver points may come outside the room due to the method used for creation of the receiver grid. Such points are shown in black, and they should be ignored.

*3.2.1. Early Decay Time (EDT)*

The EDT distribution in Fig. 8 shows very small variations over the main floor. With the source on the stage, EDT is somewhat lower on the balconies compared to the main floor, which is usual in an opera theatre.

*3.2.2. Strength (G)*

The G distribution in Fig. 9 is relatively even over the main floor and the first balcony. Second and third balconies have lower strength, which is natural with the increased distance.

*3.2.3. Clarity ($C_{80}$)*

With the source on the stage the Clarity is good in general, see Fig. 10. The highest values are in the back of the main floor and on the two first balconies. The lowest values are found on the foremost sides of the second balcony.

*3.2.4. Lateral Energy Fraction (LF)*

With the source on the stage the LF is relatively evenly distributed, see Fig. 11, with the lowest values in the front and central part of the main floor and on the side balconies.

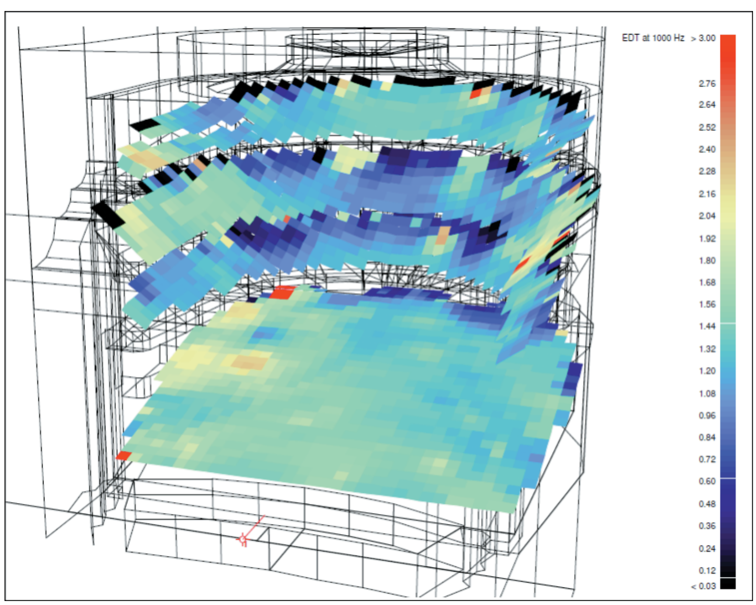


Figure 8. Grid response showing EDT at 1 kHz. Source on stage.

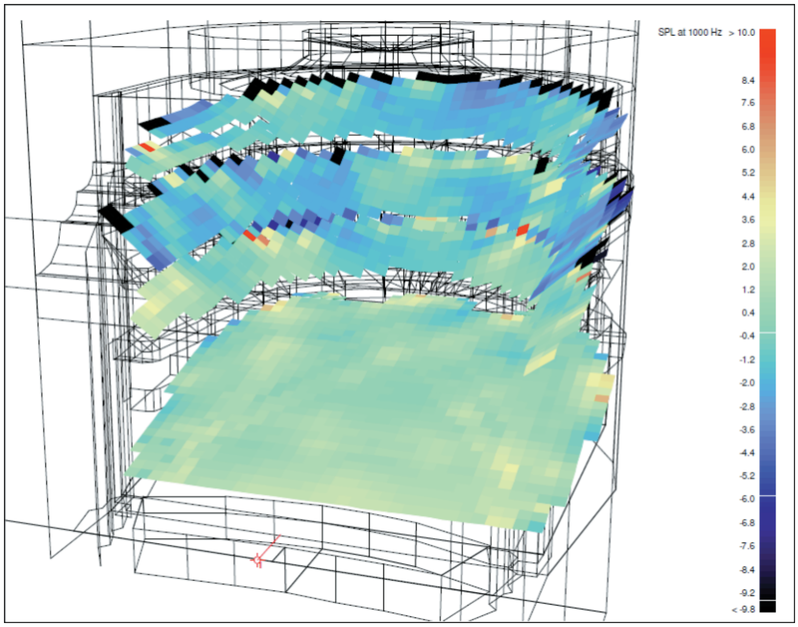


Figure 9. Grid response showing the Strength, G at 1 kHz. Source on stage.

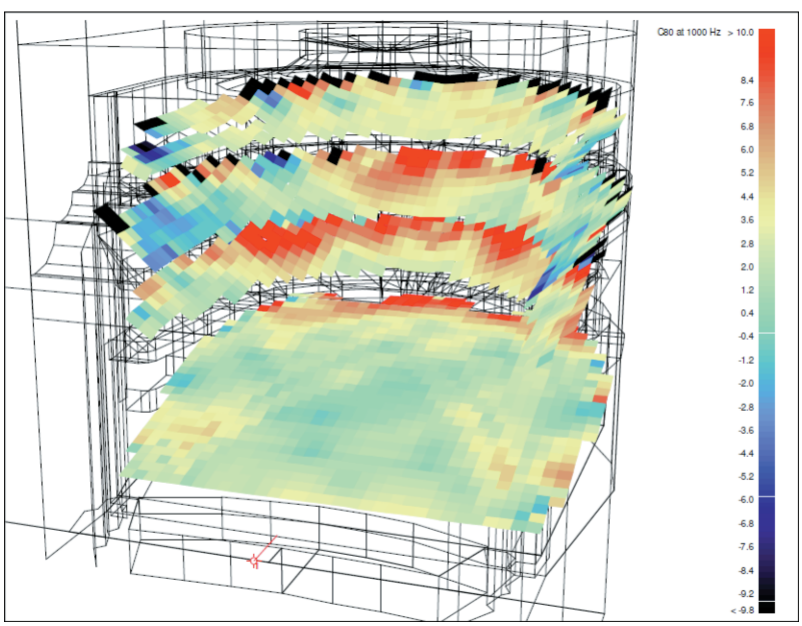


Figure 10. Grid response showing the Clarity $C_{80}$ at 1 kHz. Source on stage.

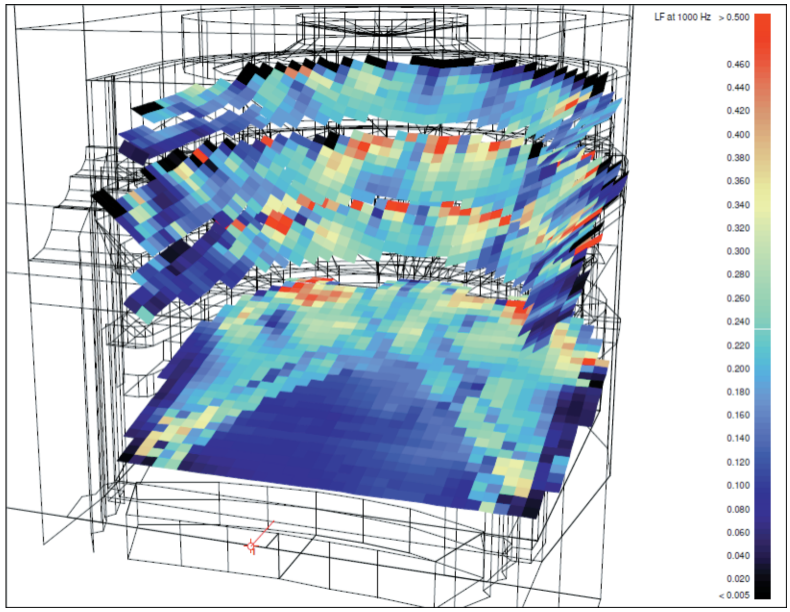


Figure 11. Grid response showing LF at 1 kHz. Source on stage.

### 3.3. Summary of Calculation Results

All of the calculated acoustic parameters have values in the optimum range recommended for an opera house. The frequency dependence of the parameters is very satisfactory and there is obtained a uniform distribution in the auditorium. Also the balance between stage and orchestra pit is very good.

It is concluded that the acoustic qualities of the auditorium can be expected to be excellent. The final result depends on details like the final choice of surface materials and the degree of sound diffusion from the surfaces.

## 4. SCALE MODEL

### 4.1. General

The scale model was delivered by Jordan Akustik, Denmark and it was built in the scale 1:20. This means that the actual frequencies used for the measurements were 20 times the normal full-scale frequencies. The room acoustic measurements were made in accordance with ISO 3382:1997. Octave bands were used with the centre frequencies 2.5 kHz–80 kHz, corresponding to 125 Hz–4 000 Hz in full scale. In the following the equivalent full-scale frequencies are used. A photo into the interior of the model is shown in Fig. 12.

### 4.2. Measurement Equipment

Measurements were carried out using a BK 4136 1/4” microphone, a BK 2636 measuring amplifier and a Rockland 852 dual high/low-pass filter. Measurement

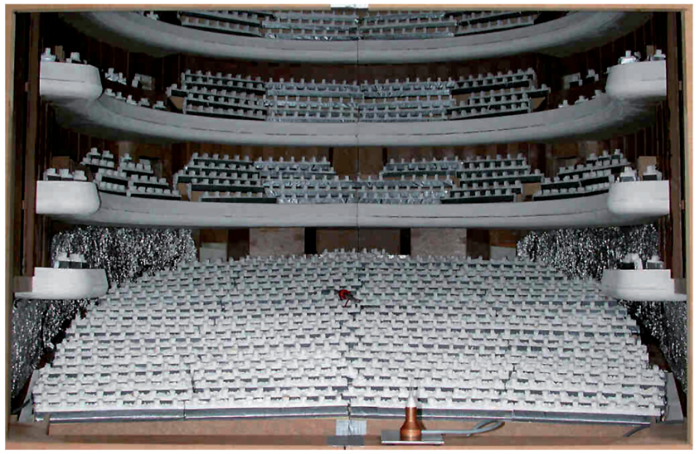

Figure 12. View into the auditorium of the 1:20 scale model. The spark source is seen on the stage in the front.

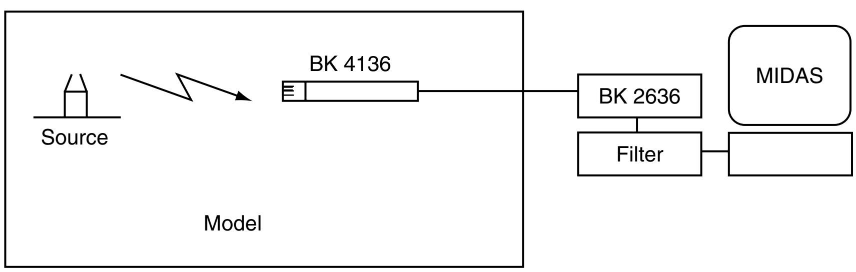


Figure 13. Setup for scale model measurements.

acquisitions, analyses and calculations were done with the MIDAS software [4] for Apple Macintosh II. Impulses were generated with an electrical spark source. The measuring schematic is shown in fig. 13.

The frequency spectrum of the spark source is shown in fig. 14. The impulse responses were measured from 1600 Hz–110 kHz in the 1:20-scale model, corresponding to a full-scale frequency range of 80 Hz – 5500 Hz. The humidity was controlled with an air-washer. In this way it was possible to keep the humidity around 60% RH. Temperature and humidity were measured with a Novasina MIK3000 electrical hygrometer and a reading was taken for each series of measurements. The MIDAS system automatically compensated for the air attenuation.

**4.3. Scale Model Audience**

The construction of the scale model audience was based on sound absorption measurements by (Beranek & Hidaka, 1998) for audience on medium upholstered seats. It consists of a front made of a wooden fibre plate (A), glued to a styrofoam back (B),

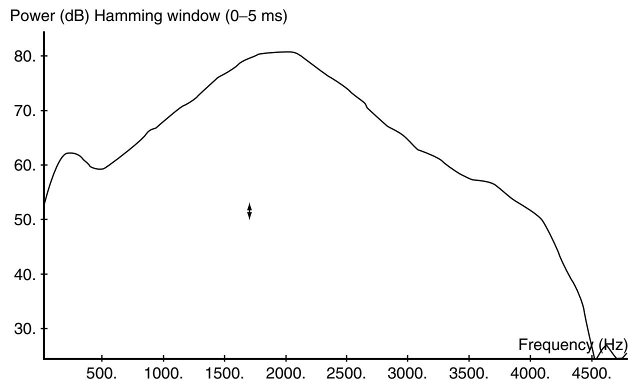


Figure 14. Frequency spectrum of the spark source (frequency axis is full scale).

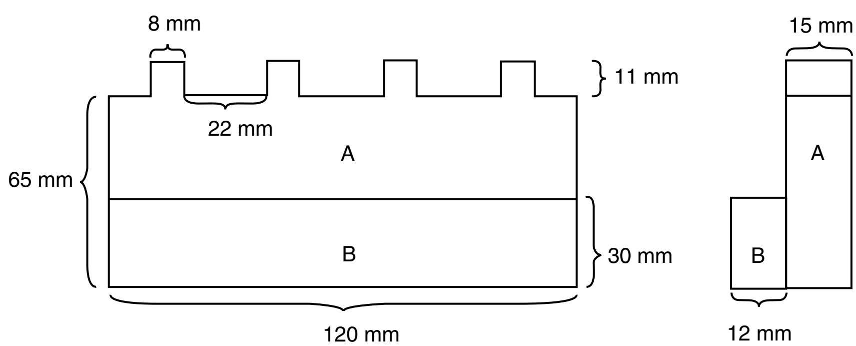


Figure 15. Schematic drawing of 1:20 model audience.

in which the shapes of the "heads" of the audience are cut out (see Fig. 15). Later some of the surfaces of the front and back were covered with a layer of metal tape, in order to adjust the absorption, see Fig. 16.

Absorption coefficient measurements were carried out in a scale model of a reverberation room. The room was box-shaped with the dimensions 60 cm* 47 cm* 38 cm, which corresponds to a full-scale volume of about 850 $m^3$. 13 diffusers (curved plastic sheets) were placed along the sides and ceiling of the room to achieve diffusivity of the sound field. In order to obtain the absorption coefficient, the reverberation time in the room was measured with and without a test specimen of the audience. These measurements were carried out according to the ISO 354 standard.

Fig. 17 shows the absorption coefficient of two different types of scale model audience measured in the small scale reverberation room, compared to the data obtained on real audience by (Beranek & Hidaka, 1998). Both models are covered with a layer of tape on the back, and on the front side of the styrofoam (the "chest"). Model 1 also has a layer of tape on the front of the wooden fibre plate (thus the entire surface of the model audience is covered), whereas this surface is uncovered on model 2.

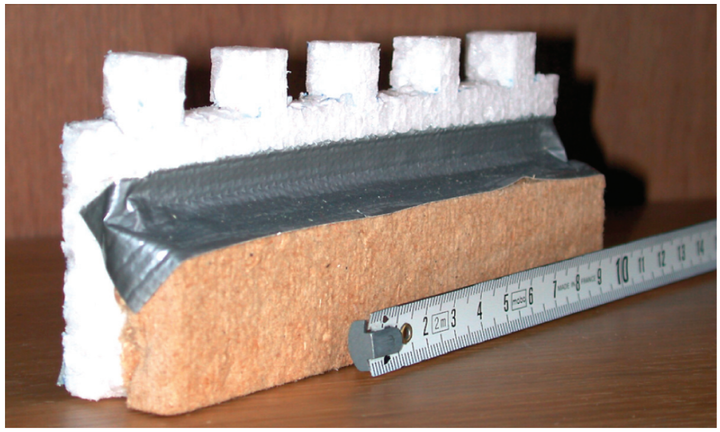


Figure 16. Model audience for the 1:20 scale model.

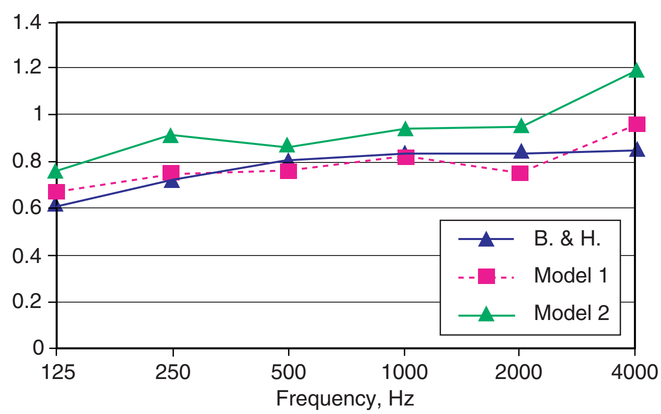


Figure 17. Absorption coefficient of audience for the 1:20 scale model compared to the Beranek & Hidaka data.

Due to the edge effect it is assumed that the absorption coefficient measured on a 10 m$^2$ test specimen (full scale) is a little higher than for the same material measured on a very large surface in a concert hall. Since the measurements made by Beranek & Hidaka were carried out in actual concert halls and not in a reverberation room, the goal was to construct a scale model audience, which showed a slightly *higher* sound absorption when measured in a reverberation room. Therefore model 2 was chosen (see Fig. 16), and the audience was constructed for the entire model (approx. 1400 seats).

**4.4. Adjustment of Material Absorption**

The measurements in the auditorium were made in accordance with ISO 3382:1997. Initial measurements of the reverberation time were made with audience, but without the stage tower. These measurements were made with the iron curtain down, i.e.

with the stage opening closed. The receiver points were chosen in order to match those from the computer model. The source was placed in the pit. The purpose of these measurements was to adjust the reverberation time of the auditorium to match the computer simulation. Different types of absorption was added or removed during these measurements.

In the initial measurement of the auditorium with audience the reverberation time at low frequencies was too high. So, a number of membrane absorbers were added to the wall above the reflectors over the stage opening and to the ceiling (see photo in Fig. 18). Finally a coating of sealing wax was added to some of the surfaces.

The final reverberation time adjustments were made in the stage tower. Some absorption material was added to the side and ceiling in the stage tower and also some membrane absorbers, in order to achieve the closest similarity between the measured and simulated reverberation time, see Fig. 19 and 20.

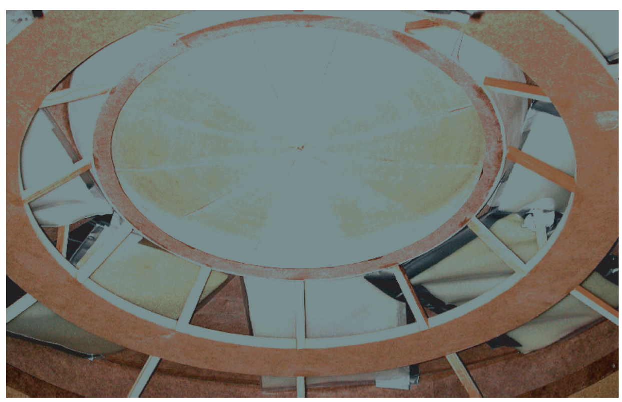

Figure 18. Membrane absorbers inserted in the roof of the auditorium.

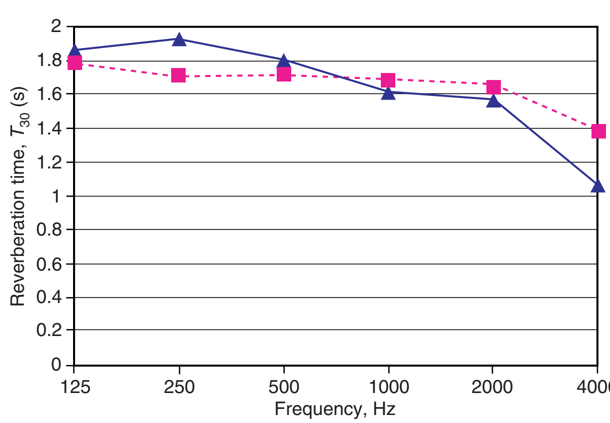


Figure 19. Reverberation time of the auditorium with the source on stage. Blue triangles: Measured. Red squares: Simulated.

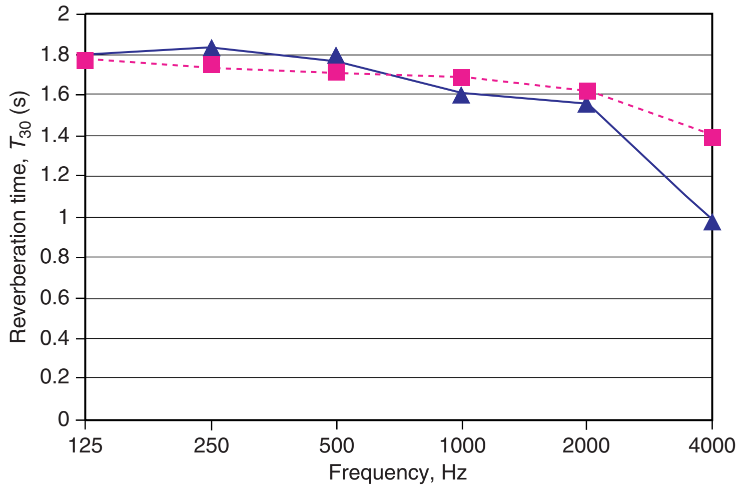


Figure 20. Reverberation time of the auditorium with the source in the pit. Blue triangles: Measured. Red squares: Simulated.

## 5. MEASUREMENT RESULTS

### 5.1. Spatially Averaged Results

In the following figures the parameters measured with the source on the stage and in the orchestra pit are shown. The results are averaged over seven receiver positions, identical to the ones from the computer model, i.e. three positions on the floor, two on the first balcony and one on each of the second and third balconies, see Fig. 1. The scale model results are shown together with the results from the computer simulation.

The sound absorption from the orchestra (chairs, instruments and musicians) was represented by a sound absorbing floor in the computer simulations, and in the scale model by a number of the model persons placed in the pit. For the EDT the results in Fig. 21–22 show satisfactory agreement with the computer simulations with the source on the stage, whereas there are some deviations with the source in the pit. At the high frequencies there seems to be more absorption of the reflected sound than in the simulations. This can be explained partly by the absorption from the scale model orchestra in the pit, partly by the very high attenuation of sound at high frequencies. This air-attenuation is much higher in a scale model than it is in full scale. The MIDAS measuring system can make an automatic compensation for the air attenuation, but still the high frequency results are less reliable.

For the Strength the results in Fig. 23–24 show good agreement with the computer simulations below 2 kHz, but at higher frequencies the results from the scale model show more attenuation. A possible explanation could be that sound propagation across the audience has more attenuation in the scale model than in the computer model.

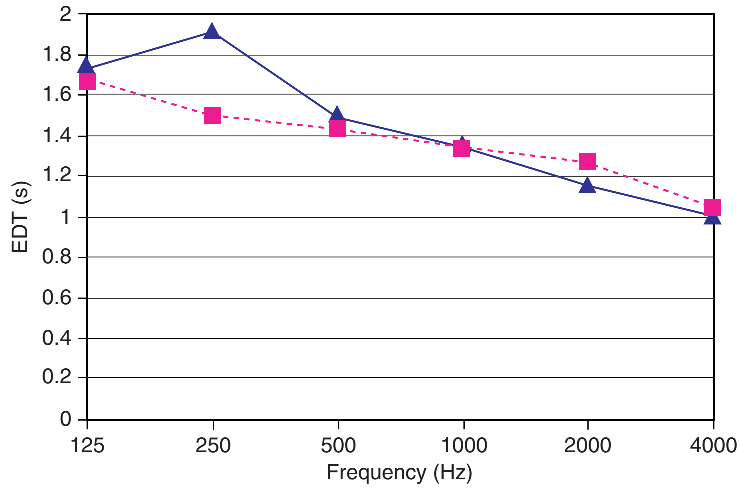


Figure 21. Average EDT with the source on stage. Blue triangles: Measured. Red squares: Simulated.

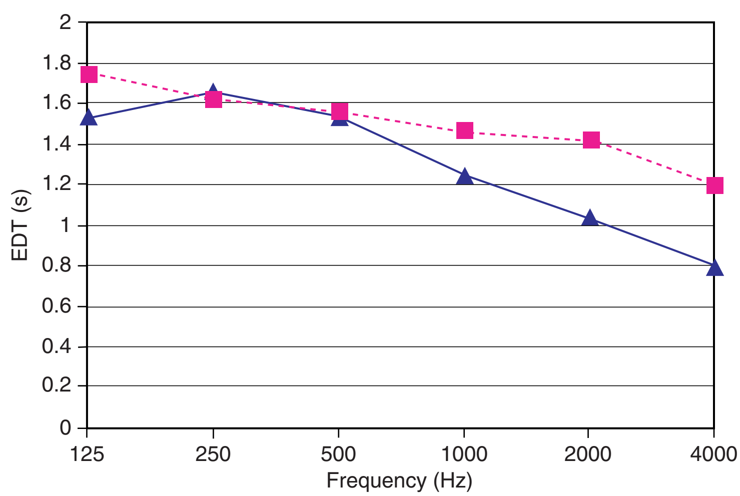


Figure 22. Average EDT with the source in the pit. Blue triangles: Measured. Red squares: Simulated.

The results for the Clarity in Fig. 25–26 show satisfactory agreement with the computer simulations, especially with the source on the stage. As for the other results there seems to be more high frequency attenuation in the scale model with the source in the pit. The lateral energy fraction, LF was not measured in the scale model, because a 1:20 scale microphone with figure-of-eight characteristic was not available.

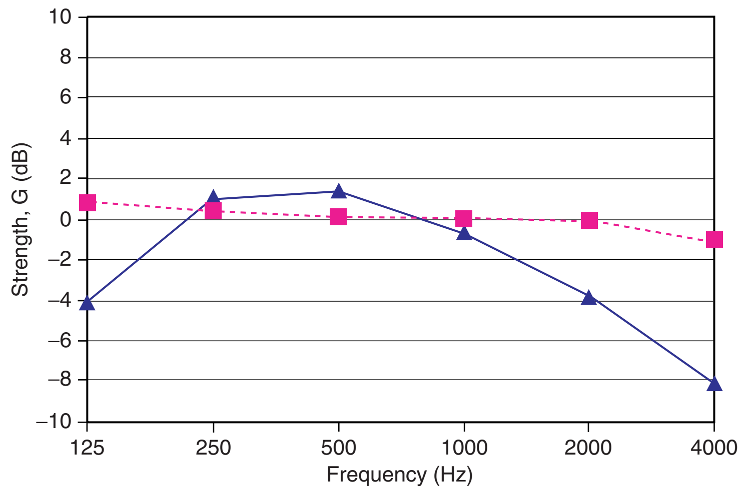


Figure 23. Average Strength, G with the source on stage. Blue triangles: Measured. Red squares: Simulated.

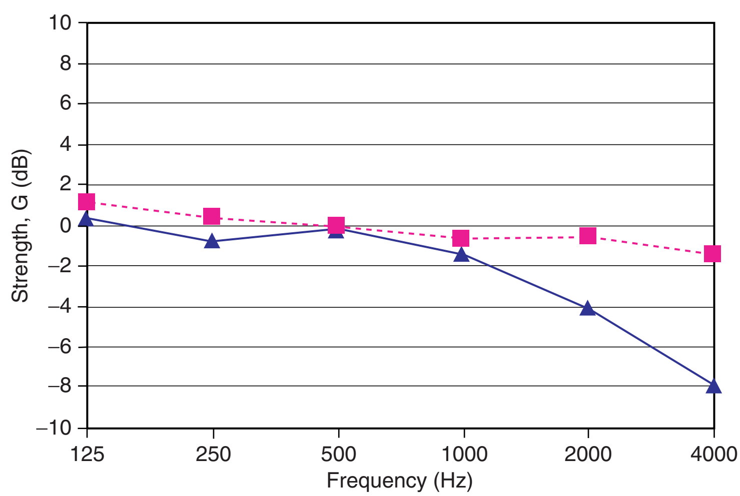


Figure 24. Average Strength, G with the source in the pit. Blue triangles: Measured. Red squares: Simulated.

**5.2. Variation of Results with Position**

The more detailed variation of acoustic parameters over the receiver positions has also been studied. In Fig. 27 the variation of the Strength at 500 Hz is shown. While the measurements show about 2–3 dB difference between stage and pit in pos. 2 and 3 (on the floor), there is no such difference in the simulation results. The explanation may be the attenuation of sound propagating across the audience, being more pronounced

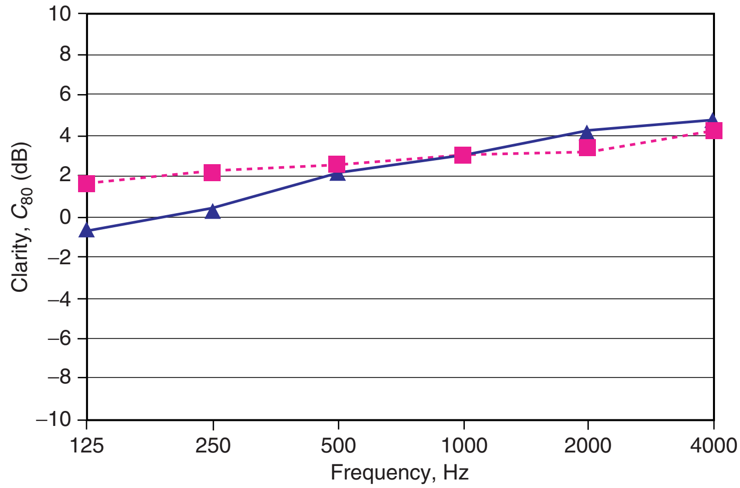


Figure 25. Average Clarity, $C_{80}$ with the source on stage. Blue triangles: Measured. Red squares: Simulated.

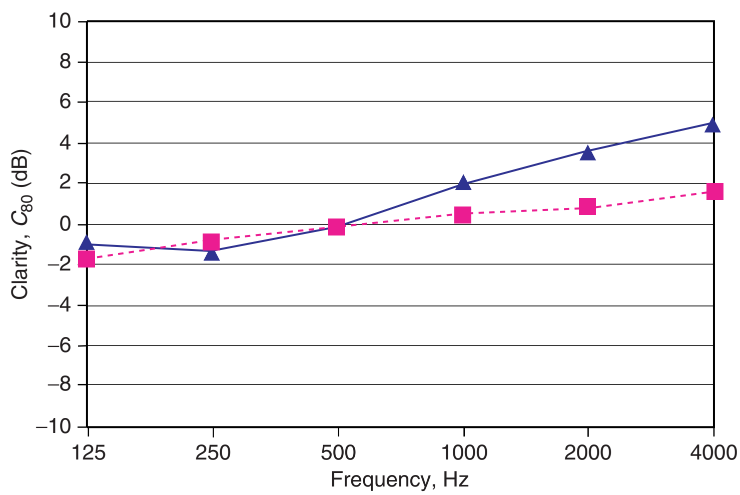


Figure 26. Average Clarity, $C_{80}$ with the source in the pit. Blue triangles: Measured. Red squares: Simulated.

with the source in the pit than in the elevated position on the stage, but not modelled correctly in the simulations.

In Fig. 28 the variation of the Clarity at 500 Hz is shown. One clear effect is the low values in pos. 2 and 3 when the source is in the pit, whereas the Clarity is high with the source on stage. Although not identical, scale model measurements and simulations show the same tendency in variation.

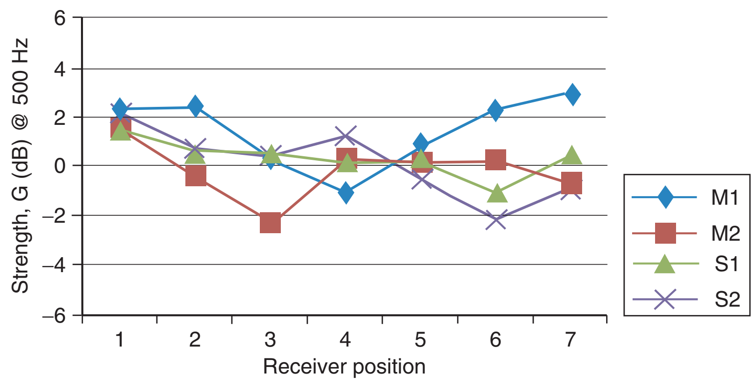


Figure 27. The Strength, G at 500 Hz in seven receiver positions. M1: measured, source on stage; M2: measured, source in the pit; S1 and S2: simulated, stage and pit positions.

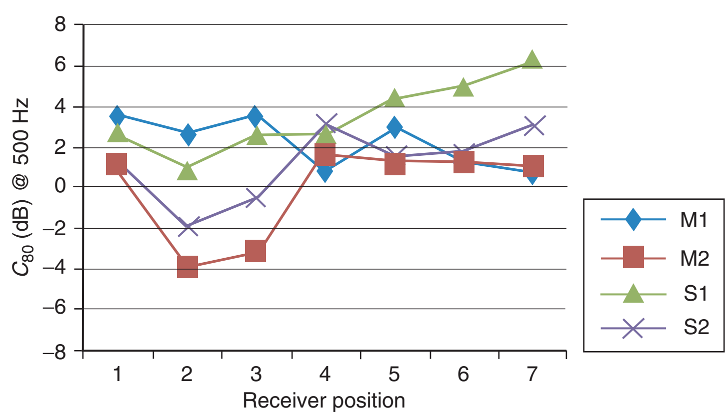


Figure 28. The Clarity, $C_{80}$, at 500 Hz in seven receiver positions. Source positions as in Fig. 27.

### 5.3. The Effect of a Diffusing Wall Treatment

In order to test the effect of diffusing walls on the ground floor, a layer of wrinkled foil was taped to the walls on both sides of the auditorium beneath the first balcony; see Fig. 29. The depth of the sound scattering structure was about 20 mm (400 mm full scale).

Measured results of EDT, Strength and Clarity in the three receiver positions on the floor were compared with those measured with smooth walls. The difference was negligible for EDT and Clarity, while the Strength increased up to 3 dB with the diffusing walls.

Figure 29. The scale model with sound diffusing treatment of the wall under the balcony.

### 5.4. Summary of Scale Model Measurements

The scale model measurements have confirmed the results from the computer simulations. The deviations between measurements and simulations found at the high frequencies should not be given too much weight, because the measuring technique is less reliable at the very high frequencies, i.e. at 2000 and 4000 Hz full-scale.

The scale model cannot give information about the reverberation time; initially the model was tuned to give approximately the reverberation time that was predicted from the computer simulation. The other room acoustic parameters EDT, Strength and Clarity have values that are considered very satisfactory for an opera hall and the sound distribution in the auditorium is very even. Also the balance between stage and pit has been shown to be very good.

## 6. DISCUSSION

The main results from the two different modelling methods are in a reasonable agreement, and thus both methods can be considered a useful acoustical design tool for a project like the opera house. However, there are different strengths and weaknesses associated with each method. First the possible reasons for the different results should be discussed.

- The room geometry and the degree of detail in the scale model and the computer model are not exactly identical, and this may lead to some unknown differences in the results.
- The absorption characteristics of the materials are not the same, those in the scale model being more different from the real materials than the absorption data applied in the computer model.

- The air attenuation is too high in the scale model, which can only partly be compensated for by frequency dependent amplification of the impulse response and/or by surface materials with too little absorption.
- The reflection, scattering and diffraction effects are accurate in the scale model, but only approximated by theoretical models in the computer simulation.

The problem with the absorption of the materials in a scale model means that a scale model cannot be used to check the reverberation time, which must still be considered the most important overall acoustic parameter of a hall. This is in contrast to the computer model, which is dedicated to estimate the reverberation time, also in cases where Sabine's equation is not valid.

Modelling the audience area is particularly interesting, because absorption, scattering, and influence on sound propagation across the surface are all important. While these effects may be reasonably well approximated in the scale model, it is more difficult in the computer model. Especially the attenuation of direct sound and early reflections propagating across the audience area are not modelled correctly in the computer model.

The results from the scale model are limited to some room acoustical parameters, whereas the computer model offers several additional possibilities and tools for ananlysis:

- Analysis in 3D of early reflection paths and identifying the surfaces that generate the reflections (see example in Fig. 30); in a scale model this can be done for the first order reflections using a laser beam, if the surfaces are treated with light reflecting material.
- Calculation of results in a grid that may cover every single seat in the audience area; in a scale model the information about distribution of sound is limited to a few selected receiver positions, and areas with acoustical problems may not be discovered.

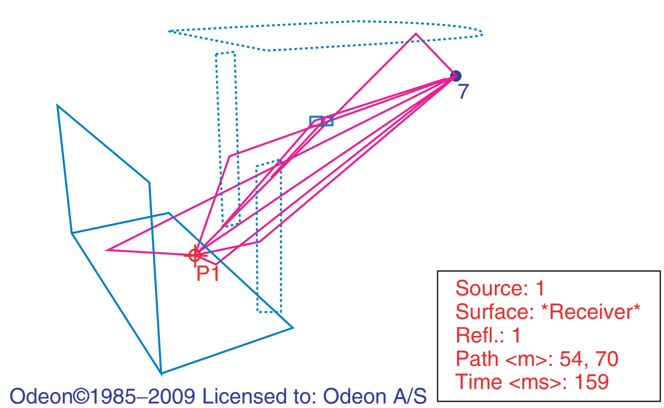


Figure 30. Example of an analysis in 3D of the reflection paths of early reflections.

- The possibility of auralisation and thus to include an evaluation through listening is straight forward and easy in the computer model. With a scale model this is also possible in principle, but with severe demands on the transducers, e.g. a miniature dummy head, and still with a limited frequency range and dynamic range.

The reflection paths for 1$^{st}$ and 2$^{nd}$ order reflections from the source on stage to the receiver 7 on the third balcony are shown in Fig. 30. For clarity only the reflecting surfaces are shown in this example.

Finally, there is a big difference between the two modelling methods when the time consumption and the costs are considered. To create the room model is obviously a much bigger job with a scale model, but in addition comes the extra time for alterations and modifications, if the first design is not fully satisfactory. In the case of the Ankara Opera, several adjustments of volume and geometrical details were made during the first phases of the computer simulations.

Next comes the time for doing the measurements in a sufficient number of source and receiver positions; this may take weeks, whereas the same results can be obtained with a computer model within a few minutes, and a complete grid response within a few hours.

## 7. CONCLUSION

The comparison of the scale modelling technique with the computer simulation technique has shown that there is a good agreement between the results, and both methods can provide useful information for the acoustical design.

The computer modelling technique is fast and cheap, and it offers a lot more than the scale modelling technique, like grid mapping, analysis of reflection paths, and auralisation. The main draw-back is the approximate theoretical models for various wave phenomina, like scattering, diffraction, and angle dependent reflection.

The scale modelling technique is time consuming and expensive. It can be used for a final check of the acoustical design of a hall, but it is not well suited for experiments with alternative solutions. Changes in the room geometry are difficult. The results are limited to some, but not all relevant acoustical parameters. The most important parameter, the reverberation time, cannot be predicted with a scale model.

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