Prediction of sound insulation in buildings: a tool to improve the acoustic quality

Eddy Gerretsen
TNO TPD, Delft, The Netherlands; Email: gerretsen@tpd.tno.nl

Introduction

Noise from neighbours is an important item in the acoustic climate in which we live and work. And yet the requirements remain essentially the same as fifty years ago, though the noise situation in and around dwellings has changed. In the past the acoustic performance of a building design could largely be based on the experience gained from existing buildings and the needed knowledge could be developed on the basis of field measurements. But nowadays the building industry is moving more and more towards light and sustainable constructions and the applied materials and methods are changing more quickly. These developments call for a higher acoustic performance level of buildings and for new tools to evaluate and improve this in the design stage.

Short historic overview

To describe and interpret the current situation in Building Acoustics, it is useful to look back in time and see what has happened the past decades. Though the developments have not been identical for all (European) countries, the trend has been quite the same. So the Dutch situation will be used to sketch the global picture.

1950

In the beginning of the fifties the first proposals were formulated for the acoustic requirements in buildings. Both the expression of the desired performance in a single number as well as the means to achieve that performance in the field got some attention. It was in this period that the first International Congress on Acoustics was held in Delft, with a symposium on sound insulation where presentations were given by Kosten, Cremer and Gösele [1]. Both theoretical and practical insight in the sound transmission through building elements and buildings grew in that period.

1960

In was only in the sixties that a final version of the standard NEN 1070 was published with requirements for buildings, measurement methods to determine the performance in the field and guidelines on how to build dwellings that could fulfil the requirements. The reference curves used to derive the single number ratings were the same as the *Sollkurven* proposed in Germany, though the procedure to derive the single number rating was different. However, the applicability of that curve for airborne sound was first checked by a study on *My neighbours Radio* [2], with a positive conclusion.

1970

Although the requirements were in force on the local level for some years now, the results of a study showed that only 25% of the new dwellings fulfilled the requirements for airborne and impact sound. Though this was not a real surprise, it was disappointing. It seemed that impact sound was judged differently by people and on the other hand the builders and consultants understood the sound transmission insufficiently. More field measurements were performed on the common types of buildings, studies were started to develop a new rating system for impact sound and to improve knowledge about sound transmission in buildings. Especially flanking transmission and transmission at junctions [3], [4]. The standard NEN 1070 was renewed just giving the measurement methods and requirements. More extensive guidelines were in preparation as separate documents.

1980

In the eighties the activities were largely focussed on transferring the newly gained knowledge to the building industry and local authorities. Practical guidelines were produced for the common building practice, based on practical experience and the new prediction models for sound transmission. Presentations were given for various groups involved in the process. And this had some success. At the end of this period it showed that now about 90% of the new dwellings fulfilled the requirements and stupid mistakes, like using heavy but porous bricks for party walls, had become rare.

1990

Based on the standard legal minimum requirements were specified. This was done in a somewhat new way to which the building industry had to adjust. But after a while the majority of new dwellings again fulfilled these requirements. The common building practice apparently was acoustically under control. Yet the number of people annoyed did not really reduce, it was still 15%-20% highly annoyed by noise from their neighbours. It seems that the success in meeting the requirements was counter balanced by an increase in the amount of sound sources in dwellings and the expectation of people. In this period the focus is widened to Europe through the CPD [5], the foundation of CEN/TC126 'Building Acoustics' and the start of the working group for European Building Acoustics transmission models (EN 12354).

2000

And just when the building industry knows 'the game', knows how to built according to the regulations, 'the rules of the game' are changed: building is changing and there is a clear call for a higher acoustic quality. This call for a higher acoustic quality is serviced in the Netherlands and elsewhere by new (versions of) standards, specifying different classes of acoustic quality, not only minimum requirements. These new challenges to the building industry and the acoustic world will be discussed in the next paragraphs.

Topics and trends in building

There is a trend to concentrate various functions in the built-up environment - the compact city - bringing living, working, shopping, entertaining and transportation close to each other. It is clear that such a concentration of various functions and various noise sources has acoustic consequences.

In the buildings itself more and more technical installations are applied - smart buildings - for energy conservation, heating and airconditioning or for the comfort of the inhabitants. Again more potential sound sources than before. The aim for more sustainable buildings effects the building methods and materials used. More lightweight and prefabricated elements are used. Building becomes more and more assembling.

Most of these trends threaten the acoustic climate and certainly in combination. More noise sources close to our dwellings, where we desire a quite atmosphere. More equipment in dwellings, mounted on lighter building elements, thus exiting more structure-borne sound. And this itself is in contrast with the clear desire for a more quiet living and working environment, a higher acoustic quality.

In order to cope with these trends it is no longer possible to base the building designs and building methods just on past experience. Furthermore, these methods and applied materials change faster than in the past, making it impossible to gain knowledge from buildings in time. Thus the building industry has to change from a 'trial-and-error' approach to optimising building designs and construction details in an early stage. To this end the acoustic simulation of building designs becomes more and more important, as it is already a long time in other industries. Therefore it is essential to develop acoustic prediction models for buildings. At the same time the appropriate measurement methods need to be available to characterise the acoustic performance of building elements in a way that is relevant for such models. This coincides nicely with the standardization activities in CEN.

Acoustic quality

The (legal) acoustic requirements are essentially still the same as fifty years ago. Yet the world has changed. Realizing buildings that fulfil those requirements was a challenge, but nowadays a higher acoustic quality should be required and could be realised. In the Netherlands as well as elsewhere an effort has been made to develop a rating system for different classes of acoustic quality [6], [7], [8], [9]. In the Dutch system the acoustic performance for each aspect (airborne, impact, outdoor and equipment noise) can be expressed in a rating level, taking into account the type of sound and subjective judgements, leading to a quality number k. This quality number is for all these aspects also globally related to the percentage of people (highly) annoyed; see Figure 1.

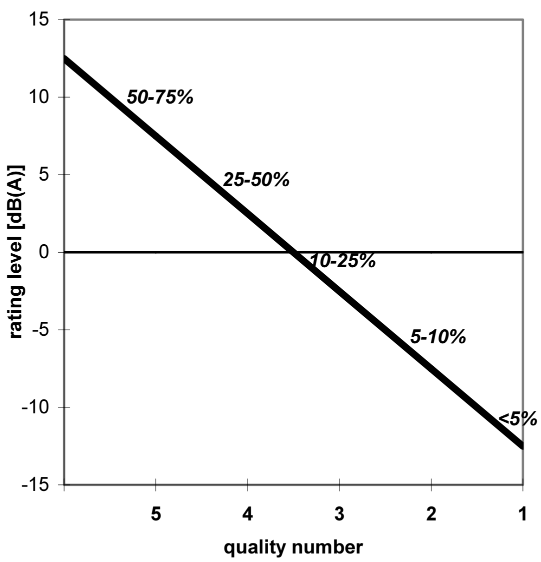

Figure 1: Global relation between the rating level for various sources and the subjective quality expressed in a quality number; for each number an indication is given about the percentages of people annoyed.

The current legal requirements correspond with the quality number k = 3 for all aspects, so a Acoustic quality class III. One could say that this is apparently considered as *'sufficient'*, the standard specifies that this class *'gives protection against unbearable disturbance under normal behaviour of the occupants, bearing in mind the neighbours'*. At least one class higher quality (class II) would be desirable, which could be called *'good'*, giving *'normally a good protection against intruding sound without too much restraints on behaviour of the occupants'*. As maximum one higher class (I) is specified, just reachable with practical means, and two lower classes than the legal minimum, spanning the allowable legal deviations in case of renovations.

So class II would be the preferred acoustic quality for future sustainable buildings and as an example Table 1 indicates the corresponding requirement for airborne sound insulation between dwellings. This is compared with the requirements specified for the corresponding quality in the German and Swedish standard [6], [7]. For comparison also the required sound insulation for a lower class is given in the table, which is globally the legal quality level in these countries.

Country, standard, quantity	*'sufficient'* I or 3 or C	*'good'* II or 2 or B
D, VDI 4100 R'_w	53-57	56-63
NL, NEN 1070 $D_{nT,A}$ $=D_{nT,w}+C$	52	57
S, SS 025267 $R'_w(+C_{50})$	52	56

Table 1: Requirements for airborne sound.

The table indicates that the quality levels in the different documents are reasonably comparable, though quantities and rating system are different. In Germany the requirements within a quality class are higher for certain types of dwellings, up to one class compared to the other systems, while in Sweden the lower frequencies are included (up from 50 Hz), but for the higher quality classes only.

So the preferred acoustic quality *'good'* requires about 5 dB better insulation than the current legal level. This is of course possible but does require improved building designs, details and accuracy of production. Prediction models - simulation models - are an essential tool in improving and optimising building designs.

European prediction models

Background

The European standardisation activities for Building Acoustics started from the CPD [5] within CEN/TC126 'Building Acoustic'. The main aim of the CPD is the free trade of building products in Europe and for that purpose the products should be fit to be used in creating buildings that fulfil certain essential requirements. Acoustics is one of these essential requirements. The acoustic performance of products follows from standardized measurement methods. To see if they are fit to be used, the acoustic performance of products needs to be related to the acoustic performance of buildings. Hence the need to create prediction models, the task of working group 2 of CEN/TC126.

The essential requirement 'protection against noise' concerns six acoustic aspects, for each of which a prediction model is to be prepared. Table 2 gives an overview of these aspects, the parts of the standard (EN 12354) that covers that aspect and the year in which a first version is published or probably will be published. We can see that four parts have already been published (airborne and impact sound, insulation and radiation of facades) and are also available as national standard (i.e NEN-EN 12354-1 or DIN-EN 12354-1 or NF-EN 12354 -1, etc.) [10], [11], [12], [13].The part on sound absorption is finished and will be published this year [14], but the work on part 5 on noise from service equipment in buildings has just been started. And that will be a real hard job, not only because it involves such a large variety of systems and equipment, but mainly because the structure-borne sound excitation by sources is a difficult subject where many questions still have to be solved [16].

Acoustic aspect	EN 12354 part	year
Airborne sound insulation	1	2000
Impact sound insulation	2	2000
Façade insulation	3	2000
Façade sound radiation	4	2000
Service equipment sound	5	>2005
Absorption in rooms	6	2003

Table 2: Overview of EN 12354 parts and dates.

While preparing a prediction model, it becomes clearer than before what kind of input data actually is needed for such a prediction. And for the results of a prediction, the input data is at least as important as the model itself. For some types of input data the appropriate quantities and measurement methods already are available, like the measurement of sound insulation of walls or the impact insulation of floors (although even here the development of the prediction models gave rise to new ideas about improving those measurement methods as we will see). For other types that is not the case and the prediction model indicates what type of data and measurement method is actually needed. That concerns for instance junctions between building elements [15], but also the characterisation of sources of structure-borne sound. Those methods are developed by other working groups within CEN and/or ISO, often in close cooperation with (members of) WG2.

For this paper we will concentrate on the model for airborne sound transmission in buildings. The approach for impact sound transmission is largely the same, while the models for the facade and for absorption are based on already more commonly used models, although the opportunity is used to make those models more general, where possible.

Airborne sound transmission

Choice of approach

At the start of the work on prediction models a small comparison was made between various models available in the various countries. Some methods used frequency bands like octaves and others just single number ratings like R_w. Building situations were used that were typical for those various countries and as far as possible the reference was measured results. The outcome was quite disappointing even for these simple situations. The deviations varied from 7 dB too low to 8 dB too high predicted sound insulation, while the standard deviation for each situation was 3 dB or more. In some cases the result looked quite accurate. For instance for two living rooms with a 460 kg/m^2 party wall and mostly heavy walls and ceiling the measured result of R'_w= 54 dB, was accurately predicted by both the simple French and German model [17], [18]. However, the sound insulation assumed for the party wall in these two models differed by as much as 7 dB! So if indeed measured input data would have been used, that would be the difference in outcome. It became also clear that additional linings were not always treated correctly with the models using single number rating numbers. Hence it was decided that the working group should develop a model for frequency bands that had a physical basis rather than an empirical one. The basis for such a model was already available, thanks to the work done in several countries since the fifties.

Derivation of the transmission model

The chosen approach is to consider the transmission between rooms to take place along different independent structure-borne sound paths between source and receiver room, considering only bending waves (see Figure 2). The velocity of the excited element in the source room can be deduced from the sound reduction index R of that element (ratio of radiated to incident sound power), realising that the radiated power follows from the velocity v^2 and the radiation efficiency σ. The velocity level of the element at the receiver side follows from the velocity reduction over the junctions ($D_{v,ij} = 10\lg v_i^2 / v_j^2$) and finally the radiated sound power from the velocity, area and radiation efficiency σ at the receiver side element. This gives eq. 1 for the flanking sound reduction index for the path from element i in the source room to element j in the receiver room, the index being related to the area S_s of the common separation wall. The basis for this approach was given already by Gösele [19].

$$R_{ij} = R_i + D_{v,ij} + 10\lg\frac{S_j}{S_s} + 10\lg\frac{\sigma_i}{\sigma_j} \qquad \text{eq. 1}$$

This looks like a rather simple relation but there are some ‘problems’ with it. The relation does not give the same result when applied to the opposite transmission direction (ji), the quantities R and D_v are no product properties but situation dependent, data for the radiation efficiencies are not readily available and the equation is only valid for frequencies above the critical frequency.

Possibilities to solve these problems have been studied since then [4], [20] and the main points are: to use the reciprocity relation (exchanging source and receiver position gives the same ratio of sound pressure p to source volume flow U, $p_j / U_i = p_i / U_j$, giving $R_{ij} = R_{ji}$, which also results in the vanishing of the σ's), to take into account the effect of damping of the elements and to correct were necessary the measured data for the forced transmission (R*) so the relations become valid in the whole frequency range. This results in eq. 2, with eq. 3 and eq. 4 to transfer the lab data to the relevant in-situ data by taking into account the structural reverberation time T_s.

$$R_{ij} = \frac{(R_i^* + R_j^*)}{2} + \overline{D_{ij}} + 10\lg\frac{S_s}{\sqrt{S_i S_j}} \qquad \text{eq. 2}$$

$$R^* = R_{lab}^* + 10\lg\frac{T_{s,lab}}{T_{s,situ}} \qquad \text{eq. 3}$$

$$\overline{D_{ij}} = K_{ij} - 10\lg\frac{l_{ij}}{\sqrt{a_i a_j}} ; a = \frac{2{,}2\pi^2 S}{c_o T_s}\sqrt{\frac{f_{ref}}{f}} \qquad \text{eq. 4}$$

The junction transmission is here described by the average of the velocity level differences in the two transmission direction ($\overline{D_{ij}} = (D_{v,ij} + D_{v,ji})/2$) which can be derived from a newly defined quantity, the vibration reduction index K_{ij}, that characterises the junction transmission as an invariant ‘product’ property. Actually, K_{ij} is defined by a turned around version of eq. 4 under standardized laboratory situations.

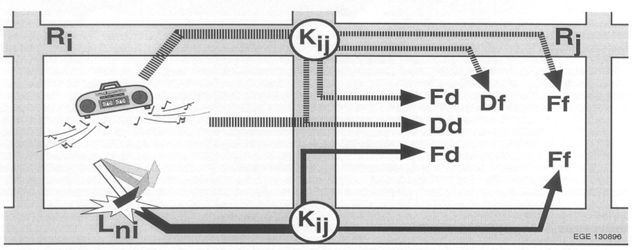

Figure 2: Illustration of direct (Dd) and flanking (Ff, Fd, Df) transmission path for airborne and impact sound transmission.

A demonstration of the fact that for flanking transmission only the resonant transmission is important is given in figure 3. It shows results of measurements of the direct transmission of a wall and of the flanking transmission without any junction effect of the same type of wall. It can clearly be seen that below the critical frequency the forced direct transmission (mass-law) gives a much lower sound reduction index, while otherwise the values are equivalent.

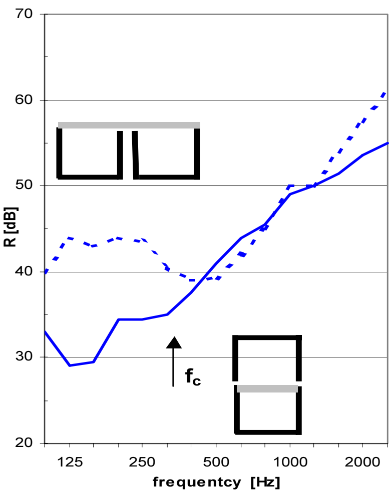

Figure 3: Sound reduction index for direct (___) and flanking (----) transmission; from [21].

The importance of the structural reverberation time and its dependence on the boundary condition of the elements has recently been demonstrated again in a German inter-laboratory comparison on the measurements of the sound reduction index of heavy walls in the laboratory [22]. Figures 4 and 5 give the results of this comparison with and without a standardization of the results to a fixed laboratory damping, as far as resonant transmission is concerned [23]. By standardizing by means of the structural reverberation time the variation reduced from σ = 2,3 dB to σ = 1,6 dB.

For the prediction model the structural reverberation time can be predicted from characteristics of the element and the surrounding structures. As a first estimation the structural reverberation times can also be considered to have a fixed value, leading to a simplified version as in eq. 5.

$$R_{ij} = \frac{(R^*_{lab,i} + R^*_{lab,j})}{2} + K_{ij} + 10\lg\frac{S_s}{l_{ij}} \qquad \text{eq. 5}$$

This equation could also be used for estimates of the flanking transmission on the basis of single number ratings of the quantities involved.

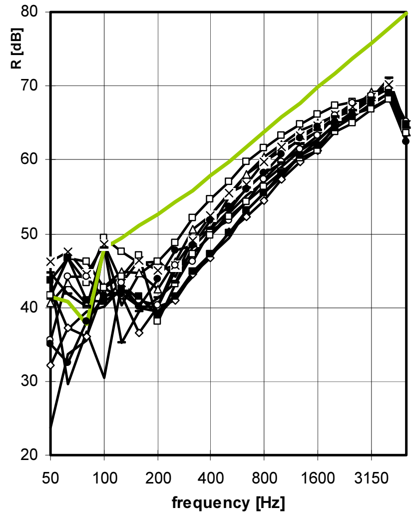

Figure 4: Measured sound reduction index of a 440 kg/m² wall in various laboratories with mass-law curve for comparison; from [22].

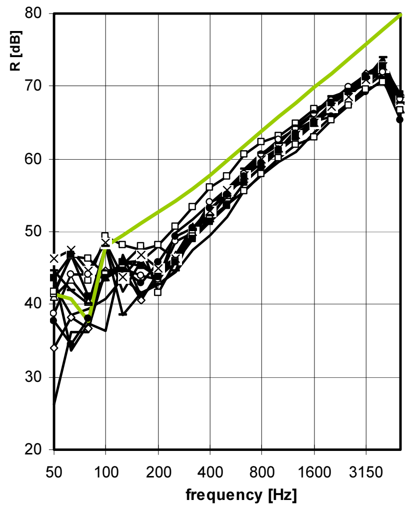

Figure 5: Results as in figure 4 after standardization to a typical laboratory structural reverberation time for resonant transmission; [23].

Impact sound transmission

The transmission of impact sound can be described in the same way as airborne sound, only the resulting velocity of the element that is excited by the tapping machine is derived differently. Also here a reciprocity relation can be applied, which in this case can be written as $F_i / p_j = U_j / v_i$ with the resulting pressure p due to the applied force F in the one direction and the resulting velocity v due to the volume flow U of the airborne sound source in the opposite direction. This leads to eq. 6, where the difference between the sound reduction indices replaces primarily the differences in radiation efficiency between the considered elements.

$$L_{n,ij} = L_{n,ii} + \frac{(R^*_j - R^*_i)}{2} - \overline{D_{ij}} + 10\lg\frac{S_i}{S_j} \qquad \text{eq. 6}$$

Also here the various quantities (R, L_n) for the elements and the junction need to be transferred from the lab to the in-situ situation by using the structural reverberation time.

SEA

Since the seventies als the Statistical Energy Analysis (SEA) has been applied to buildings, extending the possibilities over the years [24]. SEA provides a very general framework for sound transmission between coupled elements, including the possibility to consider other wave types than bending waves but with the restriction to resonant systems with sufficient modes per frequency band. In a building situation normally the walls, floors and rooms are considered as subsystems, each with an energy E. This energy is directly related to measurable quantities like squared-pressure or squared-velocity. The power flow in the system is related to these energies by the frequency and the, internal or coupling, loss factors η through $W = \omega\eta E$. The essence is that for each subsystem the power balance ($W_{in} = W_{out}$) can be specified, giving sufficient relations to solve for the subsystem energies if the reciprocity relation is applied. The reciprocity relation for the transmission between two subsystems relates the coupling loss factors in the two directions through the model density n of the subsystems: $n_1\eta_{12} = n_2\eta_{21}$. Thus solving the power balance system gives the energies or energy ratios of the subsystems, which can be expressed in quantities like the apparent sound reduction index between rooms R'.

Instead of solving the power balance it is also possible to consider transmission paths and sum the transmission by principally an infinite number of such paths to get the same result, as Craik shows [24]. Using this approach the flanking sound reduction index for such a transmission path can be written as in eq. 7.

$$R_{ij} = 10\lg \frac{\eta_i \eta_{i+1} \cdots \eta_j}{\eta_{1,i} \eta_{i,i+1} \cdots \eta_{j,2}} \frac{2{,}2 S_s}{0{,}16 V_1} \qquad \text{eq. 7}$$

Considering a single junction with only bending waves and applying the appropriate theoretical values for the loss factors it has been shown that this results is identical to eq.2 in combination with eq's 3 and 4 [4],[25]. Thus the models in EN 12354-1&-2 can be considered as a first-order approximation of a SEA model, in principle both with the same restrictions and assumptions.

The main advantages of applying SEA would be that it is easier to include more paths when needed and easier to include effects of other wave types. However, the advantages of the EN 12354 approach are a directer relation to known product quantities, an easier possibility to include in a comparable way other types of elements, like light, damped elements, the simple way to include the effect of additional layers and the direct insight in predominant transmission paths. An important issue for both methods is actually the same: how to get reliable input data describing accurately the coupling between elements. And since the physical basis is the same, the relevant quantities, K_{ij} and η_{21}, are directly related as given in eq. 8. So empirical or theoretical data can easily be used for both models.

$$K_{ij} = -10\lg \eta_{ij} \frac{\pi^2 S_i}{c_o l_{ij}} \sqrt{f f_{ref}} \sqrt{\frac{f_{ci}}{f_{cj}}} \qquad \text{eq. 8}$$

As indicated before, an important item nowadays is the developement of reliable and practical measurement methods for this type of quantities [15], [26].

Application of prediction models

As an example of calculation results with a computermodel based on EN 12354-1 figure 6 compares the measured standardized sound level difference D_{nT} between two living rooms with the calculated values. The party wall is a 265 mm calcium-silicate brick wall (465 kg/m^2). Adding a lining to the party wall with a laboratory improvement of ΔRw = 16 dB, results here in an improvement of only 3 dB (measured). The calculations agree quite good in both situations, so prediction befor applying the lining could have avoided the big disappointment for the occupants.

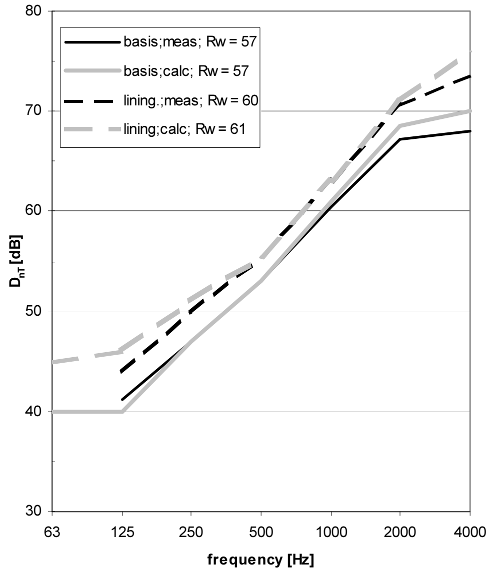

Figure 6: Measured and calculated sound level difference between living rooms with a 465 kg/m^2 party wall, without (basic) and with (lining) an additional lining (ΔR_w = 16 dB).

In general the accuracy of predictions depends on the complexity of the situation and the reliability of input data. It is rather impossible to give just one number to indicate the accuracy in general. From various studies, see for instance [27], on a variety of building types the following global picture emerges:

air-borne sound mean deviation = 0 to 2 dB, σ = 1,5 – 2,5 dB
impact sound mean deviation = 0 to 5 dB, σ = 2 – 5 dB

There seems to be a tendency that with the use of measured input data for homogeneous elements the predictions tend to overestimate slightly, while with theoretical values the predictions are on average correct. The larger deviations for impact sound are partly due to unreliable input data for floating floors (vertical transmission) and partly to the fact that for horizontal transmission the prediction is directly related to the input data for one junction only. The lower variations are comparable with the variations measured between nominally identical buildings that are often quoted as being typically in the order of $\sigma \approx 2$ dB.

For cases where accurate input data are not available, the prediction models can always be used for a parameter study. By varying the questionable input data, the importance of it in the total transmission can be verified.

Concluding remarks

In most Eurpean countries the current requirements for the acoustic quality of buildings are globally the same as those formulated over fifty years ago. But there is a clear tendency that people now ask for a higher acoustic quality in the living and working environment. However, various trends in the built-up environment (compact city) and in building technology (sustainable and smart building) threaten this desire rather than giving it new chances.

These developments call for optimised building designs, using acoustic simulation models and appropriate element data, rather than the usual ‘trial-and-error’ approach. In this respect the activities in the field of Building Acoustics within the European standardization organization come at the right moment.

A lot of work has already been done in the last decade, but still a lot is to be done. Current efforts should focus on the collection and determination of reliable input data, on gathering indications on the accuracy of prediction and on the development of models for the noise due to service equipment in buildings. That last item is still a huge task, especially the appropriate characterisation of equipment as source of structure-borne sound.

In these aspects we can all benefit from a common European approach. One Building Acoustic language instead of many local dialects helps the exchange of information and accelerates the developments. And that is necessary in order to realise a higher acoustic quality in future buildings.

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