

ROOM ACOUSTIC PREDICTION MODELLING

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ABSTRACT

The development of room acoustic modelling technique over more than forty years is briefly outlined by introducing the most important methods. An important issue is the scattering properties of surfaces, how they are measured and modelled. Two different cases are used to show some of the challenges to room acoustic computer modelling. The first case is a turbine hall with very large sound sources which cannot be modelled by simple point sources. The other case is a new school project where the entire building model has been imported for acoustic simulations, either in selected rooms, or as a more complex soundscape scenario that includes the sound transmission between rooms.

Keywords: Room acoustics, Computer model, Auralisation

1. INTRODUCTION

Room acoustic modelling technique and especially the room acoustic computer models have developed over the last decades (Rindel, 2002) and highly accurate prediction models are available today. Although the room acoustic modelling technique has originally been devoted to the acoustic prediction and design of auditoria, the problems are equally challenging in work rooms, and to a great extent the same methods can be adopted. One fundamental problem is that the rooms can be very irregular, the diffusion of sound can be uneven and very different from the simple assumption of a diffuse sound field, and the sound absorption is unevenly distributed over the surfaces; all together this means that the reverberation time can be significantly different from that calculated by the classical equations of Sabine and Eyring. Another problem is that even if the reverberation time can be measured and predicted, it may not be the most relevant parameter to describe the acoustical condition of a room. In auditoria and performance spaces the room acoustic parameters are laid down in ISO 3382-1. In workrooms and open plan spaces the spatial decay rate of the sound may be a more relevant parameter, and in other rooms the Speech Transmission Index (STI) is more relevant (Pop & Rindel, 2005). The room acoustic modelling offers a simulation of such measurements, and in addition the possibility of auralisation, i.e. to evaluate the acoustical conditions of a space by listening.

2. PRINCIPLES FOR COMPUTER MODELLING

2.1. Image Source Models

This method is based on the principle that a specular reflection can be constructed geometrically by mirroring the source in the plane of the reflecting surface. In a rectangular box-shaped room it is very simple to construct all image sources up to a certain order of reflection (Allen & Berkley, 1979). But in an arbitrary room the number of possible image sources increases exponentially with the order of reflection,

and thus the method is not suitable for rooms like concert halls where reflection orders of several hundred are relevant for the audible reverberant decay.

2.2. Particle racing Models

A more realistic way to simulate the decaying sound is to trace a large number of particles emitted in all directions from a source point. Each particle carries a certain amount of sound energy that is reduced after each reflection according to the absorption coefficient of the surface involved. As shown in Fig. 1 the result is the average decay curve for the room from which the reverberation time is evaluated (Schroeder, 1970).

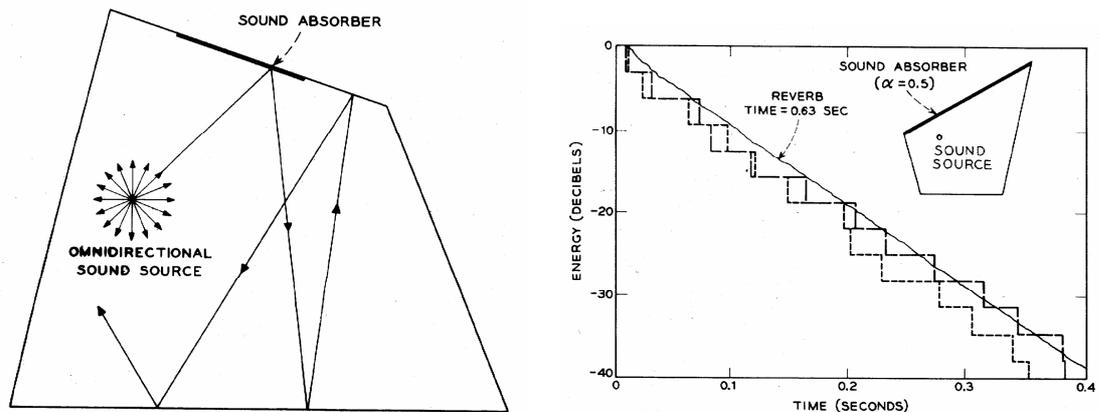


Figure 1. Particle tracing based on geometrical acoustics. Left: The sound energy follows the path of several hundred rays (only one is shown), and the energy of the particles is reduced when they hit an absorbing surface. Right: Average decay curve. (Schroeder, 1970).

2.3. Ray Tracing Models

The first computer model that was used for practical design of auditoria was a ray tracing model (Krokstad et al., 1968). A large number of sound rays are traced from a source point up to high order reflections following the geometrical/optical law of reflection. The main result of this early model is the distribution of ray hits on the audience surface, analysed in appropriate intervals of the time delay. So, this is a qualitative presentation of the sound distribution in space and time. For a closer analysis the direction of incidence of each ray can also be indicated. In order to obtain quantitative results it is necessary to introduce receiver surfaces or volumes for detection of the sound rays. So, an approximate energy-reflectogram can be calculated and used for an estimate of some room acoustic parameters.

2.4. Cone Tracing Models

An alternative to the receiver volume used in ray tracing models is a point receiver in combination with cones that have a certain opening angle around the rays. Cones with circular cross section have the problem of overlap between neighbour cones (Vian & van Maerke, 1986). Cones with a triangular cross section can solve this problem, but still it is difficult to obtain reliable results with this method.

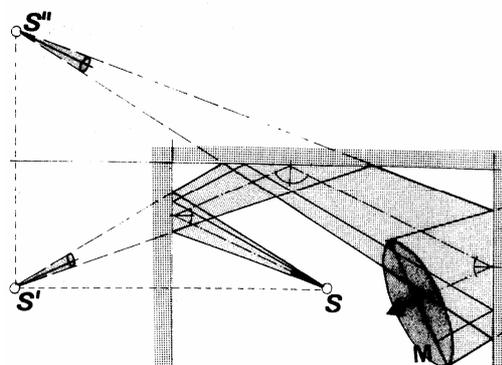


Figure 2: Tracing of a circular cone from the source S to the receiver M. The first order (S') and second order (S'') image sources are also shown. (Vian & van Maerke, 1986).

2.5. Radiosity Models

The principle is that the reflected sound from a surface is represented by a large number of source points covering the surface and radiating according to some directivity pattern, typically a random distribution of directions (Lewers, 1993). This method has also been used as an efficient way to model the scattered part of the early reflected sound.

2.6. Hybrid Models

The disadvantages of the classical methods have led to development of hybrid models, which combine the best features of two or more methods. Thus modern computer models can create reliable results with only modest calculation times. The inclusion of scattering effects and angle dependent reflection with phase shifts has made it possible to calculate impulse responses with a high degree of realism. This in turn has been combined with Head Related Transfer Functions (HRTF) to give Binaural Room Impulse Responses (BRIR), which are convolved with anechoic sound recordings to make auralisation of high quality.

A hybrid model is used in Odeon for the calculation of late reflections. The rays are treated as carriers of energy and each time a ray hits a surface, a secondary source is generated at the collision point, see Fig. 3, left side. The energy of the secondary source is the total energy of the primary source divided by the number of rays and multiplied by the reflection coefficients of the surfaces involved in the ray's history up to that point. Each secondary source is considered to radiate into a hemisphere with a directivity that may take the frequency dependent scattering of the surface and the angle of incidence into account. The contributions from the secondary sources are collected from the receiver position, see Fig. 3, right side. The time of arrival of a reflection is determined by the sum of the path lengths from the primary source to the secondary source via intermediate reflecting surfaces plus the distance from the secondary source to the receiver. A visibility test is made to ensure that a secondary source only contributes a reflection if it is visible from the receiver. Thus the late reflections are specific to a certain receiver position and it is possible to take shielding and convex room shapes into account.

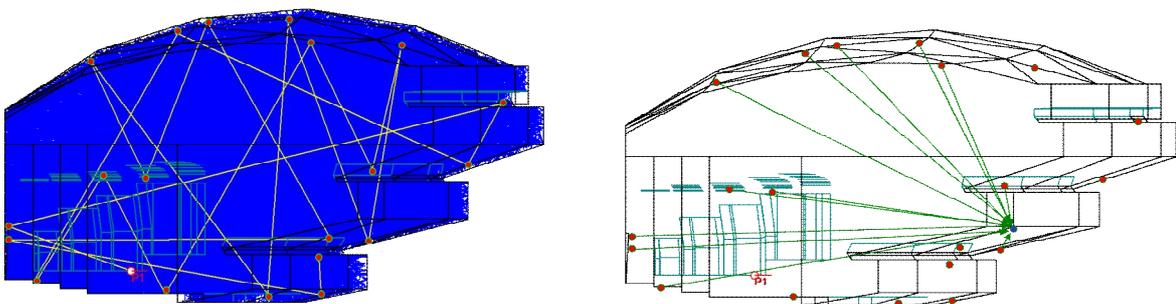


Figure 3: Principle of late reflections in Odeon. Left: Secondary sources created on the surfaces by one of the rays in the ray tracing. Right: A receiver point collects contributions from the visible secondary sources.

3. SCATTERING

3.1. Scattering due to surface roughness

Due to the wavelength of sound being comparable to typical dimensions of reflecting surfaces in rooms, the scattering effects are very important for a room acoustic simulation model. The scattering effects can be divided into two; the scattering due to the surface roughness, and the scattering due to edges and finite

dimensions of the reflecting surface (Christensen & Rindel, 2005). Both can be described by a frequency dependent scattering coefficient, s_s and s_d .

The surface scattering coefficient can be measured at random incidence according to the method laid down in ISO 17497-1. A circular test specimen is placed on a turntable in a reverberation chamber, see Fig. 4, and the reverberation time is measured four times (with and without the test specimen, with and without rotation of the turn table). From the measured reverberation times the scattering coefficient can be derived. It typically increases with the frequency as shown in Fig. 5. Thus, for practical use it may be sufficient to assign a single, mid-frequency value for surfaces with high roughness; then the scattering at other frequencies is assumed automatically.

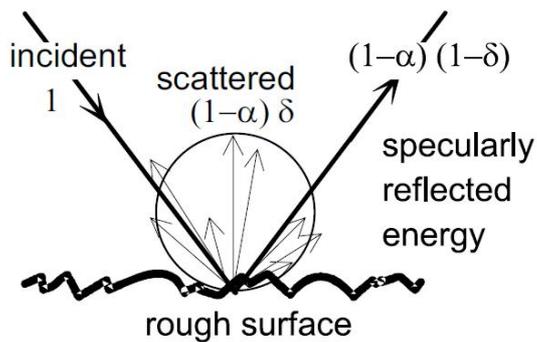


Figure 4: Measurement of the random incidence scattering coefficient. Left: principle. Right: A 1:5 scale reverberation room with the measurement setup. (Ref.: Vorländer et al. (2004)).

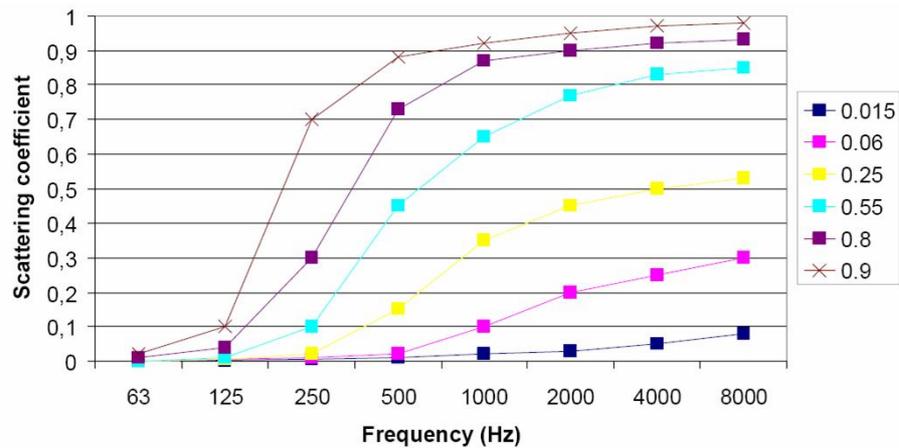


Figure 5: Frequency dependent scattering coefficients for surfaces with different roughness. The mid-frequency scattering coefficients are indicated in the right side of the graph.

3.2 Scattering due to surface size and distance

The diffraction related scattering coefficient depends on the surface dimensions, the distance from surface to source and receiver, and the distance of the geometrical reflection point to the nearest edge of the surface. It is also frequency dependent, being higher at low frequencies.

It follows from diffraction theory that the scattering from the edges of a finite size panel increases with the distance from surface to source and receiver. In Odeon the combined scattering effect is called the reflection based scattering coefficient s_r , and it is calculated from:

$$s_r = 1 - (1 - s_d) \cdot (1 - s_s)$$

where s_d is the scattering coefficient due to diffraction and s_s is the scattering coefficient due to surface roughness.

An example of how the reflection based scattering works is shown in Fig. 6. If a relatively small surface (e.g. a table) reflects sound from a source close to the surface, there is very little scattering, but when the source is far away from the surface the scattering is high, in accordance with the diffraction theory.

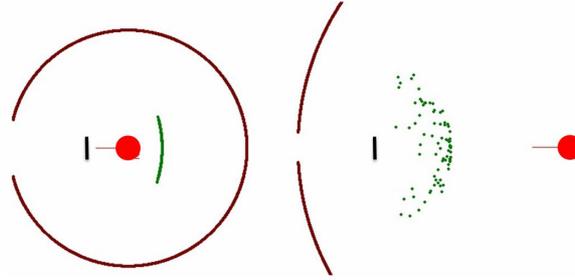


Figure 1: Reflection based scattering from a small surface; the source is the red dot. Left: source close to surface. Right: Source far from surface.

3.3. Application of scattering coefficients

In a simplified room model the scattering coefficient of the surfaces representing more complicated structures, e.g. a floor representing the audience area in an auditorium should be assigned a scattering coefficient. If a measured scattering coefficient is not available the suggestions in Tab. 1 can be used as a guideline.

Table 1: Suggested mid-frequency scattering coefficients for various structures.

Material	Scattering coefficient at mid-frequency
Audience area	0.6 – 0.7
Rough building structures, 0.3 – 0.5 m deep	0.4 – 0.5
Bookshelf, with some books	0.3
Brickwork with open joints	0.1 – 0.2
Brickwork, filled joints but not plastered	0.05 – 0.1
Smooth surfaces, general	0.02 – 0.05
Smooth painted concrete	0.005 – 0.02

In room models with a high degree of detail, the scattering effect comes automatically from the structures, and it may be sufficient to apply a default low scattering coefficient of 0.05 to all surfaces.

4. CASE 1 – A TURBINE HALL

4.1. Room modelling

This example is a large turbine hall with the main dimensions: 153 m, 34.5 m, and 20 m. The hall contains two turbines, one of which is seen on the photo in Fig. 7. A wireframe model of the entire hall is seen in Fig. 8. It can be noted that the model is much simpler and rough, many details being omitted.

The material data used for the calculations were based on material descriptions and known absorption coefficients for similar materials and the default scattering coefficient of 0.05 at mid frequencies was applied to all surfaces.



Figure 7: Turbine hall used as an example of room acoustic modelling.

Fig. 8 shows twelve receiver positions that were used for measuring the sound pressure level in the hall, and the same positions were used for calculations in the model. A single source position is also shown; this is used for calculation of the reverberation time and other room acoustic properties in the model as explained below.

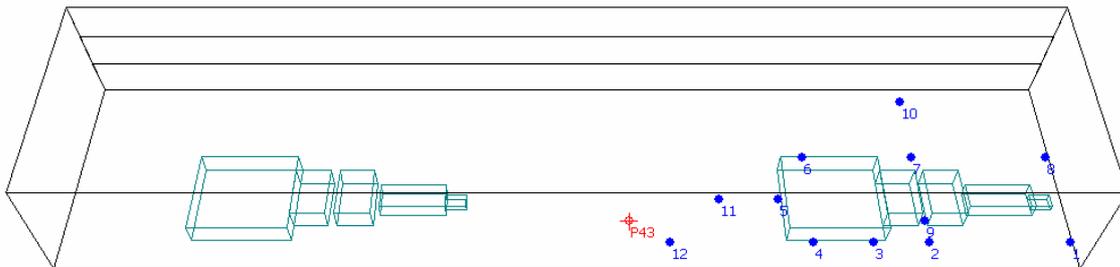


Figure 8: Wireframe model of turbine hall with two turbines roughly modelled. Twelve receiver positions and a single source position have been inserted.

4.2. Calculation results with a point source

The first question concerning the acoustics of a hall is often the reverberation time, although this may not be the most appropriate acoustical descriptor in case of large industrial halls. However, even in a very difficult acoustical environment, i.e. in a room that is far from obeying the assumptions of a diffuse sound field, a quick and very efficient calculation method for the reverberation time is the so-called global decay. In principle it is the method of particle tracing originally proposed by (Schroeder, 1970) but further improved in Odeon with the vector-based scattering method for sound reflections.

Instead of the reverberation time (Ondet & Sueur, 1995) found that the slope of the spatial decay curve calculated with a single omni-directional sound source could provide a better basis for an acoustical evaluation in typical non-diffuse work rooms. This method has been described in detail in ISO 14257, and

with a computer model it is simple to simulate this measurement procedure. Using the point source and the 12 receiver positions in Fig. 8 the calculated spatial decay is shown in Fig. 10.

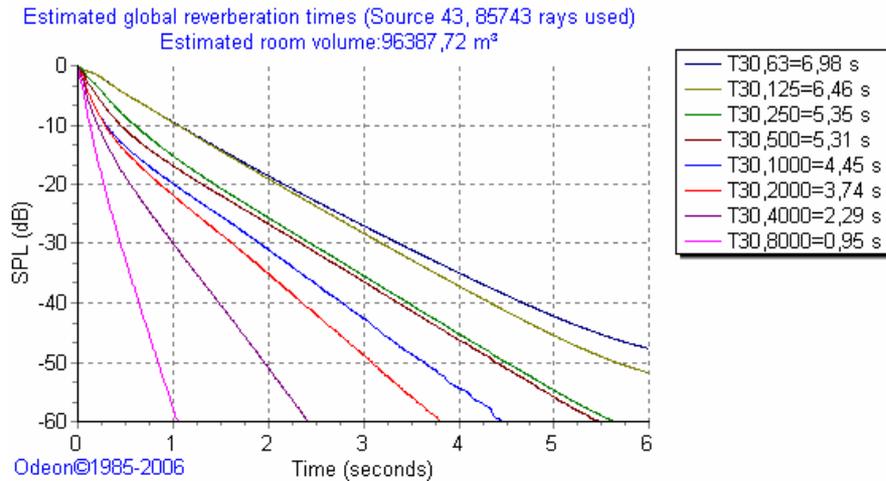


Figure 9: Global decay curves calculated for eight octave bands. The derived reverberation times for a 30 dB evaluation range are listed in the box to the right

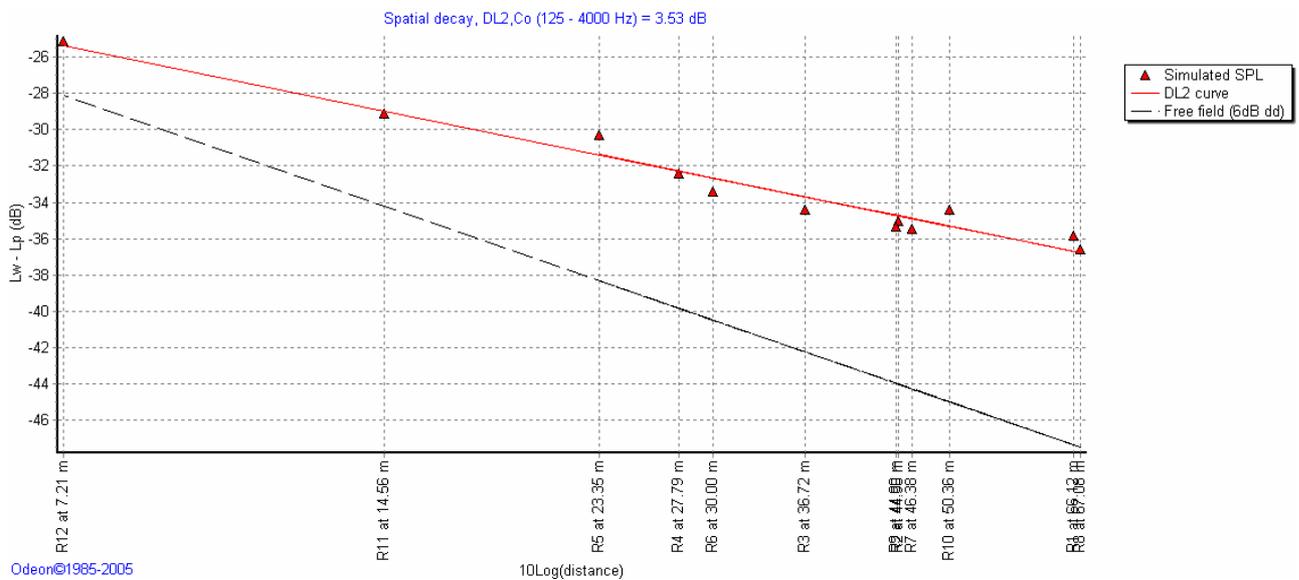


Figure 10: The spatial decay curve calculated for the omni-directional source and the 12 receivers shown in Fig. 8. The frequency averaged slope is $DL_2 = 3.53$ dB per distance doubling.

4.3. Modelling large noise sources

In work rooms and industrial halls the typical noise sources are big and complicated. Thus, for a good simulation it is not possible to use only point sources, as usual in auditorium acoustics. Instead the geometry of the noise sources should be approximately modelled, and the surfaces should be used as sources radiating sound. In Fig. 11 is shown how one of the turbines has been modelled using 17 surface sources and two point sources. In this example the radiated sound power was measured using intensity measuring technique, so each surface in the model could be assigned a certain radiated sound power in octave bands. Further details are given in (Christensen & Foged, 1998).

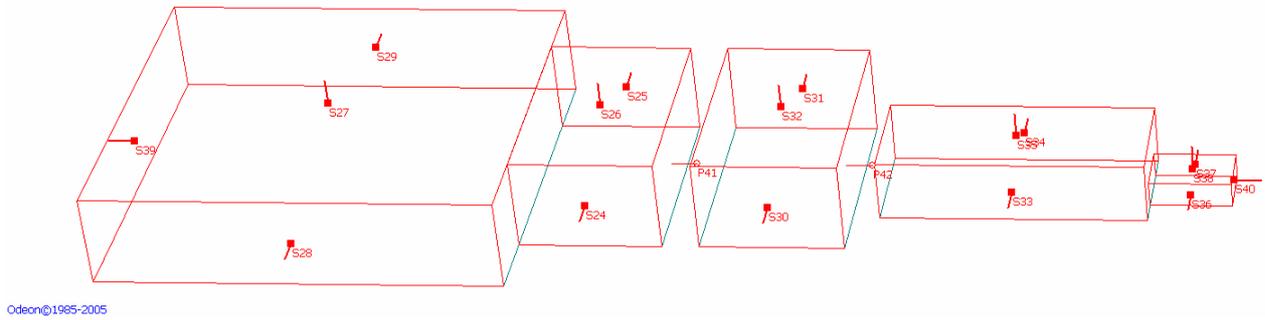


Figure 11: One of the turbines modelled by 17 surface sources and 2 point sources. Each source is assigned a sound power level in octave bands.

4.4. Calculation results with large noise sources

The A-weighted sound pressure had previously been measured in the turbine hall in the 12 positions shown in Fig. 8. A similar calculation was made with the computer model using in total 34 surface sources and four point sources. The calculation results are compared to the measured results in Fig. 12, and good agreement can be observed. The average difference is 0.3 dB and the maximum deviation is 2.2 dB in position 12.

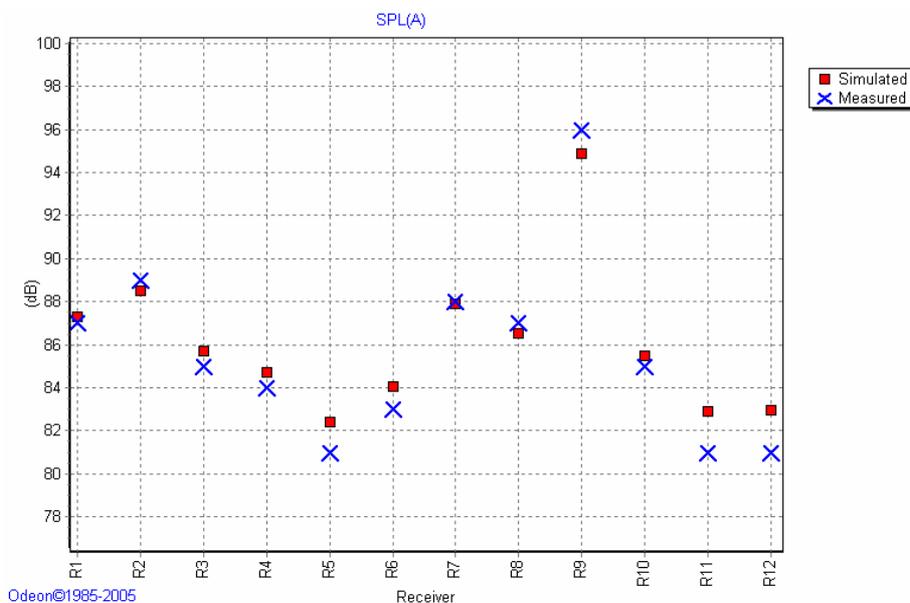
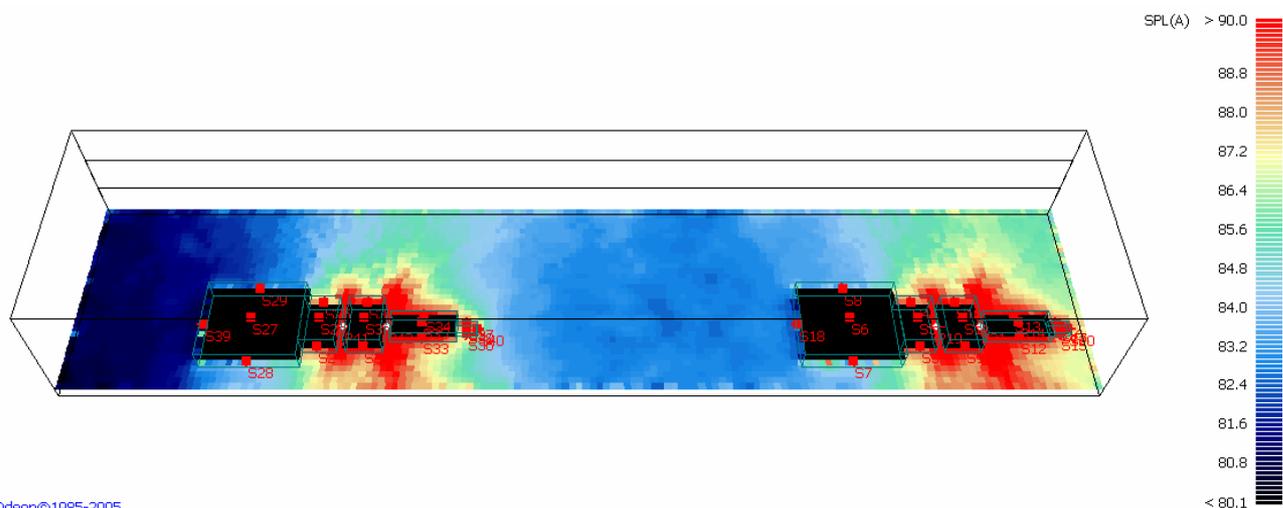


Figure 12: Comparison of calculated and measured A-weighted sound pressure levels in 12 receiver positions.

One very useful feature of a room acoustic computer model is the possibility to calculate the sound pressure level in a large number of receiver positions and display the result in a grid map as shown in the example Fig. 13. In this case with 38 sources and 5202 receivers the calculation time is several hours, so this kind of calculations are typically made over night.



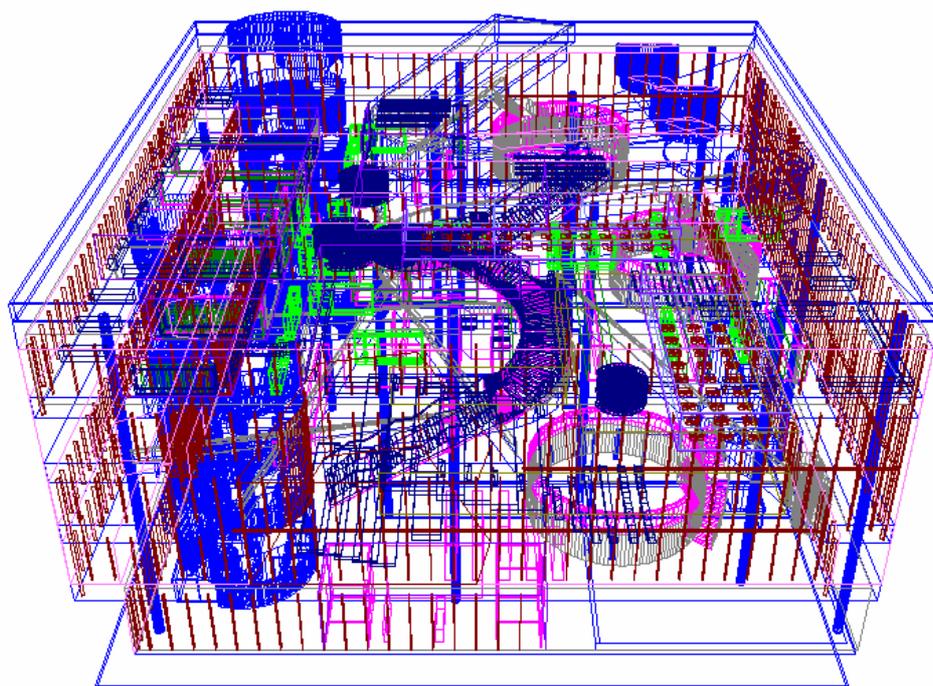
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Figure 13: Mapping of the A-weighted sound pressure level with both turbines active. The grid size is 1 m and the height is 1.5 m above the floor.

5. CASE 3 – A HIGH SCHOOL WITH OPEN PLAN DESIGN

5.1. Import of the building model

This example is a project for a high school in Denmark, see Fig. 14. In this case it was possible to have access to the architect's very detailed 3D model. However, it is questionable which degree of detail is necessary for a good acoustical simulation; too many details may even make the model less useful for the acoustic purpose.



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Figure 14: Wireframe picture of the room model as imported in Odeon. Total dimensions are 54,4 * 54,4 * 34,1 m. The model has 36 585 surfaces and 15 layers shown in different colours.

For the import of models, e.g. in the dxf interchange format or the 3ds format, Odeon has a very efficient import function, which automatically can make geometrical checks and an intelligent reduction of the number of surfaces by gluing triangles and rectangles that define parts of the same surface and creating polygons instead.

Another challenge to the acoustic modelling is the fact that the architect's model covers the entire building. This means that the digital model can be extremely large in terms of the number of surfaces, and it may be difficult to extract the parts necessary for the acoustical simulation of a particular room in the building. After import to Odeon and the automatic gluing of surfaces, the model contains 36 585 surfaces. The import from the dxf file has been highly optimised, but still it takes several minutes.

When the geometry of the model is ready the material properties (absorption and scattering) has to be assigned to the surfaces. In this process it is a very big advantage if the model has been made with the use of layers. Typically the layers refer to different materials, and when this is the case, it is possible to assign the right material properties to all surfaces in a particular layer in one single stroke.

5.2. Calculations

The calculation method used in Odeon for late reflections as described in section 2.6 is very efficient when it comes to complicated room geometries with remote receiver positions.

To achieve good results it is recommended to look at the reflection density in the calculated impulse response; it is suggested that the reflection density should be at least 50 per ms. If the reflection density is too small the calculated decay curve will be far from smooth and thus the calculated room acoustic parameters will have a relatively high uncertainty. For a calculation to a remote receiver position with no direct sound and no first order reflections, it is important to include as many details as possible in the late part of the impulse response and it may be necessary to increase the number of rays. In Table 2 is shown results obtained with four different calculations, the number of rays ranging from 4000 to 500000.

Table 2: Calculation times and some room acoustical parameters calculated with different number of rays for a single source and a remote receiver position.

Number of rays	4 000	20 000	100 000	500 000
Calculation time (mm:ss)	00:06	00:24	02:03	10:40
Reflection density (per ms)	20	100	500	2 500
EDT at 1kHz (s)	2.82	2.15	2.29	2.40
T ₃₀ at 1kHz (s)	1.29	1.75	1.65	1.66
SPL, dB(A)	32.9	33.8	33.3	33.1
STI	0.37	0.38	0.34	0.36

Some parameters like SPL and STI are not very sensitive to the quality in the impulse response calculation, as these only need a small reflection density to be determined. Other parameters like EDT and especially the reverberation time T₃₀ are more sensitive to the reflection density. Obviously 4000 rays are not sufficient, but already with 20000 rays the decay curves look reasonably smooth. Very little is gained with more than 100000 rays. For the STI parameter it should be mentioned, that in these calculations the background noise was not included. This could easily be included in the calculations with the sufficient information about the background noise level and spectrum.

5.3. Auralisation scenario

In open plan spaces with multiple activities it is often the case that acoustics cannot be settled within the usual requirements. Sometimes new solutions and new ways of learning and working are inherent in design of a building. The best way to achieve a mutual understanding of the acoustics of a new design may be by presenting an auralisation scenario representing various sources in a soundscape including typical activities within the building. This was done in the described school project and as a result it was decided already in the design phase to apply an additional amount of sound absorption materials to selected wall surfaces.

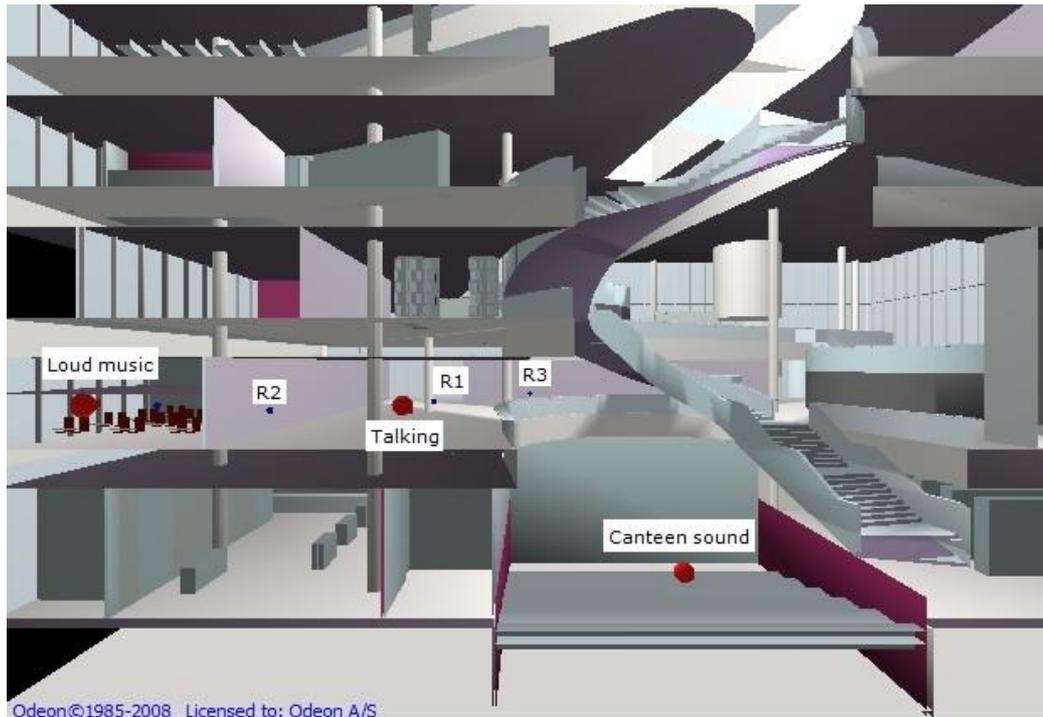


Figure 15: Section of the model showing the sources and receiver positions used for the auralisation scenario.

A scenario for auralisation may include many sound sources. In order to demonstrate the principles an example with only three sources has been chosen; a nearby person talking, noise from the canteen area on a different floor in the building, and sound from loud music being transmitted through a wall from the adjacent classroom, see Fig. 15. Three different listener positions have been chosen. For each listener position a mix is made from the single auralisations from each of the sources.

The wall consists of glass, gypsum board and a door. The extension of the room acoustic calculation method to include sound transmission between rooms has been described in detail elsewhere (Rindel & Christensen, 2008).

6. CONCLUSION

The main reasons for developing room acoustical computer models have been (1) that the assumption of a diffuse sound field is not fulfilled and thus the classical reverberation equations are not reliable, and (2) in many rooms other parameters than reverberation time have proven to be important, and such parameters can only be derived from measurements or computer simulations. In addition the computer models offer tools for 3D analysis of sound reflections, for mapping of sound distribution, and for auralisation. The latter has become a useful supplement to the graphs and figures for the acoustic consultant, especially in the dialogue with architects and building owners about the acoustic solutions for the design of a new building.

In recent years there has been a development of computer based 3D modelling tools for architectural design, and thus there has been an increasing demand for efficient interface between the architects' models and the acoustical models. Great efforts have been made to meet this demand as demonstrated in the second case above.

Originally room acoustic computer models have mainly been applied for concert halls and other important auditoria, in place of - or as a supplement to scale model investigations. Today the computer models are widely used for all kinds of rooms such as industrial halls, music studios, classrooms and school buildings, open plan offices, PA-systems for public buildings, sports facilities, train wagons, ships, off shore facilities, and much more.

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