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Comparison of Simple Room Acoustic Models Used for Industrial Spaces

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Summary

In order to select the most cost-effective noise control solution, the influence of the noise control measures on noise level should be reliably predicted. Reasonably accurate commercial ray-tracing, image source and finite element method modeling programs are available. However, the creation of a model and sometimes the calculations are time-consuming and their use in preliminary room acoustic design is not always cost-effective. These sophisticated room acoustic modeling programs demand special expertise which limits their use in practice. Several simple room acoustic models have been developed for noise control but information on their usability and prediction accuracy is rather hard to find. The purpose of this study was to examine simple room acoustic models developed for predicting noise levels and reverberation times in octave bands. Seven simple sound pressure level models, seven simple reverberation time models and a validated ray-tracing program (ODEON 3.1) were tested in four industrial workplaces, in which major noise control measures were implemented. The prediction results were compared to measurement results which were performed using an omni-directional sound source before and after the implementation of noise control measures. Accuracies of predicted sound pressure levels were determined as differences between measured and predicted sound pressure levels in octave bands of 125–4000 Hz. Accuracies of predicted reverberation times were similarly determined. The accuracy of the ray-tracing model was the most acceptable, as expected. The accuracy of simple sound pressure level models developed by Kuttruff, Osipov *et al.*, and Thompson *et al.* was comparable to the accuracy of the ray-tracing models. The accuracy of the simple reverberation time model developed by Heerema and Hodgson was almost comparable to the accuracy of the ray-tracing model. The above-mentioned simple sound pressure level models provided sufficient accuracy for predicting average insertion loss, e.g. by using acoustic tiles or sound-absorbing materials. For more detailed or complex room acoustic design, sophisticated room acoustic modeling programs are recommended.

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1. Introduction

Accurate prediction of insertion loss (IL) of noise control measures is useful, because their cost is usually high. Recommended practices for design of low noise workplaces including noise control strategies, noise control measures and noise level predictions are presented in, e.g. ISO 11690 [1, 2, 3]. Efficient and preferably fast modeling is a key question in practical design, because the planning expenses should be kept as low as possible, and finding the most cost-effective noise control measures is most important.

The authors have used ray-tracing and image source models to predict the IL of noise control measures in several noise control projects. In many cases, these sophisticated models have been experienced as too computational intensive, because the creation of the model and verification of the modeling results is very laborious. To create a ray-tracing model, there are still several details to be collected, although, the useful simplification rules of Keränen *et al.* were applied [4]. For example, information on the geometry and dimensions of the workplace, the size and shape of the fittings, the sound absorption and scattering properties of the surfaces, the position, orientation and directivity of noise sources and measurement positions is needed. With more flexible and fast approach it could be possible to compare alternative noise control measures in real time, e.g. during a meeting with clients, and to guide acoustic design instead of making too detailed and tedious work. This idea has been very useful in the design of open offices, where a simple engineering model [5] has been used in several cases.

The accuracy of various room acoustic modeling programs has been examined in several case studies. In the 1st round robin test, Vorländer compared the prediction accuracy of 14 different room acoustic modeling programs in an auditorium [6]. Lam [7] compared three room acoustic models in a multipurpose auditorium [7]. In the 2nd round robin test, Bork [8] compared the prediction accuracy of

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16 room acoustic modeling programs in a concert hall [8]. The 3rd international round robin test was published by Bork [9]. The 21 participants came from 15 countries and they used 9 different room acoustic modeling programs. A recording studio was measured and modeled by the participants. These studies showed that the most sophisticated modeling programs are applicable in the design of acoustically complex spaces, e.g. large auditoria and concert halls. They also showed that the sophisticated modeling programs need to be used by an experienced acoustician.

In workplaces, the accuracy of different simple and sophisticated room acoustic models has been studied by, e.g. Ondet and Barbry, Hodgson, and Dance. In a workshop Ondet and Barbry compared five different models based on geometric acoustics, two simplified image source methods, an image source method including randomly distributed fittings, and a ray tracing method [10]. The image source and the ray tracing methods that took fittings into account provided the most accurate results.

In another study, Hodgson compared the results of five image source models, one ray-tracing and one empirical model to the measured results in a 1:50 scale model and in a factory-like warehouse [11]. The ray tracing model outperformed all the other models in both empty and fitted room.

Hodgson has also compared eight simple sound propagation models in 30 acoustically different industrial workrooms [12]. This extensive and thorough study lacked in published details. The sound absorption data was presented only for mid-frequency (average of 500–2000 Hz) and the results were presented only in A-weighted total SPL and 1 kHz octave band. In conclusions, the models developed by Kuttruff [13] and Hodgson [14] were found to be the most accurate. Five of these models; developed by Embleton and Russel [15], Hodgson [14], Kuttruff [13], Osipov *et al.* [16], and Thompson *et al.* [17] were also included as simple sound pressure level (SPL) models in our study. Three of the models were not considered in our study, because they predicted only the A-weighted sound pressure levels. In our study, the average SPL prediction accuracy is published in the octave bands of 125–4000 Hz and in A-weighted SPL.

Dance compared two empirical sound propagation models developed by Hodgson [14] and Heerema and Hodgson [18] to an image source model developed by Dance and Shield [19] in a simulated textile workroom using six different fitting configurations, in an engineering workroom, and in a bottling plant [20]. All the models took fittings into account. The image source model, as expected, was the most accurate. The empirical models were included also in our study.

More recently, empirical reverberation time and sound propagation models developed by Heerema and Hodgson [18] were compared to a ray tracing model in three different workshops [21]. In long and flat workshops, sound propagation predictions using the empirical model agreed, within 2 dB, with ray tracing predictions at distances less than 20 meters. The agreement deteriorated in a quasi-cubic workshop.

Though reverberation time (RT) is constantly applied in noise control as a design criterion, no detailed comparison of models for reverberation time predictions in industrial workrooms was found. Comparisons have been carried out e.g. in auditorium [6, 7] and concert halls [8], but their results may not be directly applicable in industrial spaces.

The purpose of this study was to determine the accuracy of simple room acoustic models that can predict SPL and RT in the octave bands of 125–4000 Hz. To reach high practical relevance, the study was carried out in four industrial workspaces before and after noise control. All the input and result parameters were presented in detail. This knowledge could be used in engineering prediction tools which were the practical outcome of this work.

Previously published seven simple SPL and seven simple RT engineering models were implemented, verified and validated in this study. Verification was a process to ensure that the mathematical equations of each model were correctly applied. It was done by repeating the calculations presented in the original publication in which the model was introduced. Validation consisted of comparison to measured results and to results predicted with a proven ray-tracing modeling program. This gave an estimation of the accuracy of the prediction models. The studied parameters were SPL and RT in the octave bands of 125–4000 Hz, A-weighted SPL, and average RT. Final judgement was based on the average prediction accuracy of A-weighted SPL and the average prediction accuracy of RT.

2. Materials and methods

The experiments were carried out during noise control projects in four workplaces where room acoustic computer modeling (ODEON 3.1) was used to predict IL of realizable noise control measures. Other models were applied afterwards.

The workplaces selected for this study represent very different industrial spaces. The workplaces with their assigned reference numbers are presented in Table I, and 3D-views of the room acoustic models of the workplaces are presented in Figure 1. A short description of the workplaces and the implemented noise control measures has already been given in an earlier study [4]. The workplaces included in this study are briefly re-described.

1. *Engineering works.* The room was very high ($H = 25$ m). Concrete floor was acoustically hard. The roof structure and brick walls with several windows were rather sound-absorbing. Initially, the workplace was fitted with stock 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. In ODEON, the model (Figure 1) consisted of 78 surfaces with low absorption coefficients (0.02–0.10) except the sound-absorbing surfaces. The scattering coefficients of the surfaces were 0.1–0.6 depending on the surface size, shape and roughness.

Table I. The workplace description and the parameters used in the simple SPL and RT models (H, L, W = room height, length and width, h = fitting height and d = fitting density, before/after the noise control measures).

Workplace	Type of industry	Volume (m^3)	H (m)	L (m)	W (m)	h (m)	d (m)
1	engineering works	48600	25	72	27	1.5/3.0	0.1/0.1
2	weaving factory	6400	8	40	20	2.0/2.0	0.1/0.1
3	engineering works	51100	12	142	30	3.0/3.0	0.1/0.1
4	electronics works/office	13600	6	54	42	0.0/2.0	0.0/0.2

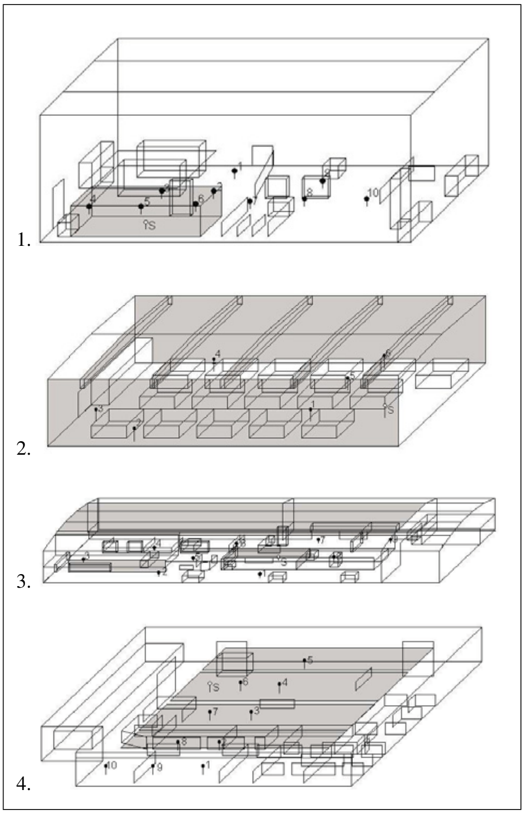

Figure 1. 3D-views of the room acoustic ray-tracing models of the four workplaces (not in relative scale). The sound source is noted with S and the measurement points with black dots. The grey areas show the implemented noise control.

2. *Weaving factory.* Brick walls, concrete floor and ceiling were hard. Initially, there were 16 large weaving machines (height 2 meters) which were modeled 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. In ODEON, the model (Figure 1) consisted of 107 surfaces with various absorption coefficients (0.02–0.95). Scattering coefficients were 0.1–0.9.

3. *Engineering works.* The room was long and rather narrow (L = 142 m, W = 30 m). The brick walls and concrete floor were acoustically hard. The curved roof structure and side walls with large window areas were rather sound-absorbing. Initially, there were several noise sources of different sizes (hand-held tools, machines etc.). Several hard screens and a couple of sound-absorbing noise screens were set around workstations (average height 3 meters). The curved ceiling was covered with 30 mm mineral wool. In ODEON, the model (Figure 1) consisted of 145 surfaces with various absorption coefficients (0.02–0.95). Scattering coefficients were 0.1–0.9.

4. *Electronics works/landscaped office.* Initially, the room was empty. Concrete ceiling, walls and floor were hard. Large windows on the side wall increased sound absorption. The noise produced in the packaging area propagated to the office area. The work stations in the landscaped office were separated by several 2-meter-high sound-absorbing office screens. The ceiling was covered with a sound-absorbing 25-mm-thick spray-on material. In ODEON, the model (Figure 1) consisted of 68 surfaces with various absorption coefficients (0.02–0.95). Scattering coefficients were 0.1–0.9.

2.1. Measuring methods

SPL produced by a calibrated sound source including a pink noise signal generator, a power amplifier and an omni-directional loudspeaker with 35-cm-diameter dodecahedral enclosure and 12 speaker elements (Brüel&Kjær 4296) was measured before and after the noise control measures using the same measurement points and source positions. The omni-directional loudspeaker was placed in a carefully selected position, e.g. close to a noisy machine. The measurement points were in the manned work stations so that the measurement data could be used in noise control design (Figure 1). Thus, the effect of the noise control measures on the noise exposure of the workers in those particular work stations was easy to determine. The height of the loudspeaker center and the measurement points was 1.5 meters. The sound power level L_w of the omni-directional sound source was measured in the octave bands of 125–4000 Hz in a reverberation chamber in the Finnish Institute of Occupational Health according to ISO 3741 [22]. The sound power level in the octave bands of 125–4000 Hz was 105, 106, 106, 104, 104, and 100 dB, respectively. The frequency response of the loudspeaker in the studied frequency range is reasonably flat. According to the manufacturer's information the directionality of the loudspeaker is spherical.

The noisiest production machines were stopped during the measurements to reduce the background noise. The output level of the sound source was set so that the background noise level was at least 6 dB lower than the test signal at all measurement points.

RT was measured using a gun shot as a sound source and determined using the decay of 20 dB. RT was determined as an arithmetic average of several RT measurements. The sound source location and measurement point were changed between the measurements.

The determination of sound absorption coefficients is described in modeling methods. The effect of the noise control measures on sound absorption coefficients and fitting parameters was estimated, SPL and RT were predicted, and then measured after implementation of the noise control measures.

2.2. Modeling methods

During the noise control projects, ray-tracing models were created using hybrid modeling software, ODEON 3.1 [23, 24]. The method of ray-tracing modeling has been described in several studies [23, 25, 26, 27]. The creation of the models was described in the earlier study by Keränen *et al.* [4]. Room and fitting dimensions were measured in the workplaces. Surfaces were visually inspected, and absorption coefficients and scattering coefficients were estimated according to the available material information in the literature [24, 28, 29]. Before the noise control, the absorption and scattering coefficients of some surfaces, e.g. floor, ceiling or walls were slightly adjusted to achieve better accuracy with RT and SPL measurements. This was a way to verify that IL predictions gave reasonable results. When modeling the noise control measures, the only changes to the model were those that simulated real changes in the workplace, e.g. mounting sound-absorbing panels.

Several models for SPL and RT predictions exist, but the models selected for this study enabled predictions in the octave bands 125–4000 Hz. Seven simple models for predicting RT and seven simple models for predicting SPL at the distance of r [m] from the sound source were examined. The models were taken as they are presented in the literature. It was not the purpose of this study to modify or improve the models. The SPL models were originally aimed for sound level predictions in large halls or workrooms, but there were not many RT models specified for industrial workrooms. Therefore, it was interesting to test if RT models intended for different spaces were usable in the industrial workrooms.

The simple models were implemented using calculation functions of Microsoft Office Excel program. The model implementation was verified by comparison to earlier published results so that the previously published input data was used and the results of the implemented models were compared to the results presented in the same publications [12, 21]. However, all the necessary information was not published in detail in the original publications, so some degree of uncertainty may exist in these implementations.

As input parameters (in S.I. units), the simple models needed the room dimensions: height H [m], width W [m], and length L [m]. Also fitting height h [m] and fitting density Q [1/m] were needed, as well as the absorption coefficients of the floor α_f, the ceiling α_c, and the walls, $\alpha_{w1} \ldots \alpha_{w4}$. The room volume V [m^3], the areas of the room surfaces, S_k [m^2], the total surface area S [m^2], and the average absorption coefficient $\overline{\alpha}$, were calculated assuming that the rooms were of rectangular shape. The dimensions, the fitting parameters and the absorption coefficients were the same between the models. All the input data is presented in Tables I and II. The simple models are briefly described below. They are referred to as T1–T7 and L1–L7 thereafter.

3. Reverberation time models

T1. Arau-Puchades [30] has derived a formula based on the Fitzroy [31] formula

$$T = \frac{-0.16V}{S[\ln(1-\overline{\alpha}_x)]^{S_x/S}[\ln(1-\overline{\alpha}_y)]^{S_y/S}[\ln(1-\overline{\alpha}_z)]^{S_z/S}} \tag{1}$$

in which S_x [m^2] is the surface area of the ceiling and the floor, S_y [m^2] is the surface area of the side walls, and S_z [m^2] is the surface area of the front and the end wall. Here, α_x, α_y, and α_z are the average absorption coefficients of the surface areas S_x, S_y and S_z, respectively. It is supposed that RT should be area- weighted arithmetic average of the reverberation in each one of the rectangular directions. Originally, the formula was validated against measurements in auditoria, theatres and studios by Arau-Puchades, so that the model was not expected to be optimal for large workrooms.

T2. Eyring [32] has presented an alternative to the Sabine [33] formula

$$T = \frac{-0.16V}{S\ln(1-\overline{\alpha})}, \tag{2}$$

in which the average absorption coefficient $\overline{\alpha}$ is $\overline{\alpha} = \sum_k \alpha_k S_k / S$, and k goes through all the surfaces. Total surface area S [m^2], is the sum of surface areas S_k [m^2]. Eyring pointed out that the Sabine formula was not fulfilled when there is considerable amount of room absorption. In the Eyring formula, all the surfaces have an equal effect on room absorption, while in the Sabine formula (T7) the most absorptive surfaces are of greater importance. The Eyring model is often used in predictions considering noise control with additional sound absorption.

T3. Fitzroy [31] has proposed an area-weighted modification to the Eyring [32] formula

$$T = \frac{-0.16V}{S^2}\left[\frac{S_x}{\ln(1-\overline{\alpha}_x)} + \frac{S_y}{\ln(1-\overline{\alpha}_y)} + \frac{S_z}{\ln(1-\overline{\alpha}_z)}\right], \tag{3}$$

in which S_x [m^2] is the surface area of the ceiling and the floor, S_y [m^2] is the surface area of the side walls and S_z [m^2] is the surface area of the front and the end wall. As in

Table II. The absorption coefficients used in the simple SPL and RT models before/after the noise control measures.

workplace	surface	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
1	Floor	0.01 / 0.01	0.01 / 0.01	0.01 / 0.01	0.02 / 0.02	0.02 / 0.02	0.02 / 0.02
	Ceiling	0.40 / 0.40	0.40 / 0.40	0.40 / 0.40	0.32 / 0.32	0.28 / 0.28	0.28 / 0.28
	Wall 1	0.28 / 0.28	0.17 / 0.17	0.12 / 0.12	0.11 / 0.11	0.10 / 0.10	0.12 / 0.12
	Wall 2	0.28 / 0.28	0.17 / 0.17	0.12 / 0.12	0.11 / 0.11	0.10 / 0.10	0.12 / 0.12
	Wall 3	0.28 / 0.28	0.17 / 0.17	0.12 / 0.12	0.11 / 0.11	0.10 / 0.10	0.12 / 0.12
	Wall 4	0.28 / 0.28	0.17 / 0.17	0.12 / 0.12	0.11 / 0.11	0.10 / 0.10	0.12 / 0.12
2	Floor	0.01 / 0.01	0.01 / 0.01	0.01 / 0.02	0.02 / 0.02	0.02 / 0.02	0.02 / 0.02
	Ceiling	0.01 / 0.20	0.01 / 0.70	0.02 / 0.90	0.02 / 0.90	0.02 / 0.90	0.05 / 0.90
	Wall 1	0.02 / 0.20	0.03 / 0.70	0.03 / 0.90	0.04 / 0.90	0.05 / 0.90	0.07 / 0.90
	Wall 2	0.02 / 0.20	0.03 / 0.70	0.03 / 0.90	0.04 / 0.90	0.05 / 0.90	0.07 / 0.90
	Wall 3	0.02 / 0.02	0.03 / 0.03	0.03 / 0.03	0.04 / 0.04	0.05 / 0.05	0.07 / 0.07
	Wall 4	0.99 / 0.99	0.99 / 0.99	0.99 / 0.99	0.99 / 0.99	0.99 / 0.99	0.99 / 0.99
3	Floor	0.01 / 0.01	0.01 / 0.01	0.01 / 0.01	0.02 / 0.02	0.02 / 0.02	0.02 / 0.02
	Ceiling	0.40 / 0.40	0.40 / 0.40	0.40 / 0.76	0.32 / 0.92	0.28 / 0.92	0.28 / 0.95
	Wall 1	0.15 / 0.15	0.50 / 0.50	0.90 / 0.90	0.90 / 0.90	0.75 / 0.75	0.50 / 0.50
	Wall 2	0.30 / 0.30	0.12 / 0.12	0.08 / 0.08	0.06 / 0.06	0.06 / 0.06	0.05 / 0.05
	Wall 3	0.02 / 0.02	0.03 / 0.03	0.03 / 0.03	0.04 / 0.04	0.05 / 0.05	0.07 / 0.07
	Wall 4	0.02 / 0.02	0.03 / 0.03	0.03 / 0.03	0.04 / 0.04	0.05 / 0.05	0.07 / 0.07
4	Floor	0.01 / 0.01	0.02 / 0.02	0.02 / 0.02	0.02 / 0.02	0.03 / 0.03	0.03 / 0.03
	Ceiling	0.10 / 0.12	0.10 / 0.29	0.09 / 0.76	0.08 / 0.94	0.06 / 0.99	0.03 / 0.99
	Wall 1	0.40 / 0.40	0.30 / 0.30	0.20 / 0.20	0.17 / 0.17	0.15 / 0.15	0.10 / 0.10
	Wall 2	0.01 / 0.01	0.02 / 0.02	0.02 / 0.02	0.02 / 0.02	0.03 / 0.03	0.03 / 0.03
	Wall 3	0.01 / 0.01	0.02 / 0.02	0.02 / 0.02	0.02 / 0.02	0.03 / 0.03	0.03 / 0.03
	Wall 4	0.01 / 0.01	0.02 / 0.02	0.02 / 0.02	0.02 / 0.02	0.03 / 0.03	0.03 / 0.03

equation (1) α_x, α_y, and α_z are the average absorption coefficients of the surface areas S_x, S_y, and S_z, respectively. This formula tried to consider also the geometrical aspects of the room. The formula was proposed for the situation where one of the surfaces has significantly higher sound absorption than the other surfaces. The formula was empirically derived through extensive tests in large number of rooms, where distribution of sound absorption varied widely in uniformity. The formula is rather often referred in the literature, but is not as widely used as the Eyring (T2) or the Sabine (T7) formula.

T4. Heerema and Hodgson [18] have presented an empirical formula

$$T = C_{t0} + C_{t1}\frac{V}{S} + C_{t2}\frac{1}{\overline{\alpha}}, \qquad (4)$$

where C_{t0}, C_{t1} and C_{t2} are tabulated coefficients (Table IV), The model was based on empirical data of 30 industrial workrooms with room length of 23–128 m, width 5–61 m, and height 4–9 m. The formula was developed using multi-variable linear regression analysis. The model has been used in predictions considering noise control measures in workrooms of various shapes and sizes. Workplaces 2 and 4 of this study were within the applicability ranges. The model was applied also in workplaces 1 and 3 to see the magnitude of prediction error in cases that were not within the applicability ranges.

T5. Kuttruff [13] has presented an improved version of the Eyring [32] formula

$$T = \frac{0.16V}{S\left[-\ln(1-\overline{\alpha})[1+(\gamma^2/2)\ln(1-\overline{\alpha})] + \frac{\sum_k (1-\alpha_k)(\overline{\alpha}-\alpha_k)S_k^2}{S^2(1-\overline{\alpha})^2}\right]}, \qquad (5)$$

in which the variance of the unequal sound path length distribution $\gamma^2 = 0.4$ was used as recommended by Kuttruff for rectangular room shapes. Absorption coefficients α_k, surface areas S_k [m^2], total surface area S [m^2], and room volume V [m^3], are defined as in the Eyring formula (T2). The improvement was to take into account the uneven distribution of sound absorptive surfaces. However, for non-rectangular rooms, the variance, γ^2, should be recalculated, e.g. using a ray tracing model.

T6. Millington and Sette [34] have developed a formula introducing the absorption exponent into the Sabine [33] formula

$$T = \frac{-0.16V}{\sum_k S_k \ln(1-\alpha_k)}, \qquad (6)$$

where V [m^3] is room volume and S_k [m^2] are surface areas with absorption coefficients α_k. The formula is based on similar assumptions as Sabine formula, but the average absorption is determined by considering the acoustic energy in series of confined sound cones reflected in sequence by each of the room surfaces. The formula does

Table III. The tabulated room coefficients in the Embleton and Russel model L1. The ceiling absorption is categorized in three classes: high, $\alpha_c > 0.5$, partial, $0.1 < \alpha_c \leq 0.5$, and poor, $\alpha_c \leq 0.5$.

Ceiling corrections, dL_c, (dB)			
distance [m] to height [m] ratio	ceiling absorption		
	high	partial	poor
1.0	0	0	0
1.25	0	0.25	1
1.6	0	1.0	2
2.0	0	1.5	3
2.5	0	2.0	4
3.2	0	2.5	5
4.0	0	3.0	6
5.0	0	3.5	7
6.3	0	4.0	8
8.0	0	4.5	9
10.0	0	5.0	10
12.5	0	5.5	11
16.0	0	6.0	12
20.0	0	6.5	13

Side-wall corrections, dL_w, (dB)	
poor absorption, $\alpha_w \leq 0.1$	3
partial absorption, $0.1 < \alpha_w \leq 0.5$	2
high absorption, $\alpha_w > 0.5$	1

not allow the use of absorption coefficients equal to 1. In industrial workrooms, this is not a problem, because there are not such efficient sound-absorbing surfaces.

T7. Originally, Sabine [33] developed the classic formula

$$T = \frac{0.16V}{S\overline{\alpha}}, \tag{7}$$

in which V [m^3] is room volume, S [m^2] is total surface area, and $\overline{\alpha}$ is average absorption coefficient. This classic model has been widely used in various rooms including workplaces, because it is simple to use.

4. Sound pressure level models

L1. Embleton and Russel [15] have developed a model

$$L_p(r) = L_w - 20\lg(r) - 10.3 + dL_w + dL_c, \tag{8}$$

in which dL_w [dB] and dL_c [dB] are the wall and ceiling correction factors presented in Table III. The corrections depend on the distance r [m] from the sound source to the receiver, the room height H [m], and the sound absorption coefficients of the side walls and the ceiling. The model was intended for empty, rectangular shaped and flat rooms.

L2. Heerema and Hodgson [18] have developed the following empirical model based on multi-variable linear regression analysis of measurement data in 30 industrial workrooms (same as in RT model T4)

$$L_p(r) = L_w + I + s\lg(r), \tag{9}$$

in which the intercept I [dB] of the sound-propagation curve is

$$\begin{aligned} I = {} & C_{i0} + C_{i1}\alpha_{\text{eff}} + C_{i2}H + C_{i3}\lg(H) + C_{i4}Q + C_{i5}\frac{h}{H} \\ & + C_{i6}\frac{S}{V} + C_{i7}V + C_{i8}S + C_{i9}\alpha_{\text{eff}}LW, \end{aligned} \tag{10}$$

and the slope s [dB/log(m)] of the sound-propagation curve is

$$\begin{aligned} C = {} & C_{S0} + C_{S1}\overline{\alpha} + C_{S2}H + C_{S3}\lg(H) \\ & + C_{S4}\frac{1}{Q} + C_{S5}\frac{h}{H} + C_{S6}\frac{S}{V}. \end{aligned} \tag{11}$$

In equation (10) the efficient absorption coefficient α_{eff}, is

$$\alpha_{\text{eff}} = C_{a0} + C_{a1}Q, \tag{12}$$

and the fitting density Q [1/m] is

$$Q = \frac{S_f}{4V}. \tag{13}$$

Here, S_f [m^2] is the surface area of the fittings. The coefficients $C_{i0\ldots i9}$, $C_{s0\ldots s6}$, C_{a0} and C_{a1} are presented in Table IV. The model was developed for industrial workshops with rectangular geometry, horizontally uniformly distributed fittings and uniformly distributed sound absorption. The model was based on the same empirical data as the RT model T4 so that the same limits for room size and shape apply. Workplaces 2 and 4 of this study were within the applicability ranges.

L3. Hodgson [14] has proposed an empirical model

$$\begin{aligned} L_p(r) = {} & L_w + I_E + dI_F \\ & - 3.3(S_E + dS_F + dS_A)\lg(r), \end{aligned} \tag{14}$$

where I_E, dI_F [dB], S_E, dS_F and dS_A [dB/log(m)] are tabulated coefficients (Table V). This model was presented before the Heerema and Hodgson model (L2), and was based on multi-variable linear regression analysis of 11 empty, 13 fitted, and 12 non-typical industrial workrooms. This model was also developed for industrial workshops with rectangular geometry, horizontally uniformly distributed fittings and uniformly distributed sound absorption.

L4. Kuttruff [13] has proposed a model for a partially diffuse sound field

$$L_p(r) = L_w + 10\lg\left[A(r, H, \overline{\alpha})\right], \tag{15}$$

in which

$$\begin{aligned} A(r, H, \overline{\alpha}) = {} & \frac{1}{4\pi r^2} + (1 - \overline{\alpha}) \\ & \cdot \left[\frac{(1 + r^2/H^2)^{-3/2} + b_K(1 - \overline{\alpha})(b_K^2 + r^2/H^2)^{-3/2}/\overline{\alpha}}{\pi H^2}\right], \end{aligned} \tag{16}$$

and b_K was set to a constant value of 3 for rooms with rectangular room geometry. The model assumes that the ceiling and the floor are diffusely reflecting and their absorption coefficients take into account the effect of the fittings on the sound propagation.

Table IV. The tabulated room coefficients in the Heerema and Hodgson models L2 and T4.

Octave band (Hz)	125	250	500	1000	2000	4000
C_{a0}	0.11	0.017	0.099	0.131	0.14	0.135
C_{a1}	4.52	5.8	4.32	2.79	2.28	1.94
C_{s0}	-91.9	-102.0	-87.7	-81.9	-60.5	-70.8
C_{s1}	-16.1	-21.9	-29.9	-26.9	-24.9	-19.2
C_{s2}	-12.1	-14.3	-12.5	-12.5	-8.5	-9.2
C_{s3}	196.0	225.0	194.0	187.0	128.0	146.0
C_{s4}	-0.037	-0.028	-0.007	0.032	0.131	0.135
C_{s5}	-5.08	-3.63	-2.33	-9.79	-11.6	-11.88
C_{s6}	15.0	18.8	17.7	18.0	15.9	13.2
C_{i0}	21.4	25.5	27.9	41.1	29.0	65.9
C_{i1}	-6.32	-2.96	19.4	-16.5	-18.2	-18.3
C_{i2}	5.84	6.58	6.46	8.61	5.59	9.74
C_{i3}	-86.7	-98.0	-99.8	-127.0	-85.5	-155.0
C_{i4}	0	0	-121.0	48.3	72.2	37.1
C_{i5}	5.03	5.0	5.13	12.4	0	0
C_{i6}	0	0	0	-9.04	-10.1	-21.4
C_{i7}	-8.33E-5	-6.25E-5	5.64E-5	-1.34E-4	0	0
C_{i8}	0	0	0	0	-4.87E-4	-8.40E-4
C_{i9}	3.10E-3	2.50E-3	1.14E-3	1.82E-3	0	2.47E-3
C_{t0}	-2.32	-2.36	-2.68	-2.96	-2.7	-2.06
C_{t1}	0.902	0.988	1.13	1.25	1.13	0.83
C_{t2}	0.387	0.362	0.369	0.368	0.368	0.368

Table V. The tabulated room coefficients in the Hodgson model L3.

	125	250	500	1000	2000	4000
I_E	−11.6	−11.3	−11.5	−11.1	−11.4	−11.2
dI_F	1.9	2.1	2.6	3.3	2.4	1.7
S_E	2.2	2.1	2.2	1.9	2.1	2.6
dS_F	1.7	1.7	1.3	1.5	1.3	1.7
dS_A	0.6	1.0	1.5	1.4	0.6	0

L5. Osipov, Sergeyev and Shubin [16] have developed a model

$$L_p(r) = L_w + 10\lg\left[\frac{1}{2\pi r^2} + \frac{(1-\overline{\alpha})(r+W)J(\overline{\alpha},\rho)}{HW(r+H)}\right], \quad (17)$$

with Bessel function

$$J(\overline{\alpha},\rho) = \frac{0.1}{\overline{\alpha}+\rho^2\exp(0.65\rho)]}, \quad (18)$$

in which

$$\rho = -rS\ln(1-\overline{\alpha})/4V. \quad (19)$$

This model assumes that the sound propagates cylindrically in the workroom. The room geometry is assumed parallelepiped in the workroom.

L6. The Sabine model [35] is the well known steady-state sound level equation according to the diffuse field theory

$$L_p(r) = L_w + 10\lg\left[\frac{k}{\Omega r^2} + \frac{4(1-\overline{\alpha})}{S\overline{\alpha}}\right], \quad (20)$$

in which $k = 1$ and $\Omega = 4\pi$ when the sound source is omni-directional and it is not located close to reflecting surfaces.

L7. Thompson *et al.* [17] have proposed a modified expression of the steady-state sound level according to the diffuse field theory

$$L_p(r) = L_w + 10\lg\left[\frac{\exp(-mr)}{4\pi r^2} + \frac{4V}{rS(\overline{\alpha}S_w + 4mV)}\right] + 10\lg\left[\frac{TM+460}{527} + \frac{30}{BP}\right], \quad (21)$$

in which S_w is the wall surface area, m is the air-absorption exponent, TM is the room temperature [°C] and BP is the barometric pressure [mbar]. The first part is nearly the same as in the Sabine equation, but it includes the sound absorption of air.

5. Determination of prediction accuracy

The scientific work of this study consisted of verification and validation of the simple SPL and RT models. Verification means that the prediction results of the implemented models were compared to the prediction results of the original publications. The original information on the room was used when ever possible. For the verification a few predictions from the original publications were selected and compared to the results of the implemented prediction models. The predicted results $L_{i,p,f}$ were compared to the prediction results published in the literature, $L'_{i,p,f}$. Similarly, the implementation of the RT models was verified comparing the predicted results $T_{p,f}$ to the prediction results in the literature, $T'_{p,f}$. In the verification, the input data and results were taken from the original publications as they were presented.

In the validation, the prediction accuracy of SPL was determined as a difference between the predicted $L_{i,p,f}$ and the measured $L_{i,m,f}$ SPL at measurement point i in the octave bands f, 125–4000 Hz.

The average prediction accuracy of SPL was determined by averaging the repetitive difference between the predicted and measured SPL in all of the N measurement points,

$$A_{L,f} = \frac{1}{N} \sum_{i=1}^{N} \left| L_{i,p,f} - L_{i,m,f} \right|. \tag{22}$$

Standard deviation of the SPL prediction accuracy was determined from the repetitive difference between the predicted and measured SPL in all of the N measurement points,

$$SD_{L,f} = \sqrt{\frac{\sum_{i=1}^{N} \left(|L_{i,p,f} - L_{i,m,f}| - A_{L,f} \right)^2}{N-1}}. \tag{23}$$

The prediction accuracy was determined in eight cases (four workplaces, both before and after the noise control). The prediction accuracy of the A-weighted sound pressure level was determined similarly in all of the measurement points of the eight cases. Finally, the average $A_{L,A}$ and the standard deviation $SD_{L,A}$ of the accuracy of the A-weighted SPL predictions were determined.

The accuracy of the RT predictions in the 125-4000 Hz octave bands $A_{T,f}$ was defined by the difference between predicted and measured RT.

$$A_{T,f} = \left| T_{p,f} - T_{m,f} \right|, \tag{24}$$

in which $T_{p,f}$ was the predicted RT, and $T_{m,f}$ the average of the measured RT in the octave band f. The prediction accuracy $A_{T,f}$ was determined in the 125–4000 Hz octave bands except in workplace 1 before the noise control, because RT was not accurately measured at 125 Hz there. The average accuracy, A_T, was determined by averaging the octave band accuracies in workplaces 1–4 before and after the noise control. Because the RT prediction models give only one result for a workroom, there was no need to determine standard deviation of the RT predictions. The deviation would only have reflected the deviations in the measurement results.

Two-step accuracy criteria were selected so that the strictest limits should reveal the models with good prediction accuracy. The strictest limits were set the same as the survey grade measurement accuracies described in standards ISO 3746 and ISO 3382-2 [36, 37]. The 3 dB limit was chosen for the strictest accuracy limit of SPL predictions, because there is no reason to expect better accuracy than is possible to measure in situ. The reverberation time accuracy limit of 10% was chosen, because this accuracy is presented in ISO 3382-2 as a nominal accuracy for RT measured using a survey method. The survey measurement method should be appropriate for the assessment of the amount of room absorption for noise control purposes. Thus, this accuracy should be reasonable also for the RT predictions. The limit for the unacceptable accuracy of predictions was set to twice the above-mentioned limiting values, 6 dB for the A-weighted SPL and 20% for RT, respectively. If the higher accuracy limits are exceeded the model cannot be, accurately, used for noise control design.

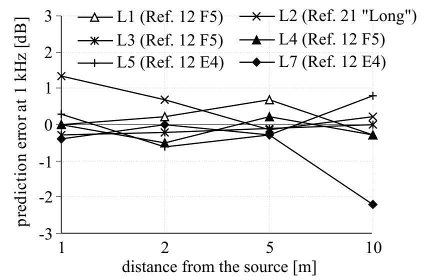

Figure 2. Prediction error in the verification of the SPL model implementations at 1000 Hz. The difference between the predicted and the original published SPL is presented in various distances from the sound source.

6. Results

Verification proved that the implemented RT and SPL models gave very similar results as in the original studies. An example of the verification of the implemented SPL models in 1000 Hz octave band is presented in Figure 2. The verification was not possible in all the octave bands 125–4000 Hz, because in the original publications all the results were not presented.

Predicted and measured A-weighted SPL in the measurement points in the four workplaces before and after the noise control are presented in Figure 3. The points are presented according to the distance from the sound source.

Predicted and measured RT in the octave bands 125–4000 Hz before and after the noise control is presented in Table VI. All the models indicated decrease in RT when the amount of sound absorption in the room was significantly increased.

The average accuracy of the SPL predictions in the octave bands 125–4000 Hz, $A_{L,f}$, is presented in Table VII. The accuracy of the RT predictions in the octave bands 125–4000 Hz, $A_{T,f}$, is presented in Table VIII. The average $A_{L,A}$ and the standard deviation, $SD_{L,A}$ of the accuracy of the A-weighted SPL predictions are presented in Table IX. The average accuracy of the RT predictions, A_T, is presented in Table X. A summary of the prediction accuracy of the RT and SPL models is presented in Figures 4 and 5, respectively. Because the accuracy of the RT predictions was over 20% in most of the cases, an additional limit of 30% was included in Figure 4. This revealed a little more differences between the RT models.

Table VI. Predicted and measured RT in the octave bands 125–4000 Hz before and after the noise control for workplaces 1–4.

	Workplace 1, before						Workplace 1, after					
	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	125 kHz	250 kHz	500 Hz	1 kHz	2 kHz	4 kHz
raytracing	...	3.7	4.1	4.4	4.1	2.5	3.0	3.6	4.0	4.2	4.1	2.5
T1	...	4.3	5.3	6.1	6.9	6.2	3.1	4.3	5.3	6.1	6.9	6.2
T2	...	4.3	5.1	6.0	6.8	6.2	3.1	4.3	5.1	6.0	6.8	6.2
T3	...	4.3	5.5	6.3	7.1	6.2	3.2	4.3	5.5	6.3	7.1	6.2
T4	...	4.2	4.9	5.5	5.3	4.3	3.7	4.2	4.9	5.5	5.3	4.3
T5	...	4.4	5.2	6.1	6.9	6.3	3.2	4.4	5.2	6.1	6.9	6.3
T6	...	4.0	4.7	5.7	6.5	5.9	2.9	4.0	4.7	5.7	6.5	5.9
T7	...	4.7	5.6	6.5	7.2	6.6	3.6	4.7	5.6	6.5	7.2	6.6
measured	...	5.2	4.4	4.2	3.5	2.1	3.3	4.1	4.7	4.6	4.0	2.6
	Workplace 2, before						Workplace 2, after					
	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	125 kHz	250 kHz	500 Hz	1 kHz	2 kHz	4 kHz
raytracing	2.1	2.0	1.9	1.8	1.6	1.1	1.5	0.8	0.6	0.6	0.6	0.5
T1	19.7	17.7	13.7	10.6	10.0	6.4	2.4	0.7	0.5	0.5	0.5	0.5
T2	5.2	5.0	4.8	4.4	4.2	3.6	2.0	0.6	0.5	0.5	0.5	0.5
T3	29.9	28.2	19.9	14.9	14.4	8.5	2.8	0.7	0.5	0.5	0.5	0.5
T4	1.5	1.5	1.6	1.9	1.9	1.8	1.0	0.7	0.6	0.7	0.7	0.6
T5	4.3	4.1	4.0	3.8	3.6	3.1	1.9	0.6	0.4	0.4	0.4	0.4
T6	1.3	1.3	1.3	1.3	1.3	1.2	1.0	0.4	0.3	0.3	0.3	0.3
T7	5.4	5.2	5.0	4.6	4.4	3.8	2.2	0.9	0.7	0.7	0.7	0.7
measured	2.4	2.3	2.2	2.3	2.1	1.7	1.6	1.2	0.9	0.9	0.9	0.8
	Workplace 3, before						Workplace 3, after					
	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	125 kHz	250 kHz	500 Hz	1 kHz	2 kHz	4 kHz
raytracing	3.2	3.3	3.1	3.3	3.1	2.2	3.2	3.0	1.8	1.6	1.6	1.4
T1	3.1	2.8	2.4	2.7	3.1	3.5	3.1	2.8	1.4	1.2	1.2	1.3
T2	2.9	2.6	2.0	2.3	2.7	3.3	2.9	2.6	1.3	1.1	1.2	1.2
T3	4.4	3.6	3.4	3.5	3.7	3.7	4.4	3.6	2.4	1.9	1.7	1.7
T4	2.3	2.5	2.7	3.0	3.0	2.6	2.3	2.5	2.5	2.7	2.5	2.0
T5	2.9	2.5	1.9	2.1	2.5	3.2	2.9	2.5	1.2	0.9	1.0	1.1
T6	2.6	2.2	1.3	1.4	2.0	2.9	2.6	2.2	0.8	0.5	0.6	0.6
T7	3.2	2.9	2.4	2.6	3.0	3.6	3.2	2.9	1.6	1.4	1.5	1.6
measured	2.1	2.8	2.8	2.8	2.5	1.9	2.2	2.0	1.7	1.5	1.4	1.1
	Workplace 4, before						Workplace 4, after					
	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	125 kHz	250 kHz	500 Hz	1 kHz	2 kHz	4 kHz
raytracing	5.4	5.2	5.3	4.4	2.5	1.4	2.7	1.8	1.6	1.4	1.1	0.8
T1	6.7	6.1	6.8	7.5	7.9	11.5	5.9	2.7	1.2	1.0	0.9	0.9
T2	5.4	5.4	6.4	7.1	7.7	11.1	4.8	2.5	1.0	0.8	0.7	0.7
T3	9.0	6.9	7.4	8.1	8.2	11.8	8.1	3.7	2.7	2.6	2.0	2.2
T4	2.5	3.0	2.8	2.9	3.0	3.5	0.6	0.6	0.5	0.6	0.6	0.5
T5	5.1	5.3	6.3	7.0	7.5	10.8	4.6	2.5	0.9	0.6	0.6	0.6
T6	5.0	5.2	6.2	7.0	7.6	11.0	4.5	2.3	0.6	0.3	0.2	0.2
T7	5.6	5.6	6.6	7.3	7.8	11.3	5.0	2.7	1.2	1.0	0.9	0.9
measured	4.0	4.1	4.1	4.1	3.3	2.1	1.4	1.0	0.9	0.9	0.8	0.7

7. Discussion

The simple SPL and RT models were implemented using calculation functions of Microsoft Office Excel program and verified comparing prediction results to the original published results. In a perfect situation verification result would be that the prediction results were identical. Unfortunately, this could not be achieved with any of the models due to a lack of exact or detailed information in the publications. The verification indicated that the models were functioning as accurately as intended (Figure 2) so that the models were not modified in any way. However, the verification did not confirm that the models could perform accurately in all the industrial workrooms.

Table VII. The average accuracy of the SPL predictions in the octave bands 125–4000 Hz before and after the noise control for workplaces 1–4. The good values (under 3 dB error) are in bold, the unacceptable values (over 6 dB error) are in grey colour.

	Workplace 1, before						Workplace 1, after					
	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	125 kHz	250 kHz	500 Hz	1 kHz	2 kHz	4 kHz
raytracing	**1.7**	**1.5**	**1.7**	**0.9**	**0.6**	**1.0**	**2.1**	3.8	**2.4**	**1.2**	**1.5**	**1.5**
L1	8.8	10.4	7.7	7.6	6.7	4.2	8.8	10.4	7.7	7.6	6.7	4.2
L2	87.0	109.9	88.1	71.9	49.7	18.5	87.1	109.9	88.0	71.8	50.6	19.0
L3	3.9	**2.3**	**2.1**	3.7	**2.4**	**1.9**	3.9	**2.3**	**2.1**	3.7	**2.4**	**1.9**
L4	8.0	9.0	5.9	5.5	5.4	**2.1**	8.0	9.0	5.9	5.5	5.4	**2.1**
L5	6.1	6.7	3.4	**2.8**	**2.6**	**1.2**	4.4	5.3	**2.1**	**1.3**	**0.9**	**2.5**
L6	3.4	3.7	**1.3**	**1.3**	**1.7**	4.1	3.4	3.7	**1.3**	**1.3**	**1.7**	4.1
L7	4.9	5.5	**2.4**	**2.0**	**2.4**	**0.9**	4.9	5.5	**2.4**	**2.0**	**2.4**	**0.9**

	Workplace 2, before						Workplace 2, after					
	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	125 kHz	250 kHz	500 Hz	1 kHz	2 kHz	4 kHz
raytracing	**0.9**	**0.9**	**0.7**	**1.1**	**1.0**	**2.6**	**2.0**	**1.9**	**2.8**	**2.0**	**2.3**	3.1
L1	4.6	4.3	4.0	4.6	3.8	3.2	4.5	5.5	4.0	3.5	3.4	3.3
L2	**1.3**	**1.2**	**1.9**	**0.3**	**0.5**	**0.8**	**1.5**	7.6	15.1	10.2	9.1	5.2
L3	**1.3**	**0.7**	**1.8**	**2.7**	**2.3**	**1.2**	**2.0**	**0.9**	**1.5**	3.1	5.2	3.6
L4	**0.7**	**0.6**	**0.5**	**0.8**	**0.8**	**0.8**	**1.5**	3.5	**3.0**	**2.5**	**2.5**	**2.4**
L5	3.8	3.9	4.0	**3.0**	3.6	3.2	**1.8**	3.1	**2.4**	**1.8**	**1.7**	**1.6**
L6	7.3	7.4	7.6	6.6	7.3	7.1	5.9	**3.0**	3.6	4.0	4.1	4.3
L7	3.3	3.2	3.2	**2.1**	**2.2**	**1.3**	**2.9**	**1.2**	**2.1**	**2.3**	**2.3**	**2.4**

	Workplace 3, before						Workplace 3, after					
	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	125 kHz	250 kHz	500 Hz	1 kHz	2 kHz	4 kHz
raytracing	4.5	**2.9**	3.5	**2.7**	**2.3**	**2.7**	3.1	3.9	**3.0**	3.4	3.3	3.7
L1	6.9	5.0	4.9	4.6	3.9	3.2	4.1	**2.4**	**1.6**	**1.5**	**1.9**	3.3
L2	15.1	21.1	21.7	21.9	17.1	7.9	12.2	18.0	21.4	22.9	17.9	6.0
L3	**2.8**	**2.6**	**2.9**	**1.5**	3.8	**2.9**	3.9	**2.2**	3.8	7.2	10.6	10.5
L4	4.8	3.1	3.7	3.1	**2.1**	**1.5**	**2.3**	**1.7**	**1.5**	**2.0**	**2.8**	4.9
L5	3.5	**2.1**	**2.8**	**2.0**	**1.7**	3.1	**2.3**	**2.7**	**1.8**	**2.3**	3.2	5.4
L6	3.5	**2.3**	**2.3**	**2.3**	3.6	4.9	4.6	5.3	4.7	5.3	6.3	8.5
L7	3.8	**2.1**	**2.5**	**2.1**	**1.6**	**1.9**	**2.2**	**2.8**	**3.0**	3.7	4.4	5.6

	Workplace 4, before						Workplace 4, after					
	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	125 kHz	250 kHz	500 Hz	1 kHz	2 kHz	4 kHz
raytracing	**1.8**	**0.9**	**1.1**	**1.0**	**3.0**	4.9	4.7	**1.2**	3.4	4.1	3.4	4.1
L1	10.2	12.4	9.3	9.1	8.8	7.5	3.9	5.2	6.4	4.7	**2.5**	**2.1**
L2	3.8	4.6	**1.0**	**1.7**	3.2	5.2	**1.8**	5.5	17.2	9.8	8.2	5.6
L3	4.9	6.3	3.5	**2.8**	3.8	6.4	**2.2**	**2.1**	**2.9**	**1.6**	4.3	4.2
L4	**2.7**	4.8	**2.9**	3.3	**2.7**	**1.2**	3.2	**1.5**	3.9	4.0	**2.3**	**2.2**
L5	**1.2**	**1.4**	**1.2**	**0.7**	**1.1**	4.2	6.5	**2.4**	3.3	3.6	**1.9**	**1.9**
L6	**1.1**	**2.1**	**0.6**	**1.1**	**1.1**	3.3	5.9	4.1	**3.0**	3.6	3.9	4.6
L7	**1.6**	3.7	**2.3**	3.4	4.3	5.6	4.7	**2.2**	**1.9**	**2.6**	**2.7**	3.2

The average accuracy of the A-weighted SPL predictions, $A_{L,A}$, was used to simplify the comparison of the SPL models. It was expected that the prediction accuracy is within certain limits in both short and long distances from the sound source. Thus, the prediction accuracies in the measurement points with various distances were arithmetically averaged.

The average accuracy of the RT predictions, A_T, was also used to simplify the comparison of the RT models, though, the accuracy in 125 Hz was a little worse than in the higher octave bands. Table VIII shows that the average prediction accuracies in the octave bands exceed the 20% limit. That is the reason for averaging prediction accuracies over all the octave bands 125–4000 Hz instead of determining average prediction accuracy only for the highest octave bands 1000–4000 Hz, where the average prediction accuracy, usually, is a little better.

The ray tracing model (ODEON 3.1) was used as a state of the art reference for the simple SPL and RT models. The accuracy of the A-weighted SPL predictions was good in seven of the eight studied cases. The accuracy was slightly above 3 dB in workplace 3 after the noise control. The ac-

Table VIII. The accuracy of the RT predictions in the octave bands 125–4000 Hz before and after the noise control for workplaces 1–4. The good values (under 10% error) are in bold, the unacceptable values (over 20% error) are in grey colour (RT was not accurately measured at 125 Hz in workplace 1 before the noise control).

	Workplace 1, before						Workplace 1, after					
	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	125 kHz	250 kHz	500 Hz	1 kHz	2 kHz	4 kHz
raytracing	...	1.5	**0.2**	**0.2**	0.6	0.5	0.4	0.5	0.7	**0.4**	**0.1**	**0.1**
T1	...	0.9	1.0	1.9	3.4	4.1	**0.2**	**0.2**	0.7	1.5	2.9	3.6
T2	...	0.9	0.8	1.8	3.3	4.1	**0.2**	**0.2**	**0.5**	1.4	2.8	3.6
T3	...	0.9	1.2	2.1	3.6	4.2	**0.2**	**0.2**	0.9	1.7	3.1	3.6
T4	...	1.0	0.5	1.3	1.8	2.2	**0.3**	**0.1**	**0.2**	0.9	1.3	1.7
T5	...	0.8	0.8	1.9	3.4	4.2	**0.2**	**0.2**	**0.5**	1.5	2.9	3.7
T6	...	1.2	0.4	1.5	3.0	3.9	0.4	**0.1**	**0.1**	1.1	2.5	3.3
T7	...	**0.5**	1.2	2.2	3.7	4.6	**0.2**	0.6	0.9	1.8	3.2	4.0
10% limit	...	0.5	0.4	0.4	0.4	0.2	0.3	0.4	0.5	0.5	0.4	0.3

	Workplace 2, before						Workplace 2, after					
	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	125 kHz	250 kHz	500 Hz	1 kHz	2 kHz	4 kHz
raytracing	0.4	0.3	0.3	0.5	0.5	0.6	**0.1**	0.4	0.3	0.3	0.3	0.3
T1	17.2	15.4	11.5	8.3	7.9	4.7	0.8	0.5	0.5	0.4	0.4	0.3
T2	2.8	2.7	2.6	2.1	2.1	1.9	0.4	0.5	0.5	0.4	0.4	0.3
T3	27.5	25.9	17.7	12.6	12.3	6.7	1.2	0.4	0.4	0.4	0.4	0.3
T4	0.9	0.8	0.6	0.4	**0.2**	**0.1**	0.6	0.5	0.3	0.2	0.2	0.2
T5	1.9	1.8	1.8	1.5	1.5	1.4	0.3	0.5	0.5	0.5	0.5	0.4
T6	1.1	1.0	0.9	1.0	0.9	0.5	0.7	0.7	0.7	0.6	0.6	0.5
T7	3.0	2.9	2.8	2.3	2.3	2.1	0.6	0.3	0.2	0.2	0.2	**0.1**
10% limit	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1

	Workplace 3, before						Workplace 3, after					
	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	125 kHz	250 kHz	500 Hz	1 kHz	2 kHz	4 kHz
raytracing	1.1	0.5	**0.3**	0.5	0.6	0.4	1.1	1.0	**0.1**	**0.1**	0.2	0.3
T1	1.1	**0.0**	0.4	**0.1**	0.6	1.6	1.0	0.8	0.3	0.3	**0.1**	0.3
T2	0.8	**0.3**	0.7	0.5	**0.2**	1.4	0.7	0.6	0.4	0.4	0.2	0.2
T3	2.3	0.8	0.6	0.7	1.2	1.9	2.2	1.6	0.7	0.4	0.4	0.6
T4	**0.2**	**0.3**	**0.1**	**0.3**	0.5	0.7	**0.2**	0.5	0.8	1.2	1.2	0.9
T5	0.8	**0.3**	0.9	0.7	**0.0**	1.3	0.7	0.5	0.5	0.6	0.3	**0.0**
T6	0.5	0.6	1.5	1.4	0.5	1.1	0.5	**0.2**	0.9	1.0	0.7	0.5
T7	1.2	**0.1**	0.4	**0.2**	0.5	1.8	1.1	0.9	**0.1**	**0.1**	**0.1**	0.5
10% limit	0.2	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.1	0.1

	Workplace 4, before						Workplace 4, after					
	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	125 kHz	250 kHz	500 Hz	1 kHz	2 kHz	4 kHz
raytracing	1.5	1.1	1.2	**0.3**	0.8	0.7	1.3	0.8	0.7	0.5	0.4	**0.1**
T1	2.8	2.0	2.7	3.5	4.6	9.4	4.5	1.7	0.3	**0.1**	**0.1**	0.2
T2	1.5	1.4	2.3	3.1	4.3	9.0	3.4	1.4	**0.1**	0.2	**0.1**	**0.0**
T3	5.0	2.8	3.3	4.0	4.9	9.7	6.7	2.7	1.8	1.7	1.2	1.5
T4	1.5	1.1	1.3	1.1	**0.3**	1.4	0.8	0.4	0.4	0.4	0.2	0.2
T5	1.2	1.2	2.2	3.0	4.2	8.7	3.2	1.4	**0.0**	0.3	0.2	**0.1**
T6	1.0	1.1	2.1	2.9	4.2	9.0	3.1	1.3	0.3	0.6	0.6	0.5
T7	1.7	1.6	2.5	3.2	4.5	9.2	3.6	1.6	0.3	**0.0**	**0.1**	0.2
10% limit	0.4	0.4	0.4	0.4	0.3	0.2	0.1	0.1	0.1	0.1	0.1	0.1

curacy of the RT predictions was good in one of the cases and acceptable in two of the cases. The highest prediction errors were in the 125 Hz octave band. This was expected, because methods based on geometrical acoustics are less accurate at low frequencies as shown in earlier round-robin tests [6, 8, 9]. Unfortunately, this applies also for the simple SPL and RT models that assume diffuse sound field i.e. statistical sound distribution in the room.

For the simple SPL and RT models the room geometries of the studied workrooms were heavily simplified, which

Table IX. The average accuracy and (standard deviation) of the A-weighted SPL predictions, $A_{L,A}$, before and after the noise control for workplaces 1–4. The good values (under 3 dB error) are in bold, the unacceptable values (over 6 dB error) are in grey colour.

Model	Workplace 1		Workplace 2		Workplace 3		Workplace 4	
	before	after	before	after	before	after	before	after
ray tracing	**1.0** (0.5)	**1.7** (1.1)	**0.9** (0.8)	**2.3** (1.1)	**2.7** (2.3)	3.1 (3.0)	**1.3** (1.0)	**2.2** (1.1)
L1	7.3 (2.7)	5.5 (3.3)	4.1 (1.3)	3.8 (0.8)	4.5 (1.9)	**1.3** (1.1)	9.2 (1.4)	4.9 (1.2)
L2	28.7 (19.1)	28.4 (19.2)	**0.4** (0.4)	7.7 (0.8)	17.3 (5.6)	17.2 (4.6)	**1.4** (0.5)	8.8 (1.1)
L3	**2.5** (1.0)	4.3 (1.4)	**2.1** (0.8)	3.2 (1.7)	**1.7** (2.0)	7.5 (1.8)	3.6 (1.4)	**1.7** (1.0)
L4	5.6 (0.9)	3.8 (1.3)	**0.5** (0.2)	**2.7** (0.8)	**2.7** (1.5)	**1.9** (1.3)	**2.9** (1.9)	**2.5** (1.6)
L5	**2.9** (0.9)	**1.4** (0.7)	3.5 (1.5)	**1.8** (0.7)	**1.8** (1.7)	**2.5** (1.6)	**0.9** (0.7)	**1.5** (1.3)
L6	**1.4** (1.0)	**2.2** (1.0)	7.1 (3.5)	3.9 (2.7)	**2.7** (2.2)	5.4 (3.7)	**1.0** (0.8)	3.5 (1.9)
L7	**2.3** (1.0)	**1.4** (0.6)	**2.4** (1.0)	**2.1** (1.3)	**2.0** (0.8)	3.4 (2.1)	3.5 (1.2)	**2.0** (1.5)

Table X. The average accuracy of the RT predictions, A_T, before and after the noise control for workplaces 1–4. The good values (under 10% error) are bold, the acceptable values (10–20% error) grey.

Model	Workplace 1		Workplace 2		Workplace 3		Workplace 4	
	before	after	before	after	before	after	before	after
ray tracing	0.61	**0.35**	0.42	0.27	0.56	0.46	0.92	0.63
T1	2.27	1.51	10.9	0.49	0.64	0.46	4.16	1.14
T2	2.17	1.43	2.34	0.43	0.66	0.41	3.58	0.87
T3	2.38	1.61	17.1	0.50	1.25	0.97	4.95	2.59
T4	1.38	0.77	0.50	0.34	0.34	0.80	1.13	0.39
T5	2.22	1.48	1.66	0.46	0.67	0.44	3.42	0.89
T6	1.98	1.25	0.89	0.65	0.91	0.63	3.40	1.04
T7	2.44	1.81	2.55	0.27	0.68	0.46	3.77	0.99

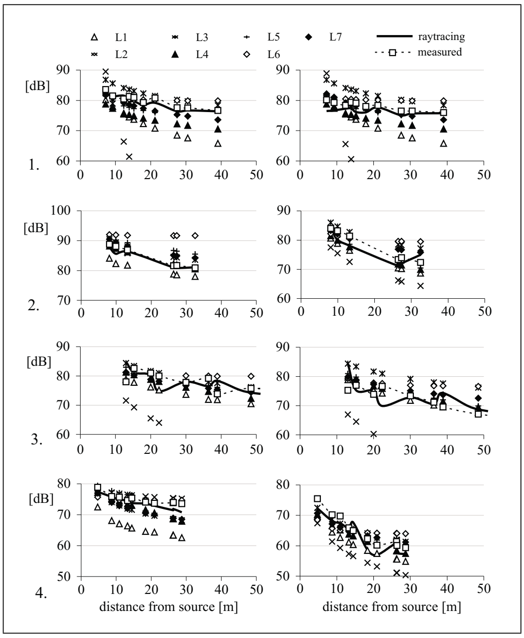

Figure 3. The predicted and the measured A-weighted SPL in the eight studied cases, four workplaces before (left) and after (right) the noise control.

increased the uncertainty of the predictions. Despite this, the prediction accuracy of SPL was good in models L4, L5 and L7 (Figure 5). Unfortunately, the prediction accuracy of RT was poor in all the models T1–T7 (Figure 4). This may imply that different absorption coefficients should be used for RT and SPL predictions, but for common practitioner it makes no sense. In the following, the prediction results of the simple SPL and RT models are discussed. A more detailed analysis is presented in [38].

The average accuracy of the A-weighted SPL predictions using model L1 was good only in one case, workplace 3 after the noise control. The model tends to underestimate the SPL in all the octave bands, except in workplaces 3 and 4 after the noise control. Unacceptable accuracy was found in two cases, workplaces 1 and 4 before the noise control, where rooms were large and contained very few sound-absorbing materials. The prediction accuracy was rather constant in each measurement point, but improved a little closer to the sound source (Figure 3). The accuracy was a little better at high octave bands. Thus, the accuracy of the A-weighted SPL predictions did not significantly depend on frequency.

The average accuracy of the A-weighted SPL predictions using model L2 was good in two cases, workplaces 2 and 4 before the noise control, but unacceptable in all the other cases. The model could not accurately predict SPL in the octave bands 125–2000 Hz (Table VII). The prediction accuracy in the octave bands was random and showed no frequency dependence. In workplaces 1 and

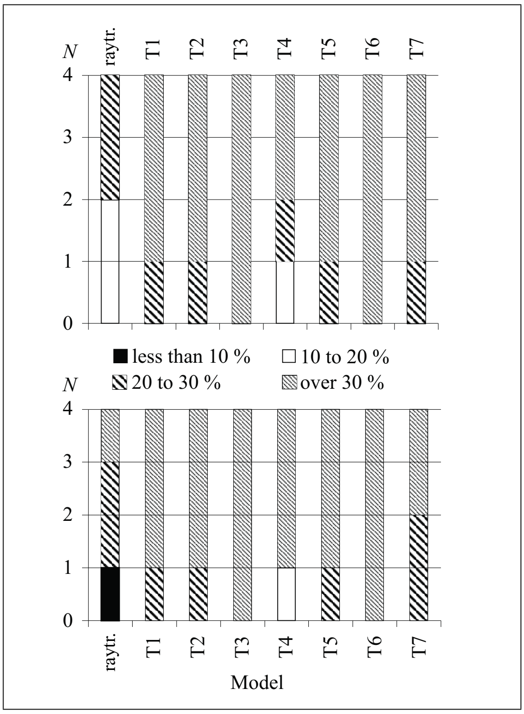

Figure 4. Summary of the prediction accuracy of the RT models. Occurrence of good (black), acceptable (white) and unacceptable (patterns) predictions in the eight studied cases, four workplaces before (upper figure) and after (lower figure) the noise control.

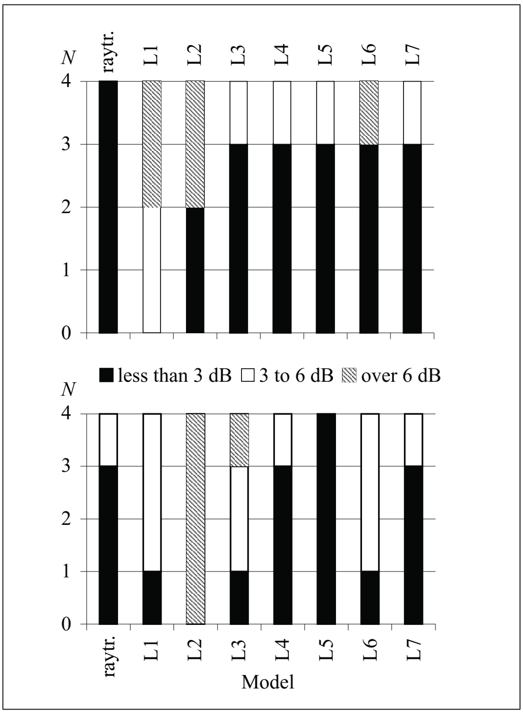

Figure 5. Summary of the prediction accuracy of the SPL models. Occurrence of good (black), acceptable (white) and unacceptable (pattern) predictions in the eight studied cases, four workplaces before (upper figure) and after (lower figure) the noise control.

3, the model failed completely, because of exceptionally large room height. In workplace 1, the model predicted even negative SPL values in the octave bands 125–500 Hz. The coefficients C_{s2}, C_{s3}, C_{i2}, and C_{i3} do not work in very high rooms. In Figure 3, it is clearly shown, how the SPL decreased very steeply as the distance from the sound source increased. This is alarming, because the implementation of model L2 was successfully verified using the data presented in [20] and [21] (Figure 2). Indeed, Dance mentioned that the model gave inconsistent results when the input parameters fell outside the empirical data set [20]. Hodgson also noted that the empirical models were inaccurate in cases for which the sound field is quite diffuse and reverberant [21]. Therefore, model L2 should be used only in long and flat workrooms that are similar to those used in the development of the model. Such restrictions also apply to models L3 and T4 which have been developed using empirical data.

The average accuracy of the A-weighted SPL predictions using model L3 was good in four cases and unacceptable in one case, workplace 3 after the noise control. The model tended to predict too high SPL (Figure 3). In the octave bands, the prediction accuracy was rather constant, but deteriorated a little in the octave bands 1 kHz–4 kHz. In workplace 3 after the noise control, this led to an unacceptable accuracy in the predictions of the A-weighted SPL. In workplaces 3 and 4, distance from the sound source also affected the prediction accuracy. Although, model L3 was based on empirical data as model L2, it was considerably more accurate and more robust than model L2 in the eight studied cases.

The average accuracy of the A-weighted SPL predictions using model L4 was good in six cases and acceptable in two cases. The model predicted too low SPL in four of the cases (Figure 3). The prediction accuracy varied more in workplaces 3 and 4 as the distance from the sound source increased. In the octave bands, the prediction accuracy showed no clear frequency dependency. The average accuracy was poor in workplace 1, because the noise control measure was a high screen around the sound source, a measure which cannot be taken into account, accurately, with any of the SPL models L1–L7. In workplaces 3 and 4, the average accuracy of the predicted A-weighted SPL remained acceptable, though the variation between the measurement points was rather large in the octave bands.

The average accuracy of the A-weighted SPL predictions using model L5 was good in seven cases and acceptable in one case, workplace 2 before the noise control. In the octave bands the prediction accuracy was rather constant, but deteriorated in the octave bands 125 Hz and

250 Hz (Table VII). However, the accuracy of the A-weighted SPL predictions was acceptable, because the 125 Hz octave band results are less significant for the A-weighted SPL. The distance from the sound source had a little effect on the prediction accuracy except in workplace 3 and workplace 4 (after).

The average accuracy of the A-weighted SPL predictions using model L6 was good in four cases and unacceptable in one case, workplace 2 before the noise control. In the octave bands the prediction accuracy varied a little and it deteriorated in the lowest and the highest octave bands (Table VII). The distance from the sound source had a significant effect on prediction error, since the assumed diffuse sound field sustained constant SPL after a certain distance that depended on the total absorption area. Thus, the model predicted too high SPL in the measurement points far away from the sound source (Figure 3). This model was the only one that could not predict the A-weighted SPL acceptably in workplace 2 before the noise control. The reason can be seen in Figure 3, where all the other SPL curves descend as expected, but model L6 predicts almost constant SPL.

The average accuracy of the A-weighted SPL predictions using model L7 was good in six cases and acceptable in two cases, Workplace 3 after and workplace 4 before the noise control. In the octave bands the prediction accuracy was rather constant, but deteriorated a little in the lowest octave band except in workplaces 3 and 4, where the prediction accuracy varied more strongly (Table VII). However, the accuracy of the A-weighted SPL predictions was not impaired by this. The prediction accuracy depended a little on the distance from the sound source (Figure 3). This model was more accurate than model L6, though both the models assume diffuse sound field. Evidently, the inclusion of air absorption into the model improved the prediction accuracy considerably.

According to Figure 5, the most accurate simple SPL models were L4, L5 and L7. The accuracy of these was almost comparable to the ray-tracing method in the studied cases. These findings agree with the conclusions presented by Hodgson [12]. These models have been analytically derived and they assume that the room is box-shaped, the sound field is semi-diffuse, and the sound source is constant. These models do not have fitting height or fitting density as input parameters, but the effect of fittings could be taken into account by adjusting the average absorption coefficient. The model of Osipov *et al.*. (L5) was the most promising, because it was rather easy to implement and provided acceptable results in all the studied cases. The SPL models of Kuttruff (L4) and Thompson *et al.* (L7) were almost as accurate and could also be used for noise control design in industrial workrooms.

The accuracy of the RT models is summarized in Figure 4. The accuracy of the ray tracing predictions was acceptable only in three cases. In the rest five cases the prediction accuracy was not acceptable (Table VIII). The accuracy of the simple RT model T4 was almost comparable to the ray-tracing method in workplaces 2, 3 and 4 before noise control. The accuracy was acceptable in two cases, but model T4 also showed unacceptable accuracies in the rest six cases. Considering these results the benefit from the use of sophisticated ray tracing models to predict only RT in workrooms is questionable. Certainly, when detailed analysis of noise control measures or e.g. predicted impulse responses are required, hybrid ray tracing and image sound source modeling is, currently, the most accurate way of doing so. However, it must be mentioned that RT is not the most important acoustic descriptor in the industrial workplaces. Therefore, the SPL prediction models aimed for industrial workplaces are preferred.

It was expected that the simple RT models could not work in complex industrial workrooms as accurately as in e.g. class rooms. The accuracies of the RT models T1, T2, T3, T5 T6 and T7 were not acceptable. However, it was unexpected that in the cases before the noise control, where surfaces were acoustically hard, average absorption coefficients were low, and high reverberation times existed, the accuracy of the RT models was so poor. The RT models T1 and T3 produced exceptionally high errors in workplace 2. One obvious reason for this was the fact that the models were intended for rather small rooms with one or more sound-absorbing surfaces, not for large industrial workrooms with low sound absorption.

In workplace 4 before the noise control, the accuracy of the RT models was unacceptable. The room was empty and all the models, except model T4, predicted too high RT (Table VI). Because the ray tracing model also predicted too high RT, it could be assumed that there was not enough sound absorption in the models i.e. the absorption coefficients were too small. However, with this amount of absorption model T4, which by default takes fittings into account, predicted too low RT in the octave bands 125–1000 Hz. This case demonstrates, how difficult it is to estimate correct absorption coefficients.

In the cases after the noise control, the amount of sound absorption was increased significantly and the RT models appeared to be more accurate in the higher octave bands, but the average accuracy, A_T, was still worse than 20%. The prediction accuracy $A_{T,f}$ was better than 10% only in a few random octave bands. An obvious reason for this is that the percentage limits allow less deviation when RT is low.

The number of studied cases ($N = 8$) is too low to make final judgements about the models. However, these case studies revealed major differences between the prediction models and provided insight to the parameters that affect the prediction results. It was also shown that the use of a model in a different purpose than originally intended can produce unexpected results. This inevitably means that the simple SPL or RT models cannot be directly used without knowledge on the background of the models.

These simple SPL and RT models could not accurately predict the attenuation effect of noise screens close to the sound sources or receivers. However, the attenuation effect of the screen in fairly reverberant workrooms was almost negligible. When noise screens were in such locations, they could be taken into account by increasing fitting height and density. For example, in workplace 4 before the noise control the room was empty and fitting height and fitting density was zero. After the noise control the room was fitted with several screens so that fitting density and fitting height changed correspondingly.

The most critical source of error in all room acoustic models is the estimation of the amount of sound absorption. In this study, the same absorption coefficients (Table II) were used with all the models T1–T7 and L1–L7, but to achieve better agreement with measurement results, some of the RT models seem to require different absorption coefficients. This complicates the estimation of the absorption coefficients.

Since the absorption coefficients of the materials are usually determined in reverberation chambers (diffuse field) using the Sabine formula (T7), the values may not be directly usable in the other RT or SPL models. In a real workroom, the surfaces are rarely made of only one material and completely clear of obstacles. This increases the difficulty of estimating the absorption coefficients.

Especially, when designing a new workroom it is not easy to know correct absorption coefficients, scattering coefficients, fitting densities and fitting heights in the workroom to be built. A highly potential source of error in room acoustic models is the effect of fittings. In sophisticated ray tracing models it is possible to include large obstacles, e.g. noise screens or large machines in the room geometry. However, in the simple models this is not possible. Thus, the fitting densities were visually observed in the workplace and determined using the layout drawings. The average fitting heights were measured. The fittings were taken into account as an individual input parameter only in the SPL models L2 and L3, and in the RT model T4. Unfortunately, these models were not very accurate in the studied cases. In the other SPL and RT models, the effect of the fittings should be included as additional absorption i.e. using higher absorption coefficients on one or more surfaces. The simple models also neglected the effect of the location of the sound-absorptive surfaces, because only the average absorption coefficients were used. The adjustments to absorption coefficients should be considered carefully in order to obtain reasonable prediction results.

There is a long history of using RT as a design parameter in the room acoustical noise control. Another parameter, the rate of spatial decay of sound pressure levels per distance doubling, DL_2, has been described e.g. in the standards ISO 14257 and ISO/NP 3382-3 [39, 40]. Some typical DL_2 values for industrial workrooms has been presented, already, in ISO 11690-2 [2]. Recently, DL_2 was found very useful for describing perceived room acoustical conditions in open-plan offices [41, 42], where DL_2 reacted more logically to the room acoustical changes than RT.

Sophisticated room acoustic modeling programs automatically calculate DL_2, but the effect of fittings on the predicted DL_2 results is not explicitly known. However, it would be very tempting to determine DL_2 easily and rapidly using a simple SPL model. Indeed, the slope term in the SPL models L2 and L3 is such a measure. The use of DL_2 instead of RT should be encouraged, because DL_2 shows directly how the SPL attenuates spatially in the workroom. The workers' experience of the noisy environment would be better described using spatial sound attenuation (DL_2) than local temporal sound attenuation (RT). When the sound power levels of the noise sources are known, a fast SPL model would enable real-time noise level predictions. The noise level results are even more comprehensible as they describe the workers' exposure to noise. The practical outcome of this work is a simple prediction tool that implements the SPL prediction model L5. The tool is freely available in http://www.ttl.fi/ivak [43].

8. Conclusions

These results encourage the use of simple SPL models in noise level predictions when rapid calculations are preferred and less exact results are accepted. However, in more detailed or complex room acoustic design, sophisticated room acoustic models are recommended. The use of simple RT models in predicting the effects of noise control methods includes a high risk of uncertainty, if not used by a person with adequate knowledge on room acoustics. Therefore, the effect of noise control should be predicted using the SPL models. The use of SPL instead of RT as the main room acoustic descriptor is encouraged, because it describes better the perceived acoustic environment. In conclusion, the simple models L4, L5 or L7 appear to be the most suitable simple room acoustic models for noise control design in industrial workplaces.

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