Author(s): Keränen, Jukka; Airo, Erkko; Olkinuora, Pekka; Hongisto, Valtteri

Title: Validity of ray-tracing method for the application of noise control in workplaces

Year: 2003

Version: Final published version

ACTA ACUSTICA UNITED WITH ACUSTICA
Vol. 89 (2003) 863 – 874

Validity of Ray-Tracing Method for the Application of Noise Control in Workplaces

Jukka Keränen*, Erkko Airo**, Pekka Olkinuora**, Valtteri Hongisto*
Finnish Institute of Occupational Health. **: Laboratory of Ventilation and Acoustics, Lemminkäisenkatu 14-18B, FIN-20520 Turku, Finland. jukka.keranen@ttl.fi. **: Arinatie 3 A, FIN-00370 Helsinki, Finland

Summary
Building acoustical noise control is usually very expensive to implement. Therefore, it should be optimized and argued precisely. Recommended practices for the design of low noise workplaces have been published, but in order to select the most cost-effective solution, the effect of the potential solutions on sound pressure level should be reliable. Acoustical modeling based on ray-tracing is supposed to be the best prospective tool in predicting the insertion loss of noise control measures. The purpose of this study was to show how well ray tracing can predict noise levels and insertion losses in real applications when applied by an educated and experienced user. Acoustical modeling was used in six operating workplaces, where major room acoustical noise control measures were implemented. The modeling results were compared to the results of measurement which were performed using an omnidirectional sound source. Insertion losses of noise control measures were determined using both predicted and measured sound pressure levels in the octave bands 125 Hz to 4000 Hz. Accuracies of the predicted sound pressure levels and the predicted insertion losses in the six workplaces were determined as differences between measured and predicted sound pressure levels. By following our general guidelines for the modeling of large workplaces in the six workplaces, the workplace-averaged accuracy of SPL predictions $A_{\langle \mathrm{SPL} \rangle}$ was 3±2 dB. The insertion loss for noise control measures was predictable to an accuracy of 2±1 dB. The accuracy of the models was, thus, adequate. The obtained results were acceptable considering the reasonable amount of work used in the modeling per case and the uncertainty of in situ measurements. However, fine adjustment of the model is always recommended by backing comparisons with predicted and measured SPL.

PACS no. 43.55.Ka

1. Introduction

Accurate prediction of the insertion loss (IL) of noise control measures is important because their cost is usually very high and, therefore, they should be optimized and argued precisely [1]. Recommended practices for design of low noise workplaces are presented e.g. in ISO 11690 [2, 3, 4]. In part 1, noise control strategies, and in part 2, noise control measures, are given. In part 3, a general approach to noise level predictions in workplaces is presented. Some case studies and references to the articles that deal with noise prediction methods are included. However, they do not answer the question: "How to use modeling efficiently to predict the effect of noise control measures in a workplace with reasonable accuracy?" Efficient modeling is a key question in practical design, because the planning expenses should be kept as low as possible and reasonable compared to the expenses of the installed noise control measures.

Received 18 June 2002,
accepted 30 March 2003.

During the last ten years, the Finnish Institute of Occupational Health has used an acoustical modeling software (ODEON 2.5 and 3.1) to predict the IL of noise control measures, whenever it would have been valuable for the noise control project. Most often, the modeling tool has been experienced as too heavy in small workplaces, even though its use would be valuable. The reason for this is not in calculation times, because the calculations using computer with Pentium III processor for a typical industrial workroom could be over in less than quarter an hour. In general, the most laborious task is creation of the model and verification of the modeling results, e.g., comparing predicted sound pressure level (SPL) to measured SPL. To create a model, there are several details to be collected, e.g., geometry and dimensions of the workplace, size and shape of the fittings, sound absorption and scattering properties of the surfaces, position, orientation and directivity of noise sources and measurement positions. Especially, estimation of the sound absorption and scattering coefficients for the surfaces demands experience or, alternatively, several trials and errors.

During most of the modeling projects, measurements were carried out to validate the predictions, because, until recently, there was no firm evidence that the accuracy of an acoustical model could be adequate without confirmation using series of SPL measurements. After 25 design projects, a general guide for the practitioner was published [5]. The main points of the guide, that consider the acoustical modeling of workplaces, are summarized also later in this article (the modeling procedure).

Recently, the application of the ray-tracing method in industrial noise control has been used in several case studies. Hodgson used ray tracing in a machine shop, a food-production hall and a nuclear power-generating station to predict reverberation time (RT) and slopes of sound propagation curves [6, 7, 8]. The predicted slopes were used to calculate the expected SPL in the workroom for various combinations of acoustical treatment and source control measures. Hodgson used fitting zones to simulate machines, screens and other fittings. A good accuracy in the predictions could be obtained using somewhat arbitrary values for the fitting density. Hongisto *et al.* used ray tracing to predict RT and SPL in a workshop in five different cases of acoustical treatment [9]. The predicted RT and A-weighted SPL maps were presented. However, the calculated results were compared to the measured ones only in the initial situation. Sorainen and Kokkola used ray tracing to predict the effect of noise control measures on SPL in a carpentry plant [10]. The difference between predicted and measured mean SPL was presented. In all these studies, the predictions were accurate, on average, 2 dB (A-weighted). Although real noise sources were used, the accuracies of the studies were tolerable, because the sound power levels of the noise sources were determined using accurate measuring methods e.g. sound intensity measurements. However, their result can not be applied generally because only one environment was studied.

The purpose of this study was to show, how well ray tracing can predict IL in real workplaces. This was made using a sufficiently large number of workplaces. The main parameters were SPL and IL of noise control measure, which are the most useful and interesting output of models. The reverberation times (RTs) were measured before and after the noise control in five cases. The RTs were used to estimate sound absorption in the workplace in the initial situation (before the noise control measures). The accuracy of RT predictions was also determined, though it was not the main parameter in the noise control design.

2. Materials

This study is based on work done in six workplaces where acoustical computer modeling was used in noise control design. The modeling software was used to predict the IL of noise control measures. The noise control measures were implemented and their IL was measured accurately. Technical evaluation of the noise control measures was beyond the scope of this study.

The workplaces with assigned reference numbers are presented in Table I. 3D-views of the acoustical models of the workplaces are presented in Figure 1. A short description of the workplaces and the implemented noise control measures is given below.

1. Engineering works Initially, the workplace was fitted by shelves and hard screens of height 2 to 3 meters, and a couple of 6-meter high large machines. A 6-meter high noise screen was built around one noisy work station. The inner surface of the noise screen was partially covered with 50 mm mineral wool. The outer surface was profiled steel. (This was not a good noise control solution but it was not designed by us.)

2. Weaving factory Initially, there were 16 large weaving machines (height 2 meters) which were modelled as boxes using surfaces with medium absorption. The open end led to another large hall, which was not included in the model. The side walls and the ceiling joists were covered with 50 mm mineral wool.

3. Engineering works Initially, the workplace was very fitted by obstacles of different sizes (hand-held tools, machines, etc.). Several large machines of variable height were modelled as boxes using surfaces with medium absorption. The ceiling was partially covered with sound absorbing spray-on material of thickness 18 mm. (The material performance did not fulfill the specifications. That is why the obtained noise reduction was quite small.)

4. Engineering works Initially, there were several noise sources of different sizes (hand-held tools, machines etc.). There were several hard screens and a couple of sound-absorbing noise screens around workstations (average height 3 meters). A few 3- to 6-meter high large machines were modelled as boxes using surfaces with low absorption. The curved ceiling was modelled using 5 plane surfaces tilted symmetrically along the center line of the ceiling (see Figure 1). The ceiling was covered with 30 mm mineral wool.

5. Electronic works / landscaped office Initially, the room was empty. The noise produced in the packaging area propagated to the office area. The work stations in the office were separated by 2-meter high sound- absorbing office screens. The ceiling was covered with sound-absorbing spray-on material of thickness 25 mm.

6. Knitting factory Initially, there were 8 large knitting machines (height 6 meters) which were modelled as boxes using surfaces with medium absorption. The workstation was in the intersection of the two large halls. A large wall of area 250 m^2 was built between the two halls. However, an opening of area 30 m^2 was left for traffic, so that sound transmission through the opening was the main path between the halls. The surfaces of the wall were covered with 50 mm mineral wool on both sides.

3. Methods

3.1. Measuring methods

A simple measuring method based on an omnidirectional sound source was used to determine the IL of noise control measures [11]. The sound source consisted of a pink noise signal generator (Neutrik MR1), a power amplifier (QSC 1200 W USA) and an omnidirectional loudspeaker

Table I. General information about the workplaces and acoustical models (m= number of sources, n= number of measurement points).

Work place	Type of industry	Volume (m^3)	Surfaces in model	m/n	Number of rays
1	engineering works	49 000	78	1/14	3000
2	weaving factory	6 400	107	3/6	4600
3	engineering works	33 600	134	3/10	10000
4	engineering works	60 000	145	3/9	6000
5	electronics works/ office	13 100	68	1/14	2000
6	knitting factory	33 000	140	6/1	5000

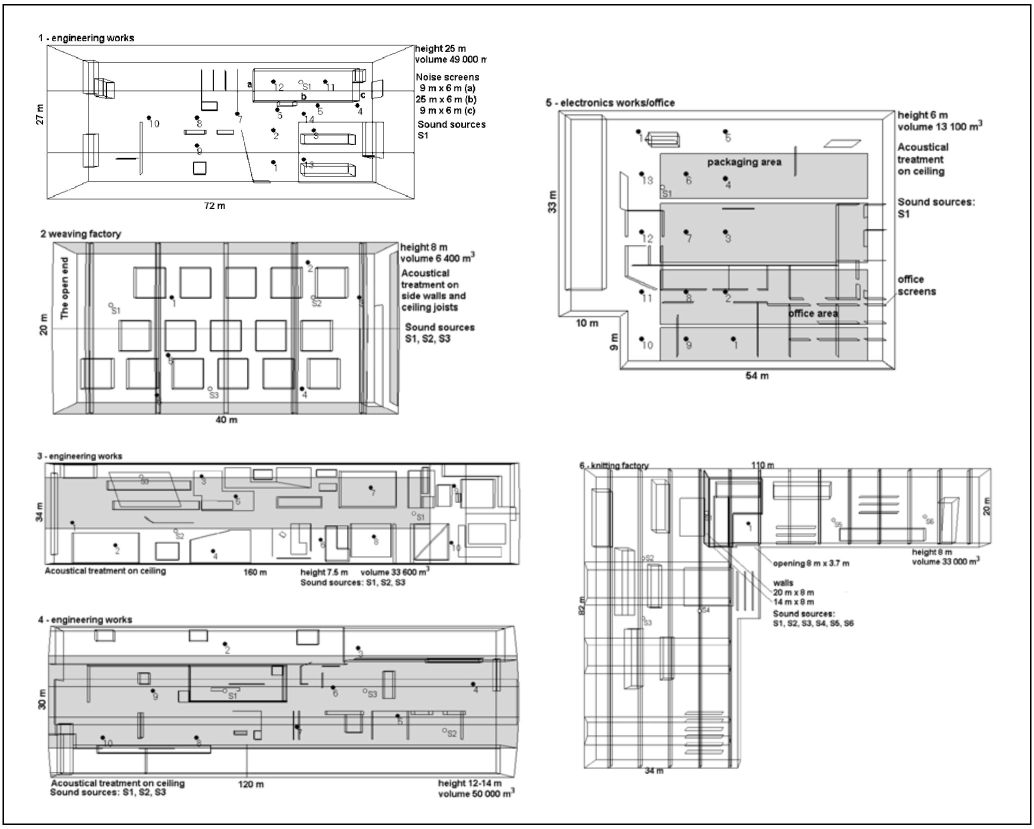

Figure 1. 3D-plan views of the acoustical models of the six workplaces (not in relative scale).

(Brüel&Kjær 4296). The sound power level $L_{w,i}$ of the source was measured in the laboratory according to ISO 3741 [12].

The noisiest production machines were stopped during the measurements, or the measurements were performed after working hours in order to reduce the effect of the background noise. The omnidirectional loudspeaker was placed in selected position(s) (usually close to a noisy machine). The output of the sound source was set to such a level that at least 10 dB difference between test signal and background noise was achieved in all measurement points. The SPL produced by the loudspeaker was measured at selected measurement points (e.g. other work stations) using a sound level meter (Brüel&Kjær 2260). Typically, the height of the loudspeaker and measurement points was 1.5 meters. The measurements were performed before and after the noise control measures using the same measurement points and source positions.

The determination of IL was based on measurements of SPL caused by a calibrated sound source. While the omnidirectional sound source produced the noise $L_{w,i}$ at the position i, the SPL at the measurement point j was $L_{1,i,j}$ before and $L_{2,i,j}$ after the noise control measures. The sound attenuation between one source and one measurement point was, respectively,

$$DL_{1,i,j} = L_{w,i} - L_{1,i,j}, \quad DL_{2,i,j} = L_{w,i} - L_{2,i,j}. \quad (1)$$

The use of the sound attenuation as the primary quantity permitted the use of different sound power levels $L_{w,i}$ of the source (different loudspeakers) in successive measurements. Naturally, the sound power level of the source was constant during measurements in a single workplace. However, the time gap between measurements 1 and 2 was typically one year so that one could not guarantee constant $L_{w,i}$.

The most important parameter in noise control design is IL because it describes the performance of a certain acoustical remedy in a certain environment. In our opinion, it is very seldom that absolute SPL predictions are needed in workplace application because all sound sources are seldom exactly known and they operate in different cycles. The insertion loss (IL) was determined using the equation

$$IL_{i,j} = DL_{2,i,j} - DL_{1,i,j}. \quad (2)$$

The mean insertion loss IL was determined as an average over the number of sources m and the number of measurement points n.

$$IL = \frac{1}{nm} \sum_{i=1}^{m} \sum_{j=1}^{n} IL_{i,j}. \quad (3)$$

The RTs were measured using a pistol shot as sound source in workplaces 1 to 5. The RTs were determined using a decay of 20 dB. The presented RT values are arithmetic averages of several RT measurements.

3.2. Modeling methods

The acoustical computer models were created using the ODEON 3.1 software which is based on geometrical acoustics [13, 14]. The earlier version (ODEON 2.5) of this software was one of the three most accurate programs included in the Vorländer's round robin test for a speech auditorium [15, 16]. A detailed description of the ray tracing method is presented elsewhere [17, 18]. The ODEON uses hybrid method which includes both image source and secondary source method. However, it is possible to "switch off" the image source method and use only secondary source method which is based on the principles of ray tracing method. In the secondary source method the rays are treated as transporters of energy [19]. Each time a ray hits a surface, a secondary source is generated at the collision point. The energy of the secondary source is the energy of the primary source divided by the number of rays and reduced by the reflections involved in the ray's history up to that point. The secondary source is considered to radiate into a hemisphere as an elemental area radiator. The radiated direction (of the reflection) is calculated as a random direction following the angular Lambert distribution of ideal scattered reflections.

In this study, the modeling was carried out using the secondary source method, because ray tracing method has proven to be the most suitable method for prediction in a fitted enclosure of arbitrary shape [20]. The number of rays depend on the geometry and volume of the workplace and the number of modelled surfaces in the workplace (see Table I). Unfortunately, it is not precisely explained in the software manual, how the recommended number of rays is calculated. Therefore, the number of rays recommended by the ODEON was doubled in order to improve the reliability of the results.

Two important parameters for calculation were impulse response length and maximum reflection order which must not be confused with number of rays. These determine the stop criterion for the ray tracing. The maximum reflection order was set to highest allowed value of 2000 so that the impulse response length was the parameter that defined the end of each run. The impulse response length was set approximately to 2/3 of the average of measured RT at the octave bands 250…2000 Hz.

The modeling procedure was as follows (explanations below) [5].

1. The room dimensions of the workplace were measured.
2. The fittings were divided into three classes by size:
   (a) Large solid obstacles like walls, screens and large machines with a size of over three meters.
   (b) Medium-size fittings with a size of 1.5 to 3.0 meters, especially the obstacles near noise sources or workstations, where the noise control is implemented.
   (c) Small fittings like shelves, air ducts, tables, small machines etc.
3. Data on the surface materials were collected and the absorption and scattering coefficients of the surfaces were estimated.
4. The positions for the omnidirectional source and the measurement points were selected so that they benefited the noise control design, not just this study.
5. The sound attenuation $DL_{1,i,j}$ and RT in the workplace was measured.
6. The first (initial) acoustical model was created using the collected data on the workplace and SPL, $DL_{1,i,j}$ and RT were predicted.
7. Predicted and measured SPL and $DL_{1,i,j}$ were compared and, if necessary, the absorption coefficients of relevant surfaces were slightly modified in order to obtain higher consistency (see Table II, modified materials). The initial situation was recomputed.
8. The second model including the noise control measures was created. The SPL after noise control measures, $DL_{2,i,j}$ and RT were predicted.
9. The noise control measures were implemented in the workplace. This took 1/2…2 years.
10. The $DL_{2,i,j}$ and RT was measured after the noise control measures.
11. The IL of the noise control measures was calculated using both of the modelled and measured values.

Walls, floor, ceiling, noise screens and large fittings (classes A and B) were modelled as plane surfaces. The

Table II. Collection of the absorption coefficients used in the acoustical models. *: material could be covered using perforated steel with perforation ratio 25% or higher.

Typical materials	work place	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
smooth concrete	1-6	0.02	0.02	0.03	0.03	0.04	0.04
rough concrete, brick work	1-6	0.06	0.06	0.07	0.07	0.08	0.08
window, double glazing	1-6	0.40	0.30	0.20	0.17	0.15	0.10
mineral wool 30 mm, on surface*	1,4	0.10	0.35	0.70	0.95	0.95	0.95
mineral wool 50 mm, on surface*	1,2,4,6	0.24	0.55	0.90	0.95	0.95	0.95
absorptive screen	1-6	0.10	0.38	0.62	0.70	0.71	0.68
lightweight screen or wall	1-6	0.28	0.22	0.10	0.10	0.10	0.10
industrial machinery	1-6	0.15	0.15	0.15	0.10	0.10	0.10
plastic curtain	1,3,4	0.10	0.16	0.45	0.35	0.25	0.20
fittings, low absorption	6	0.20	0.20	0.10	0.10	0.10	0.10
fittings, medium absorption	3	0.40	0.35	0.30	0.25	0.15	0.10
Modified materials or specified absorption coefficients	**work place**	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
ceiling, no absorption treatment	1,4	0.40	0.40	0.40	0.32	0.28	0.28
ceiling, absorption treatment	4	0.40	0.40	0.76	0.92	0.92	0.95
ceiling, no absorption treatment	3	0.50	0.45	0.30	0.25	0.15	0.10
ceiling, absorption treatment	3	0.50	0.45	0.60	0.88	0.90	0.90
ceiling, absorption treatment	5	0.12	0.29	0.76	0.94	1.00	1.00
ceiling, absorption treatment	6	0.68	0.70	0.72	0.80	0.75	0.50
brick wall, window area 50%	1,4	0.28	0.17	0.12	0.11	0.10	0.12
brick wall with fittings	3	0.08	0.09	0.12	0.16	0.22	0.24
open end of the room	2	1.00	1.00	1.00	1.00	1.00	1.00

surface boundaries were determined as polygons on the plane. The modelled surfaces were given scattering and absorption coefficients, and they produced reflections and absorbed sound energy. Small fittings (class C) were taken into account by applying higher scattering and absorption coefficients on the surfaces on which they were lying. This method is possibly less accurate than using isotropic or floor zoning methods (fitting zones), but it is more accurate than including too many small surfaces in the model [14]. The fitting zone method, where the area is presumed evenly fitted with obstacles, is described elsewhere [21]. Because ODEON does not include methods for using fitting zones in calculations, small fittings were taken into account applying higher absorption and scattering coefficients. Large obstacles of classes A and B were modelled as they were in situ. In our opinion, additional fitting zones were not absolutely necessary, because the absorption of the fittings and the random reflections from the fittings were simulated with previous actions.

The models of the workplaces consisted of 68…145 surfaces. It was impossible to measure their absorption coefficients. Therefore, literary databases were used in the first place (see Table II) [22, 23, 24]. Typically, the initial RT modelled with literary absorption coefficients was longer than the measured RT. One reason for this is that all of the surfaces are not included in the model. Therefore, the absorption coefficients were slightly modified in the initial situation, if large differences between predicted and measured $DL_{1,i,j}$ existed. (The model was not repeatedly adjusted until best fit was obtained, but the absorption of fittings on the large surfaces was taken into account.) The hard ceiling or the floor was usually totally covered with small fittings (class C) having non-zero absorption, especially at low frequencies, which justified some addition to absorption coefficient(s) in the initial model.

Another phenomenon is that the rate of room diffusion can vary a lot and, thus, affect the balance between the horizontal and vertical sound field. For example, the effective absorption coefficient of a ceiling absorbent can be much higher in a fitted room than in an empty room, because the empty room does not sufficiently feed sound energy to the vertical sound field. This justified some reduction to absorption coefficient(s) when rooms were not fitted.

In the ODEON, the scattering coefficient is estimated by a value of range 0.0...1.0. The value is used to control the degree of random directions in reflected sound ray generation according to Lambert's law. The scattering coefficient of a surface was not only applied as a property of the surface material, but was also used to mimic the small fittings close to the respective surface [5]. The scattering coefficients for the surfaces were estimated taking advantage of the guidelines presented in earlier studies and previous experience in modeling industrial workplaces [25, 26, 27]. Typically, the scattering coefficients in the models were between 0.1…0.7 depending on the complexity of the surface. Our selection rules of the scattering coefficients are presented in Table III.

The omnidirectional loudspeaker was positioned in the model as a point source with an omnidirectional directivity pattern and relevant sound power level. The mea-

Table III. Collection of the scattering coefficients (in ODEON) used in the acoustical models.

Scattering coefficient	Description of the surface
0.1, …, 0.19	large, plain surfaces
0.2, …, 0.39	large partially fitted surfaces
0.4, …, 0.59	small or fitted surfaces
0.6, …, 0.89	large densely fitted surfaces
0.9, …, 1.00	small densely fitted surfaces

surement points were positioned in the model as point receivers according to the measurement situation. The description of point receiver calculation in ODEON is presented elsewhere [28, 29]. Similarly, the RT measurements were modelled using ray tracing.

The environmental variables (relative humidity of the air and temperature) were kept constant before and after noise control. The number of rays recommended by ODEON was not significantly different between the first and the second model, so that the number of rays used was left unchanged. The only significant changes between the models were the noise control measures. They were modelled using additional surfaces or changing surface parameters (absorption and scattering coefficients). The surfaces that represented noise screens, new walls or acoustical treatment on ceiling or walls are shaded in Figure 1. The absorption and scattering coefficients of the surfaces are presented in Tables II and III.

3.3. Validation methods

The accuracy of SPL prediction was determined in two ways. The first describes the general accuracy of SPL prediction, the second describes the trend of the error in SPL predictions.

The accuracy of SPL was determined by averaging the repetitive difference between the predicted and measured SPL or DL. The accuracy of the SPL prediction, A_{SPL}, was defined by the following equation:

$$A_{\mathrm{SPL}} = \frac{1}{nm}\sum_{i=1}^{m}\sum_{j=1}^{n}\left|DL_{q,i,j(\mathrm{predicted})} - DL_{q,i,j(\mathrm{measured})}\right|, \tag{4}$$

where $q = 1$ before or $q = 2$ after the noise control, m = number of sources and n = number of measurement points. A_{SPL} was determined for each workplace before and after the noise control measures. An arithmetic average is used for simplicity in this study. Logarithmic averages are not presented because, in these cases, the maximum difference between arithmetic and logarithmic averages was less than 1.2 dB, typically below 0.5.

Equation (4) presents only the absolute error because of the magnitude operation. It does not tell whether the error was positive or negative. Therefore, the average accuracy results, $A_{\mathrm{SPL},0}$, are also given separately without magnitude operation. In these results, negative error cancels positive error but the trend of the error can be seen.

Another quantity is the accuracy of IL prediction A_{IL}. It was defined by the difference between predicted mean insertion loss and measured mean insertion loss.

$$A_{\mathrm{IL}} = \left|IL_{\mathrm{predicted}} - IL_{\mathrm{measured}}\right|. \tag{5}$$

The workplace-averaged accuracy of the models, $A_{\langle\mathrm{SPL}\rangle}$, was defined as an average of A_{SPL} in the six workplaces. Respectively, the workplace-averaged accuracy of IL predictions, $A_{\langle\mathrm{IL}\rangle}$, was defined as an average of A_{IL} in the six workplaces. These figures are used as a general estimate of the achievable accuracy of sound level prediction using ODEON.

The accuracy of the RT predictions, A_{RT}, was defined by the difference between the predicted and measured RT.

$$A_{\mathrm{RT}} = \left|\mathrm{RT}_{\mathrm{predicted}} - \mathrm{RT}_{\mathrm{measured}}\right|. \tag{6}$$

$A_{\langle\mathrm{RT}\rangle}$, the workplace-averaged accuracy of RT predictions, was defined as an average of A_{RT} in the workplaces 1 to 5.

4. Results

The predicted and measured RT before and after the noise control measures are presented in Figure 2.

The accuracy of the SPL prediction A_{SPL} before and after the noise control measures in each workplace is presented in Table IV and also in Figure 3. The arithmetic average accuracy of the SPL prediction without magnitude operation, $A_{\mathrm{SPL},0}$, is presented in Table V.

The predicted and measured mean insertion losses IL in each workplace are presented in Table VI. The accuracy of the insertion loss predictions, A_{IL}, is presented in Figure 3.

The workplace-averaged accuracy of SPL predictions, $A_{\langle\mathrm{SPL}\rangle}$, the accuracy of IL predictions, $A_{\langle\mathrm{IL}\rangle}$, and the accuracy of RT predictions, $A_{\langle\mathrm{RT}\rangle}$, are presented in Figure 4 with standard deviations.

5. Discussion

The A_{SPL} varied from 0.9 dB to 7.1 dB in six workplaces at octave bands 125 to 4000 Hz (see Table IV). In single predictions, and at single frequency bands, A_{SPL} varied considerably, where noise screens were used. The standard deviations of A_{SPL} were 0.4…3.6 dB and, on average, 1.8 dB in the six workplaces at octave bands 125 to 4000 Hz. Similarly the standard deviations of $A_{\mathrm{SPL},0}$ were 0.8…4.6 dB and, on average, 2.5 dB. In general, all models slightly overestimated the SPL at high frequencies (Table V), which may indicate that there was too little absorption in the models, although higher absorption coefficients than suggested in the literature were used for floor and ceiling surfaces. The fittings apparently absorb more sound than expected in the model. This may indicate that the fittings should be modelled using fitting zones, additional arbitrary sound absorbing surfaces or significantly higher absorption coefficients on modelled surfaces representing fittings.

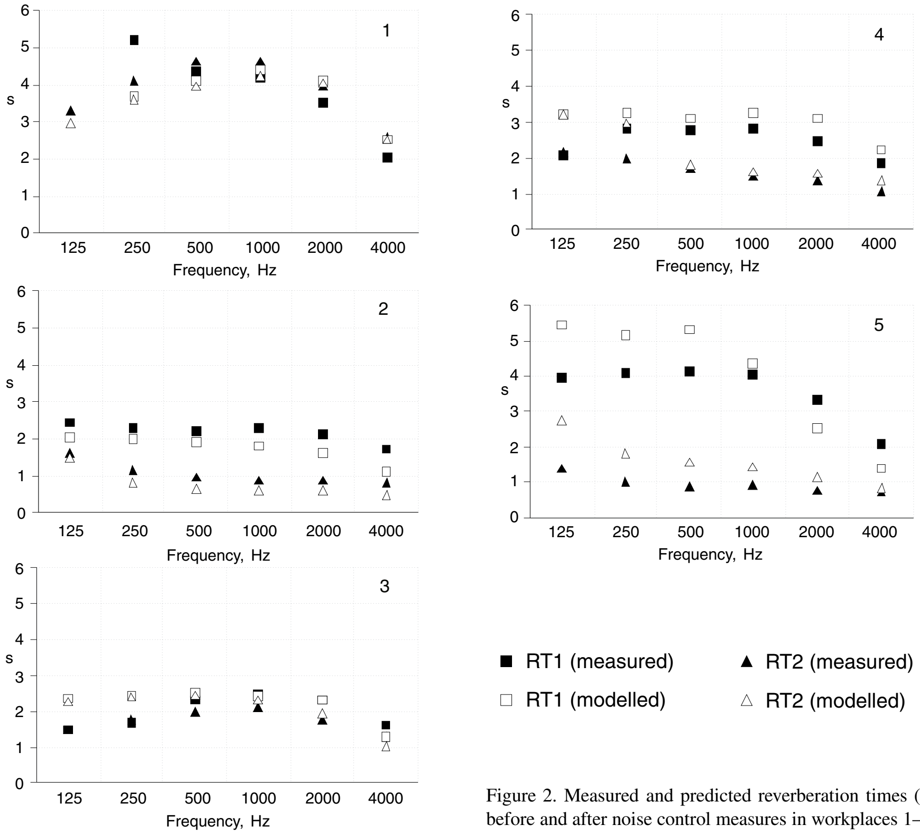

Figure 2. Measured and predicted reverberation times (RTs) before and after noise control measures in workplaces 1–5.

Some details of separate models of the workplaces are discussed in the following. In workplaces 1 and 3, the acoustical remedy did not increase the room absorption significantly. Thus, the workplace remained quite reverberant and good accuracies A_{IL} were obtained. Only in the workplace 3, the average accuracy, A_{SPL}, was less than 3 dB before and after the noise control measures. In workplace 6, the accuracy was poor at frequencies 125…4000 Hz , which was not expected. However, it was expected that the large obstacles could cause error in predicted SPL. In this workplace, the ceiling was absorptive and a large absorptive wall was installed between four of the sound source positions and the measurement point. The large absorptive wall was the main reason for the poor accuracy in the second model which included the implemented noise control measures.

$A_{\langle\mathrm{SPL}\rangle}$, the workplace-averaged accuracy, was ≤3.0 dB at 125 to 4000 Hz (Figure 4). Therefore, the accuracy is satisfactory. Typically, the accuracy was worst at the lowest (125 Hz) and the highest (4000 Hz) octave bands. This was achieved using typical absorption and scattering coefficients in the modeling (Tables II and III) and exactly known sound sources. The accuracy evaluation could be improved using more sound source locations and measurement points, which would decrease the uncertainty of measurements. Naturally, this increases the amount of work and time consumed in the project.

Despite the high standard deviation of A_{SPL}, the accuracy of IL predictions, A_{I}, was ≤2.1 dB at all octave bands (Figure 3) and 1.6 dB, on average, which is a good result (Figure 4). However, the models systematically overestimated the IL (Table VI). Standard deviation of A_{IL} was 0.7…1.1 dB, which is good. The ILs were not very high, within 0…9 dB, so that the relative error in certain workplaces was unacceptable. Obviously, the standard deviation of A_{SPL} can be higher than the IL if the latter is small (e.g. workplace 3). However, this does not imply that mean IL predictions would not be reliable.

Noise screens caused the highest standard deviations in A_{SPL} values, especially when the measurement point or the sound source was close to the screen. One of the reasons for this was that the predictions did not take into account diffraction of the sound. It is possible to approximate diffraction by using transparent diffusely-reflecting

Table IV. The absolute accuracy of the SPL prediction, A_{SPL}. The average and standard deviation of the accuracy are presented in before and after situations. $N = mn$ (m= number of sources, n= number of measurement points). The first column for every frequency band depicts average values (boldface numbers), the second column standard deviations.

workplace		125 Hz		250 Hz		500 Hz		1000 Hz		2000 Hz		4000 Hz	
1	before	**1.6**	1.4	**1.4**	1.0	**2.2**	1.1	**1.5**	1.6	**1.1**	1.1	**1.5**	1.4
(N=14)	after	**2.0**	1.7	**3.5**	1.5	**2.4**	0.9	**1.3**	0.9	**1.6**	1.2	**1.6**	1.1
2	before	**2.4**	2.3	**2.5**	2.5	**2.5**	2.7	**2.3**	2.5	**2.4**	2.7	**3.3**	2.9
(N=18)	after	**1.9**	1.2	**2.1**	1.4	**2.5**	2.0	**1.9**	1.8	**2.0**	1.6	**3.0**	1.8
3	before	**2.0**	2.0	**1.7**	1.2	**1.8**	1.2	**1.7**	1.2	**1.7**	1.1	**1.5**	1.2
(N=29)	after	**2.3**	1.6	**2.1**	1.5	**2.1**	1.5	**2.2**	1.3	**2.5**	1.8	**2.3**	1.7
4	before	**3.3**	2.6	**2.5**	1.9	**2.7**	2.2	**2.3**	1.9	**2.3**	1.7	**2.0**	1.6
(N=27)	after	**2.9**	2.8	**3.3**	2.0	**2.2**	2.3	**2.5**	2.3	**2.8**	2.8	**2.7**	2.5
5	before	**2.1**	1.1	**0.9**	0.9	**1.0**	0.4	**0.9**	0.7	**2.7**	1.3	**4.4**	1.7
(N=14)	after	**5.2**	2.1	**2.0**	1.8	**2.7**	1.9	**3.2**	2.2	**2.7**	1.9	**3.2**	2.4
6	before	**3.3**	2.0	**2.1**	1.3	**1.8**	1.5	**1.9**	1.9	**2.1**	2.1	**4.1**	1.2
(N=6)	after	**4.0**	1.5	**2.9**	2.0	**3.6**	1.8	**4.9**	3.1	**5.0**	3.6	**7.1**	3.4
Average		**2.7**	1.9	**2.2**	1.6	**2.3**	1.6	**2.2**	1.8	**2.4**	1.9	**3.0**	1.9

Table V. The accuracy of the SPL prediction, $A_{\mathrm{SPL},0}$ (without magnitude operation). The average and standard deviation of the accuracy are presented in before and after situations like in Figure 4. $N = mn$ (m= number of sources, n= number of measurement points).

workplace		125 Hz		250 Hz		500 Hz		1000 Hz		2000 Hz		4000 Hz	
1	before	**0.7**	2.1	**-0.7**	1.6	**-2.2**	1.2	**-1.2**	1.9	**-0.8**	1.3	**0.1**	2.1
(N=14)	after	**-1.8**	2.0	**-3.4**	1.6	**-2.4**	0.9	**-1.1**	1.2	**-1.5**	1.4	**-1.2**	1.5
2	before	**0.8**	3.2	**1.2**	3.4	**1.0**	3.6	**0.2**	3.4	**0.3**	3.7	**-1.3**	4.3
(N=18)	after	**0.9**	2.1	**-1.1**	2.3	**-1.4**	2.9	**-1.1**	2.5	**-1.1**	2.4	**-2.5**	2.4
3	before	**1.1**	2.6	**0.1**	2.1	**0.2**	2.2	**-0.1**	2.1	**0.6**	1.9	**-0.7**	1.8
(N=29)	after	**-1.6**	2.3	**-0.9**	2.4	**0.3**	2.5	**1.4**	2.2	**1.7**	2.5	**0.3**	2.9
4	before	**0.1**	4.3	**0.6**	3.1	**-0.6**	3.5	**0.2**	3.0	**1.2**	2.7	**-0.2**	2.6
(N=27)	after	**2.4**	3.3	**3.0**	2.5	**0.7**	3.1	**0.1**	3.4	**1.3**	3.8	**1.0**	3.6
5	before	**2.1**	1.2	**-0.5**	1.2	**0.7**	0.8	**-0.7**	0.8	**-2.7**	1.3	**-4.4**	1.7
(N=14)	after	**4.1**	1.6	**0.5**	1.6	**-2.1**	2.4	**-2.7**	2.9	**-2.2**	2.5	**-2.8**	2.7
6	before	**2.8**	2.8	**0.9**	2.4	**0.9**	2.3	**-1.2**	2.5	**-1.8**	2.3	**-4.1**	1.2
(N=6)	after	**0.6**	4.6	**0.4**	3.7	**-1.6**	4.0	**-3.9**	4.5	**-4.7**	4.0	**-7.1**	3.4
Average		**1.0**	2.7	**0.0**	2.3	**-0.5**	2.5	**-0.8**	2.5	**-0.8**	2.5	**-1.9**	2.5

and partially transmitting surfaces around the noise screen [5]. This approximation improves the accuracy of prediction even though the frequency dependency of diffraction is not taken into account. However, the diffusion coefficient may then need to be different at low and high frequencies. The modeling of single barrier in an empty enclosed space has been studied by Dance *et. al.* [30]. A comparison of three different diffraction modeling techniques demonstrated that a diffraction area around a barrier which randomly redirects rays, gives accurate results at low frequencies.

The RTs were measured in five of the workplaces and they were also predicted. The absorption coefficients in the initial models were modified in order to obtain a tolerable fit with measured SPL not to obtain a good fit with RT. Therefore, the accuracy of the RT predictions is not as good as it would be if the models were optimized to RT predictions. During a typical noise control project, it is rarely possible to fine tune the model to the maximum accuracy, so that the workplace-averaged accuracy $A_{\langle \mathrm{RT} \rangle}$ $\leq$0.4 s, at 500 to 4000 Hz octave bands, is acceptable.

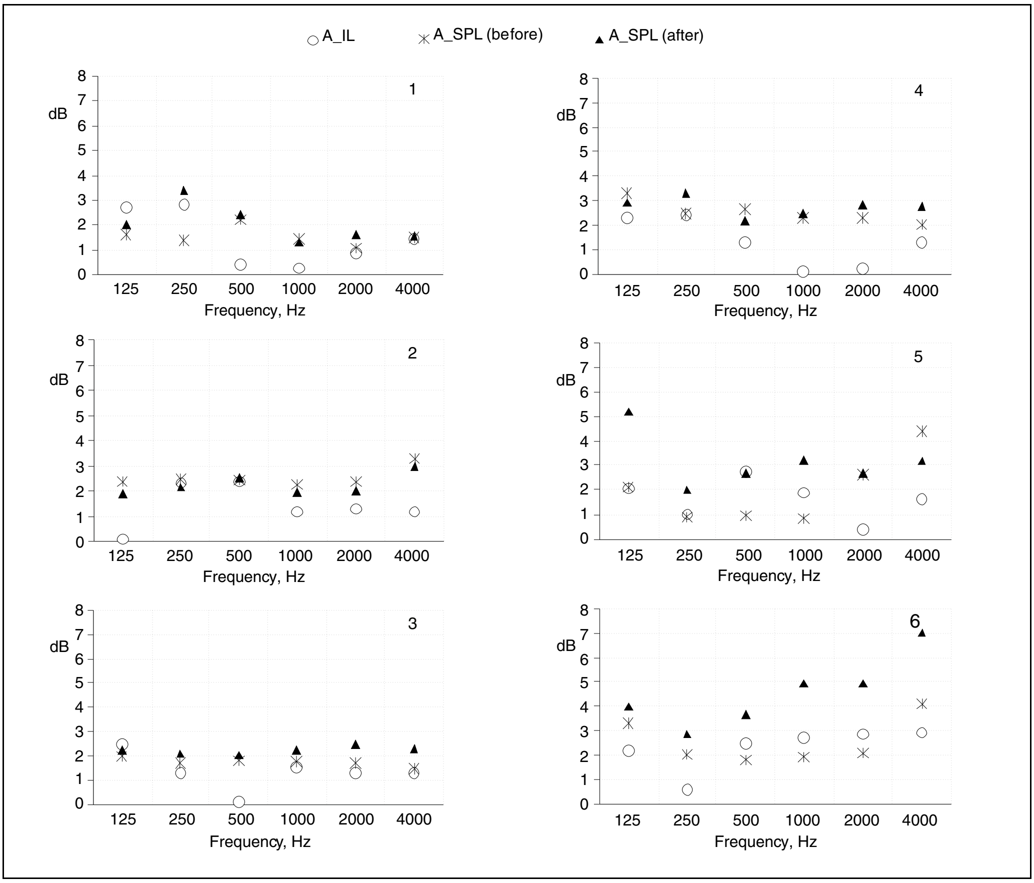

Figure 3. The accuracies of the insertion loss predictions A_{IL} (circle) and the accuracies, A_{SPL}, of the predicted SPL before (star) and after (triangle) the noise control measures in workplaces 1–6.

The most probable reason for the systematic errors in A_{SPL} and A_{IL} was, naturally, the uncertainty of SPL measurements. For example, the uncertainty of the sound power level determination of the sound source (in the laboratory) was ± 1.5 dB at 500 to 4000 Hz octave bands [12]. Other things to consider were the uncertainty of in situ SPL measurements, i.e. uncontrolled or unstable background noise; though the production was interrupted, some noise events could not be avoided. Diffractions could also be caused by the measurer or small nearby objects and interference effect at low frequencies can also cause different SPL even with small change of location. Additionally, the SPL calibration of the sound level meter may vary within ± 0.5 dB during the years of the noise control projects.

The accuracy of the predicted SPL depends strongly on randomness of calculation. Scattering and number of rays produce variation in the computed SPL in the model. However, the repeatability of calculations was quite good [5]. The repeatability was studied using slightly different numbers of rays in a workplace and determining the average and standard deviation of the predicted SPL. The maximum difference between predicted SPLs was ± 2.5 dB. It was also found that increasing the number of rays did not remarkably improve the accuracy of predictions. This phenomenon is related to the modeling algorithm of the ODEON and has been reported in case studies by Rindel and Christensen [19, 28].

In practical noise control design, poorer accuracy can be expected when real noise sources are used instead of a known omnidirectional sound source. One should keep in mind that the uncertainty of laboratory sound power level measurements is ± 1.5 dB at 500 to 4000 Hz, if the sound power level is determined according to ISO 3741 or ISO 9614-2 [12, 31]. If the sound power level is determined according to ISO 3746 (survey method), which is often the the only practical method in situ, the uncertainty is ± 3 dB for the A-weighted sound power level and undefined for octave bands [32]. One should also take into account the size and directivity of the real noise source in

Table VI. Measured and predicted insertion loss, IL.

workplace		125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
1	predicted	4.2	4.1	1.9	2.3	2.7	3.4
	measured	1.4	1.3	1.5	2.1	1.8	1.9
2	predicted	1.6	5.0	6.5	6.4	6.1	5.5
	measured	1.7	2.7	4.1	5.2	4.8	4.3
3	predicted	0.1	0.0	1.0	0.5	1.9	2.2
	measured	-2.4	-1.3	0.9	2.0	3.2	3.5
4	predicted	0.2	0.5	4.5	7.2	7.3	6.9
	measured	2.5	2.9	5.8	7.1	7.5	8.2
5	predicted	2.9	5.2	8.3	8.9	8.3	7.4
	measured	5.0	6.2	5.6	7.0	8.7	9.1
6	predicted	6.1	7.1	8.0	8.3	8.2	8.1
	measured	3.8	6.5	5.5	5.5	5.4	5.1

Table VII. The accuracy of the RT predictions.

workplace		125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
1	before	0.0	1.5	0.2	0.2	0.6	0.5
	after	0.4	0.5	0.7	0.4	0.1	0.1
2	before	0.4	0.3	0.3	0.5	0.5	0.6
	after	0.1	0.4	0.3	0.3	0.3	0.3
3	before	0.9	0.8	0.2	0.0	0.0	0.3
	after	0.8	0.6	0.4	0.2	0.1	0.3
4	before	1.1	0.5	0.3	0.5	0.6	0.4
	after	1.1	1.0	0.1	0.1	0.2	0.3
5	before	1.5	1.1	1.2	0.3	0.8	0.7
	after	1.3	0.8	0.7	0.5	0.4	0.1
Average		0.7	0.7	0.4	0.3	0.4	0.3
Standard deviation		0.5	0.4	0.3	0.2	0.3	0.2

the model. In addition, the use of sound power levels of real noise sources includes the potential for large errors, because real noise is rarely constant and unvarying. These are the reasons why real sound sources could not be used in this study.

If the number of noise sources with approximately the same sound power level is large, the noise control of a single source has a negligible effect on SPL. In such cases, the IL values obtained using single source measurements should not be presented to the client as the absolute sound attenuation results, because they are overestimates and do not represent the true attenuation of noise. This is natural, since the insertion loss is determined for a single noise source and the noise control measures are implemented considering that source only.

The insertion loss method is suitable for sound propagation and insertion loss measurements for a single source when background noise can be reasonably reduced. The Maximum Length Sequence technique (MLS) could be used in workplaces in any conditions, because it places practically no serious requirements on background noise level [33]. However, the method has some problems. There should be no spatial variations of temperature or of relative humidity of air when the MLS technique is used. The measurements should be done using fixed measuring point(s) and noise source(s). Movements of microphone are not allowed. Therefore, the use of the MLS technique should be studied more thoroughly in large industrial workplaces. Although the measurements were carried out by three different persons in different workplaces and the models were created by two different persons, the workplace-averaged accuracy, $A_{\langle \mathrm{SPL} \rangle}$, was acceptable. Therefore, it could be said that the differences between operators is not a major concern if the guidelines presented in the methods are followed.

The temperature and the relative humidity were not measured and considered in the models. However, it is known that the relative humidity has an effect on sound absorption of air. This effect should be noted especially in large spaces and at high frequencies. It is probable that, in workplace 6, the changes in relative humidity caused poor accuracy at high frequencies. In this workplace, the first measurements were performed in September (typically high relative humidity, weak air absorption) and the

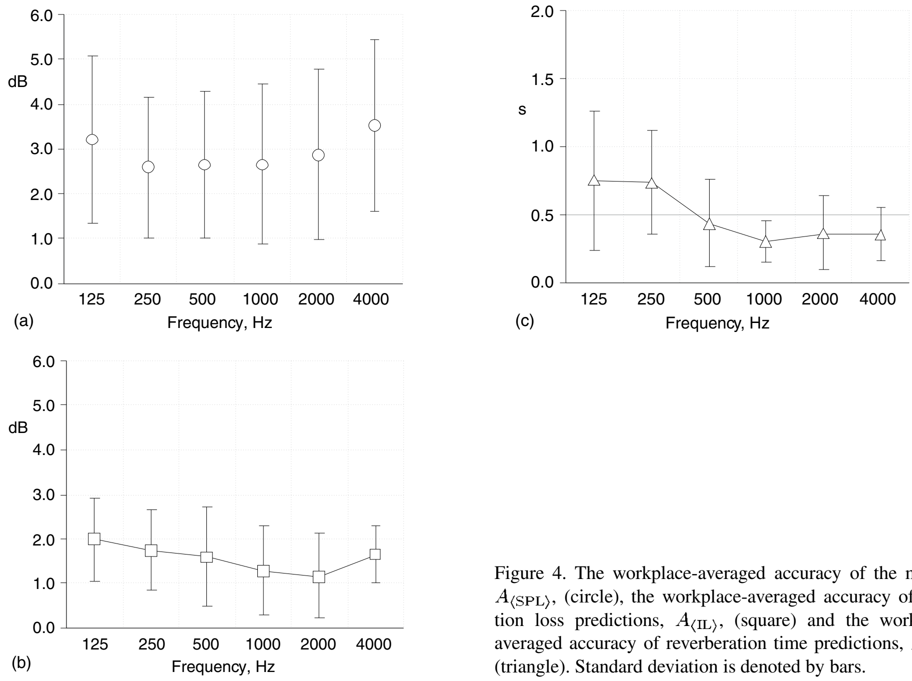

Figure 4. The workplace-averaged accuracy of the models, $A_{\langle \mathrm{SPL} \rangle}$, (circle), the workplace-averaged accuracy of insertion loss predictions, $A_{\langle \mathrm{IL} \rangle}$, (square) and the workplace-averaged accuracy of reverberation time predictions, $A_{\langle \mathrm{RT} \rangle}$, (triangle). Standard deviation is denoted by bars.

second measurements in February (typically low relative humidity, strong air absorption).

6. Conclusions

By following our general guidelines for the modeling of large workplaces in the six workplaces, the workplace-averaged accuracy of SPL predictions $A_{\langle \mathrm{SPL} \rangle}$ was 2.6…3.5 dB at octave bands 125 to 4000 Hz. Standard deviations of $A_{\langle \mathrm{SPL} \rangle}$ at octave bands were ≤2 dB. The accuracy of the models was, thus, adequate.

Similarly, the insertion loss for noise control measures was predictable to an accuracy of 2±1 dB (Figure 4, $A_{\langle \mathrm{IL} \rangle}$) at octave bands 125 to 4000 Hz in typical workplaces. This is adequate considering the reasonable amount of work needed in modeling and noise control design and the accuracy of sound pressure and sound power level measurements in situ. Good accuracy of IL predictions is most important because modeling is typically used for comparison of different acoustical remedies. The calculation of absolute SPL is seldom used in workplace design applications because sound power of noise sources L_w can not be reliably determined and they operate in different cycles.

The accuracy of the RT predictions was $A_{\langle \mathrm{RT} \rangle} \leq 0.4\,\mathrm{s}$ at 500 to 4000 Hz octave bands. This is acceptable, though results could be more accurate if the models were optimized in predicting RT.

Acknowledgement

The authors would like to thank Claus Lynge for providing the valuable information about the Odeon software. The Finnish Work Environment Fund, The Finnish Institute of Occupational Health and The Ministry of Social Affairs and Health are appreciated for the financial support given to the research project during 1998–2000.

References

[1] H. Nykänen, E. Klamka, L. Lamula, E. Räisänen: Experiences of the acoustical design of working environments using computer modeling based on ray-tracing techniques. Proceedings of Internoise 91, Sydney, Australia, 1991, 1245–1248.

[2] ISO 11690-1: Acoustics – Recommended practice for the design of low-noise workplaces containing machinery – Part 1: Noise control strategies. Genève, Switzerland, 1996.

[3] ISO 11690-2: Acoustics – Recommended practice for the design of low-noise workplaces containing machinery – Part 2: Noise control measures. Genève, Switzerland, 1996.

[4] ISO 11690-3: Acoustics – Recommended practice for the design of low-noise workplaces containing machinery – Part 3: Sound propagation and noise prediction in workrooms. Genève, Switzerland, 1997.

[5] V. Hongisto, J. Keränen, E. Airo, P. Olkinuora: Acoustic computer modeling in the planning of noise control measures (in Finnish). Työ ja Ihminen tutkimusraportti 20, Helsinki, Finland, 2001.

[6] M. Hodgson: Case history: Factory noise prediction using ray tracing – experimental validation and the effectiveness of noise control measures. Noise Con. Eng. J. **33** (989) 97–104.

[7] M. Hodgson, D. N. Lewis: Case history: Application of ray tracing to the modeling of noise in a food-production hall. Noise Con. Eng. J. **44** (1996) 249–255.

[8] M. Hodgson: Ray-tracing prediction of noise levels in a nuclear power-generating station. Appl. Acoust. **52** (1997) 19–29.

[9] V. Hongisto, P. Olkinuora, E. Airo, V. Viljanen, J. Pekkarinen, K. Saine: Computer aided acoustical modeling as a tool for industrial noise control. Proceedings of Nordic Acoustical Meeting 96, Helsinki, Finland, 1996, 81–86.

[10] E. Sorainen, H. Kokkola: Optimal noise control in a carpentry plant. Appl. Acoust. **61** (2000) 37–43.

[11] J. Keränen, V. Hongisto, E. Airo, P. Olkinuora: An exact method to determine the influence of noise control measures in workplaces. Proceedings of Internoise, Nice, France, 2000, 3443–3446.

[12] ISO 3741: Acoustics – Determination of sound power levels of noise sources using sound pressure – Precision methods for reverberation rooms. International Organization for Standardization, Genève, Switzerland, 1999.

[13] G. M. Naylor: ODEON – Another hybrid room acoustical model. Appl. Acoust. **38** (1993) 131–143.

[14] C. Lynge: ODEON Room acoustics program version 2.5 user manual, industrial, auditorium and combined editions. Technical university of Denmark, Lyngby, Denmark, 1997.

[15] M. Vorländer: International round robin on room acoustical computer simulations. Proceedings of 15th International Congress on Acoustics, Trondheim, Norway, 1995, 689–692.

[16] M. J. Howarth, Y. W. Lam: An assessment of the accuracy of a hybrid room acoustics model with surface diffusion facility. Appl. Acoust. **60** (2000) 237–251.

[17] A. M. Ondet, J. L. Barbry: Modelling of sound propagation in fitted workshops using ray tracing. J. Acoust. Soc. Am. **85** (1999) 787–796.

[18] M. Vorländer: Recent progress in room acoustical computer simulations. Build. Acoust. **4** (1997) 229–246.

[19] J. H. Rindel: Computer simulation techniques for acoustical design of rooms - how to treat reflections in sound field simulation. Proceedings of ASVA 97, Tokyo, Japan, 1997, 201–208.

[20] M. Hodgson: On the accuracy of models for predicting sound propagation in fitted rooms. J. Acoust. Soc. Am. **88** (1990) 871–878.

[21] S. M. Dance: The representation of fittings in the computer prediction of sound propagation in enclosed spaces. Appl. Acoust **52** (1997) 71–83.

[22] M. Hodgson: Measurements of the influence of fittings and roof pitch on the sound field in panel-roof factories. Appl. Acoust. **16** (1983) 369–391.

[23] C. M. Harris: Noise control in buildings a practical guide for architects and engineers. McGraw-Hill Inc., New York, United States of America, 1994.

[24] S. Dance, B. Shield: Technical note: Absorption coefficients of common construction materials for use in computer modelling of enclosed spaces. Build. Acoust. **7** (2000) 224.

[25] M. Hodgson: Evidence of diffuse surface reflections in rooms. J. Acoust. Soc. Am. **89** (1991) 765–771.

[26] Y. W. Lam: A comparison of three diffuse reflection modelling methods used in room acoustics computer models. J. Acoust. Soc. Am. **100** (1996) 2181–2192.

[27] M. Hodgson: Effective densities and absorption coefficients of fittings in industrial workrooms. Acustica - acta acustica **85** (1999) 108–112.

[28] C. L. Christensen, H. T. Foged: A room acoustical computer model for industrial environments - the model and its verification. Proceedings of Euro-Noise 98, München, Germany, 1998, 671–676.

[29] J. H. Rindell: The use of computer modelling in room acoustics. Journal of vibroengineering, **3** (2000) Paper of the International Conference Baltic–Acoustic 2000, Index 41-72 pp. 219–224.

[30] S. M. Dance, J. P. Roberts, B. M. Shield: Computer prediction of insertion loss due to a single barrier in a non-diffuse empty enclosed space. Build. Acoust. **1** (1994) 125–136.

[31] ISO 9614-2: Acoustics – Determination of sound power levels of noise sources using sound intensity – Part 2: Measurement by scanning. International Organization for Standardization, Genève, Switzerland, 1996.

[32] ISO 3746: Acoustics – Determination of sound power levels of noise sources using sound pressure – Survey method using an enveloping measurement surface over a reflecting plane. International Organization for Standardization, Genève Switzerland, 1995.

[33] D. D. Rife, J. Vanderkooy: Transfer-function measurement with maximum-length sequences. J. Audio Eng. Soc. **37** (1989) 419–444.