THE APPLICABILITY OF RAY-TRACING BASED SIMULATION TOOLS TO PREDICT SOUND PRESSURE LEVELS AND REVERBERATION TIMES IN 'COUPLED SPACES'

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ABSTRACT

Nowadays architects commonly use the 'coupled space concept'. Examples are mezzanines, half-open office spaces and exhibition rooms. Because of the need to meet acoustical standards, the need to predict sound pressure levels and reverberation times for this category of spaces is ever growing.
The transmission of sound from one space to another depends on design decisions like position, shape and dimensions of each of the interconnected spaces and of the "gap" between the spaces. In this paper the suitability of ray-tracing based simulation tools for the prediction of actual sound pressure levels and reverberation times in coupled spaces will be discussed.

INTRODUCTION

One of the ongoing research projects in the Building Physics Group deals with the prediction of sound pressure levels and reverberation times in so called 'coupled spaces'. The project is done in co-operation with the University of Leuven. We define 'Coupled spaces' as two or more adjacent spaces that are interconnected by permanent openings in separation walls and floors. The need to predict sound pressure levels and reverberation times for the here mentioned category of spaces is ever growing since nowadays architects commonly use the coupled space concept. Some well-known examples are: mezzanines, half-open office spaces and exhibition rooms.
It is clear that transmission of sound from one space to another will depend on design decisions like position, shape and dimensions of each of the interconnected spaces and of the opening or connecting space. Furthermore type, position and dimensions of applied absorption materials will also be of influence. In order to design coupled spaces which will meet predetermined acoustical standards, 'tools' will be required which allow reliable prediction of acoustical properties for coupled spaces. For simple floor plans analytical solutions for the computation of acoustical quantities can be found in literature [Kuttruff, 1991; Cremer, 1982]. However, for more complicated floor plans the use of sophisticated simulation tools is required.

Existing simulation tools in the field of room acoustics have only been developed for the prediction of sound pressure levels and reverberation times in 'single spaced rooms' like concert halls. In general, two principally different underlying computational approaches can be distinguished. One is based on the finite element technique, the other is based on the ray-tracing technique. When using finite element based tools, the required number of 'elements' will be large for frequencies above 500 Hz and for complex geometries and topologies, thus resulting in substantial computation time. For this reason, and because of the fact that the generated output is far to detailed when using finite element based tools, ray-tracing based tools have been considered.
In this paper the suitability of ray-tracing based simulation tools for the prediction of sound pressure levels and reverberation times in coupled spaces will be discussed. The ultimate goal of this research project is to compile a handbook for architects, which contains a number of coupled spaces and which explains the most relevant design parameters that contribute to 'acoustical quality'.

METHODOLOGY

The suitability of a simulation tool depends on many factors. One of the main requirements is that reliable results are generated. For the here-discussed category of simulation tools the aspect of reliability will be emphasised.
The reliability of calculated sound pressure levels has been investigated as follows. Sound pressure levels have been computed for two coupled spaces with a simple geometry, using the commercial computer program RAYNOISE and the computer program EPIKUL, developed by the University of Leuven. Having the source code of EPIKUL [Vermeir, 1995] available proved to be a major advantage for thorough research of acoustical behaviour of coupled rooms.

Computed acoustical quantities have been compared with measured values, using a large-scale model, of scale 1:2.
In order to compare calculated and measured results for coupled spaces with a more complex geometry, the same procedure has been followed for a 1:1 scale model, i.e. one of the mezzanine spaces in the building of the Delft Faculty of Architecture.
In general, the computation of reverberation times requires different program settings. The reverberation room at the faculty of Physics from Delft University (with known characteristics) has therefore been simulated and the computed reverberation times have been compared with measured reverberation times.

Performed computer simulations and measurements as well as analysis of obtained results will be discussed in the following sections. However, for a good understanding of the project it is necessary to describe briefly the computational concept of ray tracing based methods first.

RAY-TRACING CONCEPT

In ray-tracing, acoustical energy emitted by a source is considered to be composed of a large number of energy packages or pulses, concentrated along rays in all possible directions. The energy content of these pulses can be defined by the user as a function of the direction in which a ray is emitted. Each time a ray hits one of the surrounding surfaces of the space the energy content of the pulse decreases; the decrease depends on the reflection coefficient of that particular surface. In what way a ray or pulse continues its path depends on the reflective properties of the surface (specular or diffuse).
By following the path of all emitted rays for a predefined maximum number of reflections, it is possible to determine for each microphone position after how many seconds an emitted pulse 'hits' the microphone and to what extent the energy content of each pulse has decreased.

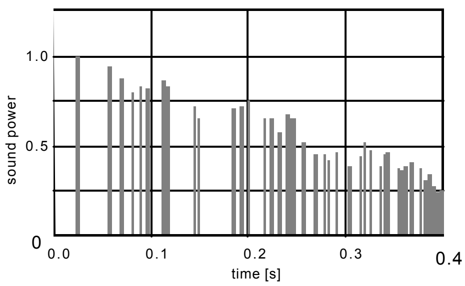

Figure 1: Received energy pulses for one specific microphone position as a function of time for all emitted rays. Sound power of each pulse is relative to the sound power of the first pulse (vertical axis).

Figure 1 shows an example of the so-called 'pulse response'.
If we denote the pulses from figure 1 as $h(t)$, the total amount of received energy $E(t)$ is given by the following expression:

$$E(t) = \int_0^t h(\boldsymbol{t})d\boldsymbol{t} \qquad (1)$$

The end value for $E(t)$ will be found for very large values of t ; see the curve shown in figure 2.

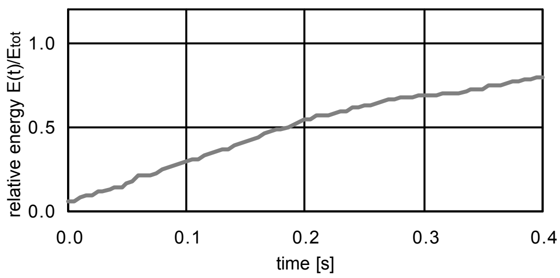

Figure 2: Integration of all received energy pulses for one specific microphone position (energy scale is relative to the end value E_{tot}).

The curve in figure 2 shows the so-called 'positive step response'. The amount of received acoustical energy is always finite. For $t \to \infty$ an asymptotic value (E_{tot}) will be reached. E_{tot} is proportional to the sound pressure level at the specific microphone position.
One of the first choices to be made when starting a ray tracing based modelling procedure, is the value of t_{stop} or, to put it otherwise, the integration interval of the numerical integration process. This choice has to result in a good balance between accurate prediction of sound pressure levels and acceptable computation times.

To calculate the reverberation time (T_{rev}) in a model room, the 'negative step response' has to be included as well. This is because in practice T_{rev} is measured by switching *off* a sound source. One example of the negative step response as well as the positive step response is shown in figure 3.

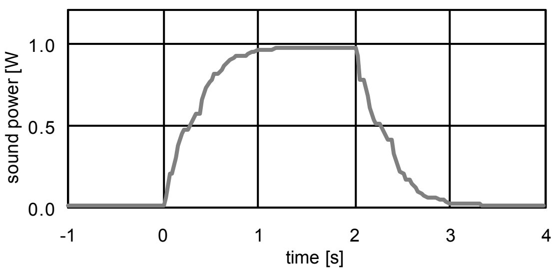

Figure 3: Positive and negative step responses. Note that the time scale in figure 3 differs from the time scale in figure 2.

At t = 0 s a source is switched on; it is switched off at t = 2 s. If the sound field in a room is more or less diffuse, both responses are exponential.

In figure 4 positive and negative responses are shown when using a logarithmic scale along the vertical axis.
Because of the more or less exponential decay the decay-curve becomes more or less a straight line when the vertical axis is taken logarithmically.

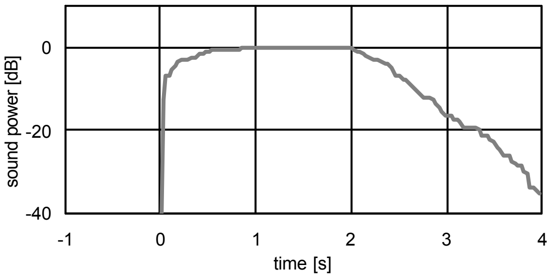

Figure 4: Step responses as shown in figure 4, using a logarithmic scale along the vertical axis.

The reverberation time T_{rev} is found by determining the period in which the sound pressure level drops 60 dB. This dynamic range, both in measurements and calculations, is very hard to accomplish. In addition much computational time would be required for the ray-tracing based simulation.
For spaces with a more or less a straight decay-curve the slope can be used to make a reliable estimate for T_{rev}. In these cases, introducing t_{stop} to reduce computation time for determination of T_{rev} is very well possible. However, spaces with a perfect diffuse sound field are not always found; especially in coupled rooms the sound field is seldom diffuse. For this reason, the choice of t_{stop} has to be made very carefully: again there is a conflict between desired accuracy and required computation time.

REQUIRED PROGRAM SETTINGS

Before performing a computer simulation, the user has to decide about a number of program settings. Program settings with a strong impact on accuracy of the acoustical quantities will be briefly discussed.

INTEGRATION INTERVAL

One program parameter that has to be chosen by the user is the length of the integration interval. In the computer program EPIKUL this interval is explicitly defined by the parameter t_{stop}. In the computer program RAYNOISE, the integration interval is implicitly defined by the maximum number of reflections that are allowed for each ray during computation.
A generally accepted approach for obtaining an estimate for the decay curve is based on the use of the so called 'Schroeder integral', representing the negative step response by a "backward integration":

$$S(t) = \int_{t}^{\infty} h(\boldsymbol{t}) d\boldsymbol{t} \qquad (2)$$

In computer programs the infinity sign must be replaced by a valueof t_{stop}, so:

$$S(t, t_{stop}) = \int_{t}^{t_{stop}} h(\boldsymbol{t}) d\boldsymbol{t} \qquad (3)$$

This equation is used for the prediction of SPL and T_{rev}. SPL is found when $t = 0$, while T_{rev} is calculated from curve fitting along the slope of the Schroeder curve.

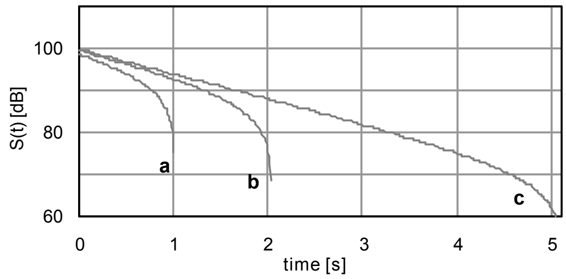

Figure 5: Three Schroeder curves derived from computer simulation for a reverberation room. The acoustical power level emitted by the modelled source equals 100 dB.

To investigate the influence of t_{stop} on calculated sound pressure levels and on reverberation times, computations have been carried out for the reverberation room of Delft University. This room has a reverberation time just over 10 seconds. Figure 5 shows three examples for three values of t_{stop}: 1.0, 2.0 and 5.0 s. The results of SPL and T_{rev} from these curves are given in table 1. The reverberation times are calculated from straightforward curve fitting along the total curves as performed by both computer programs. The rather big inaccuracies are also caused by the last parts of the curves.

t_{stop} [s]	SPL [dB]	T_{rev} [s]	*curve*
1.0	98.6	3.9	a
2.0	99.8	6.1	b
5.0	99.8	8.8	c
∞	99.8	10.2	

Table 1: Sound pressure levels and reverberation times, simulated for the reverberation room at Delft University.

The impact of the choice for t_{stop} on the decay curve and consequently on estimated reverberation times, is clearly demonstrated. From table 1 the conclusion can be drawn that in comparison with reverberation times an accurate estimate of sound pressure levels requires less integration time and hence less computation time.

It should be noted that the curves shown in figure 5 are derived from computations in a reverberation room, in other words for an almost perfectly diffuse sound field. In the 'real world' sound fields are often far from diffuse, leading to oscillations in the Schroeder curves and related reverberation times.

TAIL CORRECTION

When applying the computer program RAYNOISE the user has to decide whether or not to apply 'tail correction'. The tail correction can be seen as a feature meant to compensate for the amount of received energy that will be neglected because of t_{stop}. It is clear that stopping the computation too soon without adequate compensation will result in an inaccurate computation of sound pressure levels. The tail correction appears to work well for simulation of single spaced rooms; use of the tail correction for coupled rooms, however, may lead to significant errors. It is beyond the scope of this paper to extensively discuss this tail correction.

NUMBER OF RAYS

Besides the program parameter t_{stop} and the tail correction, the number of rays emitted by the sound source has to be defined by the user. This value stands for the opening angle of all 'energy beams' along the rays. In most cases the number of rays has to be chosen in such a way that at $t = t_{stop}$ the beam can more or less 'contain' the considered room.
In that case the opening angle is inversely proportional to t_{stop} , i.e. the computation time becomes proportional to $(t_{stop})^3$.

REFLECTIVE PROPERTIES

Another important category of parameters that has to be chosen deals with the reflective properties of all surrounding surfaces. Reflection of a ray can either be completely specular or partly diffuse. In case of partly diffuse reflection, the direction of a reflected ray is the vector sum of a specular component (**s**) and a random diffuse component (***d***) (see figure 6).

Besides reflection type, the rate of absorption has also to be defined. For many building materials the rate of absorption is a function of the angle of incidence. In literature some generally accepted assumptions concerning angle-dependent absorption can be found [Kuttruff, 1991]

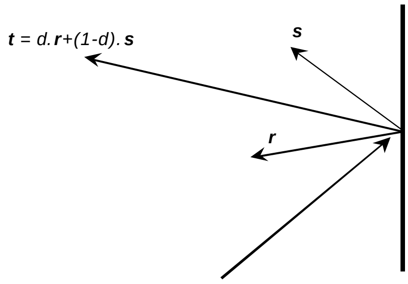

Figure 6: Direction of reflected ray in case of partly diffuse reflection.

PRE & POST PROCESSING FEATURES

AutoCAD files, containing a description of the geometry and topology of complex spaces, are used as input files. The AutoCAD layer structure can be very helpful in defining information about absorption properties of applied materials.
One of the interesting features on the output side is the possibility to represent computed sound pressure levels by isobar-maps. An example will be shown later on.

SCALE MODEL EXPERIMENT

For one specific type of coupled spaces, sound pressure levels have been computed and measured, using the large-scale model shown in figure 7.

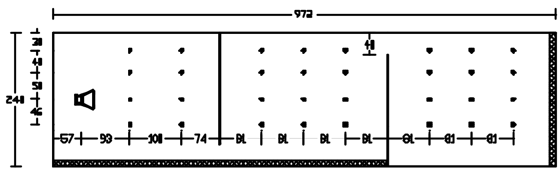

Figure 7: Scale model of a coupled room, used for measurements and computer simulation.

Dimensions are given in centimetres; position of the source and of the 32 microphones as well as of absorption materials are indicated.
Based on absorption coefficients measured in a reverberation room and assuming complete specular reflection, simulations were performed for 8 octave bands using the simulation tools RAYNOISE and EPIKUL.

APPLIED PROGRAM SETTINGS

First the minimum required number of rays and reflections have been determined. For coupled spaces these numbers were found to be relatively large in comparison with single spaces (10^5 and 10^2 rays respectively).
Furthermore, the impact of the tail correction on accuracy has been investigated with both computer

models. It has become clear that the 'tail correction' should not be used because unacceptable errors occurred. In fact tail correction can be useful, but not in the way performed by the computer models used.

RESULTS FOR SPECULAR REFLECTION

For the 2000 Hz band computed and measured numbers (compared with the numbers for one reference microphone) are shown for all microphone positions in figure 8.

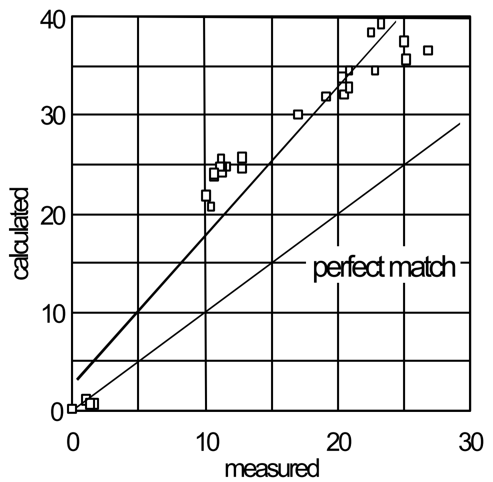

Figure 8: Comparison of measured and computed results (assuming 100% specular reflection).

Three sets of results with different correspondence between computed and measured numbers can be distinguished. These groups correspond with the rooms where the receivers were positioned. For the room where the sound source is placed, a very good correspondence is found. For the most remote room correspondence is very poor; differences from 15 up to 20 dB were found.

RESULTS IN CASE OF DIFFUSION

One of the possible causes for the poor correspondence could be the assumption of complete specular reflection.

For various rates of diffusion the impact of diffusion therefore has been investigated. In figure 9 results found for 50% diffusion are compared with results found for 0% diffusion. It is clear that the impact of diffusion on computed numbers will be around 5 up to 7 dB. This means that before mentioned differences of 15 up to 20 dB can only be partly caused by negligence of diffusion.

ABSORPTION CHARACTERISTICS

Another possible cause for the differences of 15 to 20 dB could be a difference between assumed and actual characteristics of applied absorption materials. Two approaches will now be discussed briefly.

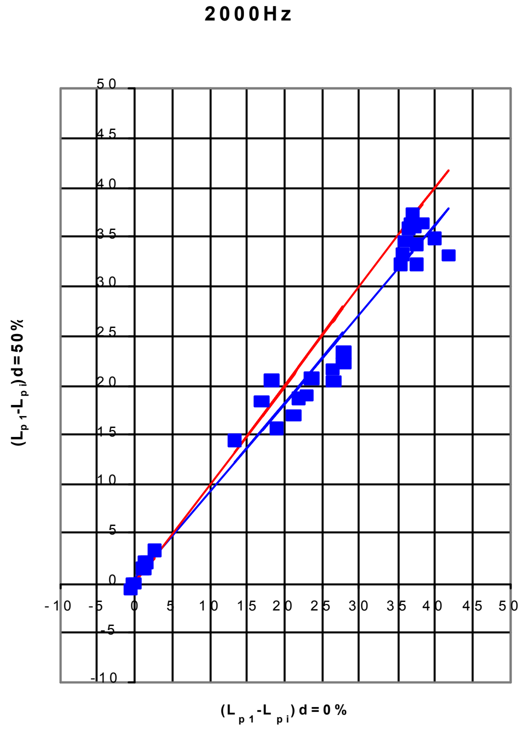

Figure 9: Comparison of computed results (assuming 0% as well as 50% diffusion).

APPROACH NR.1

In most cases the absorption coefficient is known from measurements of a material sample in a reverberation room. This value will be denoted here as α_{rev}. The value for α_{rev} includes, however, no information about the impact of the angle of incidence on absorption. To include the angle of incidence in α the following procedure has been used.

First an arbitrary value for the 'normal absorption coefficient' (for sound impinging perpendicular to an absorbing surface) has been chosen, here denoted as α_{norm}. From this value for α_{norm} the normal value for the reflection for the sound pressure R_{norm} has been calculated by means of the following equation:

$$R_{norm} = \sqrt{1-\alpha_{norm}} \qquad (4)$$

Application of acoustical theory leads to the angle dependent sound pressure reflection coefficient $R(\theta)$:

$$R(\theta) = \frac{\cos\theta - 1 + (\cos\theta + 1)R_{norm}}{\cos\theta + 1 + (\cos\theta - 1)R_{norm}} \qquad (5)$$

and from that value the corresponding angle dependent absorption coefficient $\alpha(\theta)$ is calculated:

$$\alpha(\theta) = 1 - |R(\theta)|^2 \qquad (6)$$

For a diffuse field the value for $\alpha(\theta)$ can be substituted into “Paris’s integral” to obtain a value for the ‘diffuse absorption coefficient’ α_{dif}:

$$\alpha_{dif} = 2 \int_0^{\pi/2} \alpha(\theta) \sin\theta \, \cos\theta \, d\theta \qquad (7)$$

This value of α_{dif} is compared with α_{rev}. In general both values are not equal. In that case the procedure is repeated for an adjusted starting value for α_{norm}. Repeating this loop in general results in acceptable agreement of both values.

Figure 10 shows $\alpha(\theta)$ to accomplish an overall value of 0.56.

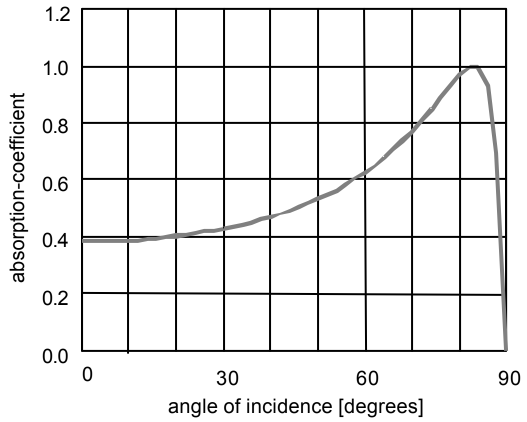

Figure 10: Characteristics of the absorption material that has been applied in the scale model. The diffuse absorption coefficient calculated with Paris’s formula equals 0.56.

APPROACH NR.2

A second, more laborious approach differs from the first approach in the way α_{dif} is calculated. In stead of using Paris’s integral, the reverberation room at the Physics Department of Delft University has been simulated (according to the ISO-standard procedure), using the absorption characteristics according to formula (6). This was done with the computer program EPIKUL because the RAYNOISE program is not equipped for simulation of angle dependent absorption. Reverberation times α_{dif} were calculated from Sabines law just like in measurements. The same iterative procedure as discussed under ‘approach nr.1’ was followed. Although results of both approaches have not yet been compared, the last mentioned procedure is more suited for situations were the sound field is not perfectly diffuse.

Here it suffices to say that also other, more refined approaches have been followed to find a description for $\alpha(\theta)$ [Nijs, 1998].

The second approach has one advantage: in real measurements absorption values well above one are found. These values can never be found in approach nr. 1, but they can in the second case. That is because Sabine’s method is explicitly meant for diffuse fields and a reverberation room with all the absorbing material within one plane is no longer diffuse. The second approach takes these affects in account.

RESULTS IN CASE OF REFINED MODELLING OF ABSORPTION CHARACTERISTICS

Sound pressure levels were simulated for the same scale model based on absorption coefficients calculated with the second method. The results are shown in figure 11.

It is clear that by taking the angle dependency of absorption into account the correspondence between computed and measured results can be improved substantially; earlier found differences of 15 to 20 dB were reduced to about 5 to 7 dB.

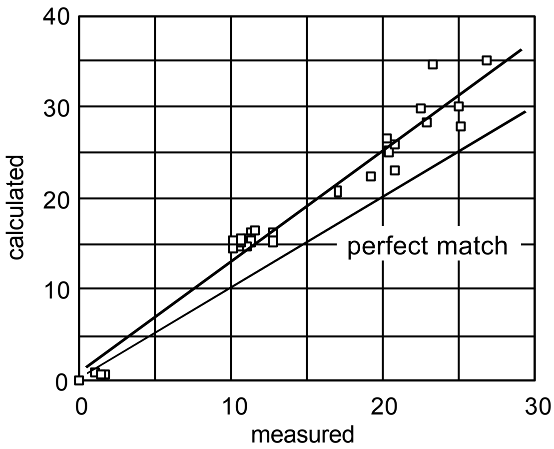

Figure 11: Comparison of measured and computed results (assuming angle dependent absorption).

Looking at the ‘main stream’ of the sound rays, going from one room to the other (figure 12), it is clear that in the case of angle depend absorption an impact on measured and computed sound pressure levels can be expected.

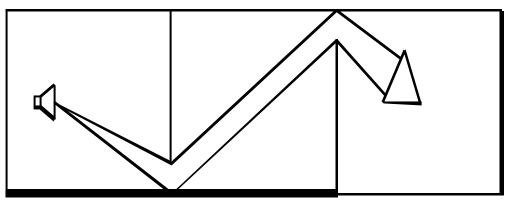

Figure 12: Main stream of the sound waves going from one room to the other.

EXPERIMENT IN A MEZZANINE

In order to investigate the applicability of the simulation tool, measurements and simulations were done or one of the complex mezzanine-spaces in the faculty of Architecture. See figure 13.

Using AutoCAD files for the geometrical input, a number of simulations were performed. Isobar-lines are shown in figure 13. Here it suffices to say that fair up to good correspondence was found between measured and computed results.

Based on the simulation, suggestions were done for improvement of the acoustical quality in the mezzanines.

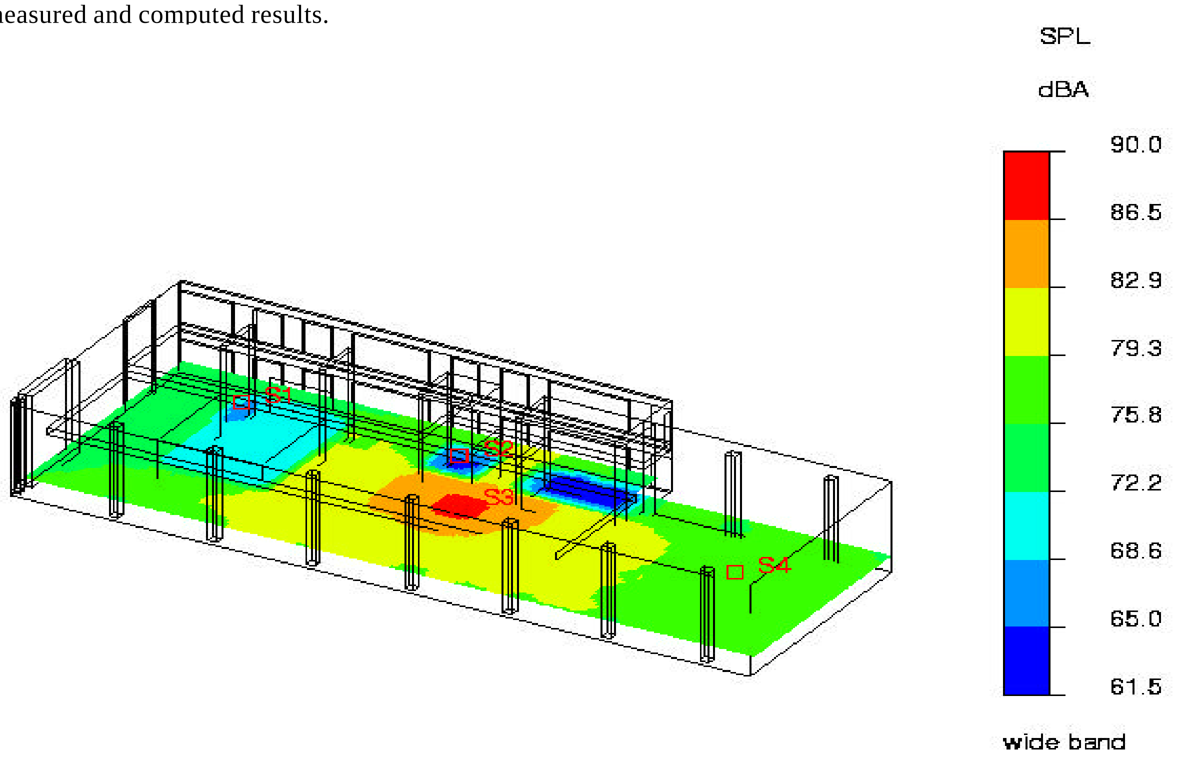

Figure 13: One of the iso-bar plots for the mezzanine space in the building of the Faculty of Architecture at Delft University.

DESIGN GUIDE

As a follow-up of the simulation experiments the acoustical behaviour of coupled spaces will be studied in more detail in the near future. Meaning that first of all the impact of the design parameters on the transmission of sound from one space to another will be further investigated.
Besides an impact on transmission of sound in general, there also will be an impact on the (before discussed) decay-characteristics of a room. In general the decay-curve of a coupled room will differ from the decay-curve of a single room. However, for a specific set of design parameters the decay characteristics of coupled and single spaces can be identical.
This raises the question if the decay-curve could be used as a criterion for categorising coupled spaces from the acoustical point of view.
If these efforts are successful, a design guide for coupled spaces will be made, meant for architects and consultants.

CONCLUSIONS AND REMARKS

Accuracy of generated sound pressure levels:

- A reliable prediction of sound pressure levels in coupled spaces is possible when applying the here discussed simulation tools.
- However, even in case of adequate modelling of absorption and diffusion characteristics of applied materials, the accuracy of calculated sound pressure levels strongly depends on the integration interval chosen by the user (defined by t_{stop}).
  For coupled spaces mainly higher values for t_{stop} must be chosen compared with single spaces.
- Use of the common ‘tail correction’ for coupled spaces will result in unacceptable errors for computed sound pressure levels. Another method is required and will be investigated in future research.

Accuracy of generated reverberation times:

- Reliable prediction of reverberation times for a reverberation room is also possible.
  Prediction of reverberation times in coupled spaces has not yet been investigated.

- In case of the prediction of reverberation times, the value for t_{stop} has to be much higher compared to the value for t_{stop} in case of computation of sound pressure levels.

Applicability of discussed tools in the design process:

- The suitability of the simulation tools is not limited to spaces with simple geometry and topology. Also for complex coupled spaces acoustical quantities can be generated and visualised.
- Due to the interface with AutoCAD the simulation process is speeded up significantly.

Modelling features:

- An adequate modelling of absorption characteristics of applied materials is one of the main requirements for a reliable simulation of acoustical sound fields.
- So far, the influence of diffusion does not seem to be dominant in coupled rooms.
- For a reliable simulation, a basic knowledge of ‘acoustics’ is required.
- The phenomenon of ‘diffraction’ is neglected in ray-tracing models. Especially in case of coupled spaces, the correspondence between computed and measured sound pressure levels could be improved by taking diffraction into account. The impact of diffraction will be a subject of future investigations.

REFERENCES

Cremer, L. and H.A. Müller, Principles and Applications of Room Acoustics (Applied Science Publishers, New York, 1982).

Kuttruff, H., Acoustics (Elsevier, New York 1991).

Nijs, L., G. Jansens and M. van der Voorden, The Prediction of Sound Pressure Levels in Coupled Rooms Using Ray-Tracing Models (Inter-noise Conference, Christchurch, New Zealand, 1998).

Vermeir, G. and P. Mees, Sound propagation in enclosed spaces (Inter-Noise Conference, Newport Beach, USA, 1995).

NOMENCLATURE

$h(t)$	Sound power of a pulse relative to the sound power of the first pulse	[-].
$E(t)$	Total amount of received acoustical energy relative to the total amount of received acoustical energy E_{tot}	[-].
t_{stop}	Integration interval	[s].
T_{rev}	Reverberation time	[s].
a_{rev}	Absorption coefficient derived from standard measurements in a reverberation room	[-].
a_{dif}	Absorption coefficient computed according to Sabine’s Law	[-].
a_{norm}	Normal absorption coefficient (for sound impinging perpendicular to an absorbing surface)	[-].
$a(q)$	Angle dependent absorption coefficient (for sound impinging under an angle q with the ‘normal vector’ of the surface)	[-].
R_{norm}	Reflection coefficient for the sound pressure (for sound impinging perpendicular to an absorbing surface)	[-].
$R(q)$	Reflection coefficient for the sound pressure (for sound impinging under an angle q with the ‘normal vector’ on the absorbing surface)	[-].