Architectural Guidelines for Living Rooms, Classrooms, Offices, Sports Facilities and Restaurants

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Abstract [241] In general technical standards to establish the acoustical quality of a room are given in terms of the reverberation time. However, depending on room shape and dimensions (from 80 to 40,000 m^3), architectural function and acoustical use (single source versus multi-source), other acoustical numbers may be more adequate. In practice there is a variety of rooms and functions on one side and a set of available acoustical quality numbers (RT, SPL, G strength, absorption coefficient, C50, U50, STI, S/N, NR-values, etc.) on the other. They may be considered as the rows and columns of a (huge) table. It is the ultimate goal of our research to fill some of the cells in this table.

Since ray-tracing programs are not very accurate in predicting RT, the results are presented in a "G-RT-diagram", which has proven to be a powerful tool for comparison between measurements and calculations. In most cases the correlation found for G is higher than for RT. This is as expected, since ray-tracing models are based on sound energy propagation.

Preliminary architectural guidelines are given in mean absorption coefficients. They are more accurate than the reverberation time and are much easier to use by architects.

1 INTRODUCTION

When designing a room, an architect needs to know how to translate "acoustical quality demands" into "building design parameters". For the acoustical quality one should think in terms of "high speech intelligibility" or "low noise levels"; building design parameters are about architectural function, room dimensions, room shape and about the acoustical properties of the materials through the room (absorption coefficients, diffusion coefficients, location of materials). To connect acoustical quality and building design parameters, the reverberation time is widely used to assess acoustical quality. The present research at our Faculty of Architecture deals with two problems:

- The reverberation time was invented to express musical quality. However, when acoustical quality depends mainly on noise levels, the reverberation time may not be the best variable.
- Eventually, an architect wants his/her information about acoustical quality expressed in room shape plus the material properties of the room.

It is the aim of the present paper to deal with these problems for a few cases like sports facilities, classrooms, offices, etc. Spaces for music, theaters, etc, where the reverberation time was invented for, are excluded.

2 THEORETICAL BACKGROUND

2.1 Acoustical parameters used

There are many acoustical variables when music is involved [1]. The following parameters are used in our research. Some are the same as in music, some are related (C_{50} instead of C_{80}) and some are for speech intelligibility only and not found in music.

Reverberation time (RT): The oldest definition for the reverberation time is Sabine's. Since it has some disadvantages, quite some alternatives have been proposed, but they all have their specific disadvantages as well, so Sabine's definition is still widely used [2]. Sabine developed *RT* for music, but since then it has been used to assess noise levels as well.

SPL and Strength G: The sound pressure level and the strength are used to define the sound pressure level produced by a source in a room. By their nature they are more suited to predict noise levels in rooms than *RT*.

Absorption coefficient α: The absorption coefficient of a material is the most important variable for an architect. It may be given per material or as one mean value calculated over all surfaces within a room.

Diffusion coefficient: The diffusion coefficient of a material is a very important value in the design of concert halls. In our research project its role is less important. In theory it does not affect the total energy in a room, but it may affect the distribution of *G*-values through the room. It is also an important value to abate echoes and flutter echoes.

STI and C_{50}: The Speech Transmission Index and the "early to late ratio" C_{50} are used to describe the speech intelligibility in situations where reverberation may disturb the sound transmission. There are more variables and discussions are still going on [3]. On the other hand, measurements and calculations have shown [4] that the correlation between these variables is very high, and for architectural guidelines it is probably not very important which one is used.

S/N and NR-curves: In classrooms there is only one speaker; in offices two or more speakers may be active at the same time. In this second case one source is considered as "wanted" by a listener; the other sources are considered as "noise". However, noise is found in *every* case; even in a classroom there will be noise from the children, outdoor noise or from ventilation systems.
The signal to noise ratio *S/N* gives an indication about the differences in strength between source and noise; *NR*-curves are used to characterize the noise itself.

STI_in_noise and U_{50}: If there is a noise source present, *STI* and C_{50} give information that is often too optimistic. In this case it is better to incorporate noise in the acoustical variable.

Frequency: The influence of the frequency is neglected throughout this paper for brevity. In the remaining parts of this article the values are valid for the 500 Hz octave band only. Actually this is not allowed, since we (for example) found strange effects ourselves in classrooms where absorbing materials were used for low frequencies only. The acoustical quality was considered as "too harsh" and extra absorption for the high frequencies was needed.

For the architect the absorption coefficients of the materials are by far the most important values. In most cases these properties can be found in product documentations. Therefore it would be very convenient if acoustical standards were given in absorption coefficients as well. However, there is one big problem: to verify if an architect and product manufacturer have done their work properly, absorption coefficients must be measured if the room has been actually built. But in-situ measurement of absorption coefficients is very difficult and therefore the reverberation time is used on most occasions.

2.2 The absorption coefficient from measurements and computer calculations

The equation for the reverberation time used in this paper is Sabine's:

$$RT = \frac{0.161\,V}{\alpha S} \tag{1}$$

where V is the volume of the room and S the total surface. The value of α denotes the *mean* value of all absorption coefficients in a room.

The equation for the strength G is given as developed by Barron (see [5] for more information):

$$G = 31 + 10\log\left(\frac{Q}{4\pi r^2} + \frac{\exp\left(-0.04r/RT\right)}{\alpha S}\right) \tag{2}$$

The directivity of the source is denoted by Q, the source receiver distance by r. Equation (1) is less complicated than the second, since it does not depend on r. This is confirmed by many results from measurements: RT is fairly constant through a room, which may well have contributed to its popularity in legal standards. At first sight, equation (2) is not so useful in this respect since it depends on Q, r and RT. However, it can be shown that for one specific distance (the mean free path: $r = 4V/S$) equation (2) can be converted into:

$$G = 31 + 10\log\left(\frac{4(1-\alpha)}{\alpha S}\right) \tag{3}$$

Equations (1) and (3) may be used backwards to calculate α from measurements of RT and G respectively. Of course these values are theoretically the same, but below we will find measurement results where this is not the case.

If two or more sources are present in a room, from which one is "wanted", equations (2) and (3) can be used to calculate a signal to noise ratio. If this ratio is calculated as a function of increasing absorption, we find an increasing signal to noise ratio in any case. This might easily lead to the simple conclusion that the absorption should be as high as possible. There are a few reasons why this is not the best suggestion to an architect:

- It is unwanted from the architectural point of view to build anechoic chambers only. Besides, people feel "uneasy" in these rooms, so only a minimum value of α should be mentioned.
- Especially in classrooms the signal level itself may be too low. An optimum value is found at specific absorption coefficients.

2.3 Disadvantages of the reverberation time

There are two advantages when applying RT for measurements:
- It can be measured with quite simple equipment.
- It appears quite constant through a room.

Most other variables, mentioned earlier, require more complicated measuring equipment and software in order to generate a sweep or MLS signal. On the other hand, a laptop belongs to the standard equipment of the present-day acoustician. The measurement of G requires a separate measurement of the sound power output of the loudspeaker, plus its directivity. They must be measured in advance in an anechoic and a reverberation chamber.

Some *dis*advantages of the reverberation time are also easily found:

- The reverberation time is for music; is it useful to describe noisy environments?
- *RT* depends on the room's volume. In the Netherlands, for instance, one value of *RT* has been used for all sports facilities, although volumes may vary from 1000 to 30,000 m^3.
- *RT* gives little information about multi-source environments.
- Using ray-tracing models as an aid for the prediction of the acoustical quality of rooms, it is quite difficult to predict the reverberation time accurately from computer calculations.

The last topic is illustrated with an example. Figure 1 gives a drawing of a school gymnasium (figure 1, left). Measurements have been done (figure 1, center) and an attempt was made to repeat these in a computer model figure 1, right). The figures show the values of *G* and *RT* for all measured receiver positions. High *G*-levels indicate receiver positions close to the source. The full line in a diagram gives the theoretical values calculated with equations (1) and (3) with different values of the absorption coefficient. From the measurements one dot on this line can be estimated, which in turn corresponds with one particular absorption coefficient for that room.
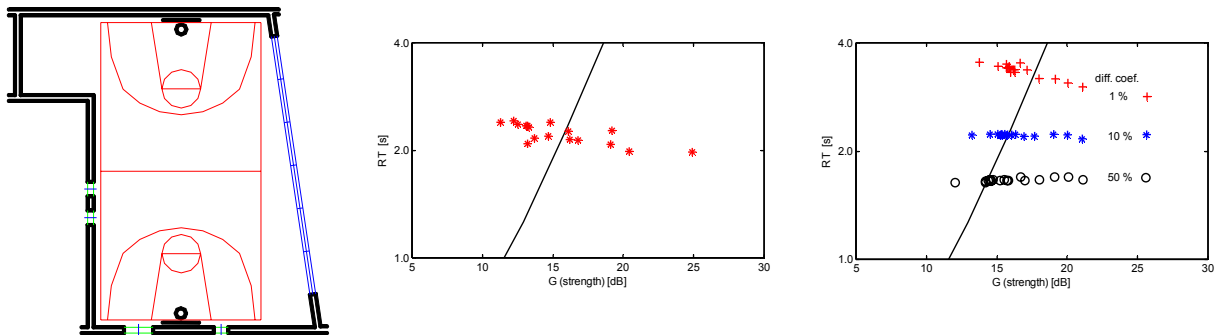

Figure 1: *Measurements (center) and computer calculations (right) in a gymnasium (left) of 21 × 12 × 5.5 m approximately. Frequency is 500 Hz. Diffusion coefficients used in the computer model are 1, 10 and 50%.*

The measurements show a small variance in *RT*-values. *G*-values have a much bigger spread, which is obvious since *G* varies with the source to receiver distance. However, when we look at receiver positions close to the mean free path, *G*-values are found very close to the full line.

From the measured *RT*-values, the mean absorption coefficient is calculated backwards as 0.12. This value was used as a starting value in a computer model made of the same situation. However, as can be seen in figure 1 (right), the computed results for *RT* may vary considerably (from 1.6 to more than 3 s). These values are influenced by a proper choice of the diffusion coefficients of the surfaces. The value of 10% is close to the measured value and hence it is often suggested by program builders and users. Actually, this is mainly to hide the flaws of computer programs.

Looking at the variations in *G* as a function of the diffusion coefficient, we find that these are much less depending on the diffusion factor. So, using *G* at the mean free path distance yields a much better estimation for α than *RT*. The reason is that ray tracing computer models calculate the *energy* through the room; and *G* is much more an energy variable than *RT*.

From similar graphs, it can be shown that the variations in C_{50}-values are as small as the variations in *G*, mainly because C_{50} is energy-based as well. The variations in *STI* are somewhat bigger, but they are never so big as the variations in *RT*.

3 PREFERRED VARIABLES FOR A FEW ROOMS

In this chapter we will do some suggestions about the preferred acoustical variables for a few different architectural spaces. For some spaces it is based on thorough investigations, in some cases results are only preliminary.

Sports facilities

The design rule for the acoustical quality in a sports facility is quite simple: increasing the mean absorption coefficient decreases G, which is the main value to determine the signal to noise ratio between the sound from a speaker and the background noise from other speakers and sporters. Dutch questionnaires in mid-size facilities (in the order of 5000 m^3) showed that the reverberation time should not exceed 1.5 s, which means that α should be at least 0.28. When the hall is much smaller (a gymnasium) or much bigger, $RT \leq 1.5$ s is not a good value since the hall's volume must be taken into account. It appears much more useful (especially for architects) to prescribe $\alpha \geq 0.28$ for *all* hall sizes [6, 7]. In practice, we think, a value $\alpha = 0.30$ is preferred to be used by architects. This value can easily be accomplished by absorption on the ceiling plus "some" absorption on the walls. Sabine's reverberation time is well suited to measure the hall when it is finished. When using ray tracing models in the design stage, the values for α can be derived from G-RT-diagrams like given in figure 1.

There can be quite some complaints about flutter echoes in sports facilities. Diffusion plus absorption on the walls may help, but there is another "trick". High absorption coefficients lead to steep decay curves, which make flutter echoes almost inaudible. In well-treated sports facilities strong single echoes can be heard, but repeated echoes vanish more or less automatically.

We found only minor influence of the location of absorbing materials. The total energy loss is the most important factor for G and it is mainly influenced by the total absorbing surface itself.

Classrooms

The variables *STI* and C_{50} are mostly used to describe the acoustical quality in classrooms, but legal standards are mainly given as RT-values. Maximum RT-values may be as high as 1.0 s (in the Netherlands, where classrooms are in the order of 150-250 m^3.) while other countries and authors prefer much lower values (0.4-0.6 s).

Measured and calculated *STI*-C_{50}-values are always high, unless a classroom is too reverberant ($RT \geq 1.2$ s), so speech intelligibility seems to be perfect in most cases. *STI*-C_{50}-values have their maximum close to the source; they tend to a constant level at bigger distances. *STI*-C_{50}-values also constantly increase with increasing absorption, so if *STI*-C_{50}-values should be used for assessment, the conclusion is that the absorption coefficient must be as high as possible.

But is an anechoic chamber the ideal place for teaching? The answer is no; teachers in highly absorptive rooms complain about not "reaching the back rows", The sound pressure level of the teacher's voice decreases with distance (equation 2) and therefore the difference between signal and noise is much higher in the front rows than in the back of the classroom. The teacher may raise his/her voice to reach the back rows, but then the levels in the front row are too high. Designing a classroom does not only mean that high *STI*-C_{50}-values must be accomplished, but the difference between the front and the back rows must be kept within certain limits as well. It can be shown (this will be done in a future article) that, in this case, it is more useful to use *STI_in_noise* and U_{50}-values instead of *STI*-C_{50}-values. It is also found that optimum absorption coefficients are in the order of 20 to 25%. For a common Dutch classroom (8×6×3 m) this corresponds with a reverberation

time in the order of 0.5-0.6 s. In a bigger "classroom" (12×9×4 m) as used for instruction in one of our University buildings, about the same optimum absorption coefficient is found, this time corresponding with $RT = 0.9$ s. The values measured in-situ are about 1.3 s.
In the smaller room a teacher has to raise his/her voice only very slightly; in the bigger room extra vocal effort is always required.

The given absorption coefficient can be used by an architect, but he/she must also consider where materials should be located. Bradley suggests [8] to "locate absorbing materials on the upper parts of the side and rear walls". It may improve U_{50} levels by 2 dB.

Offices and Living rooms

In Dutch standards a value of $RT = 0.8$ s is used for offices of all sizes. For an office with 78 m^3, this is equivalent to $\alpha = 14\%$, which is "too low" for a good acoustical climate. This value is found in an office with some absorption from people and furniture, but without absorption at the ceiling, the floor or the walls. Fortunately, an absorptive ceiling is more or less the design standard in a Dutch office, and the reverberation time drops down "automatically". Figure shows an example for a small office.
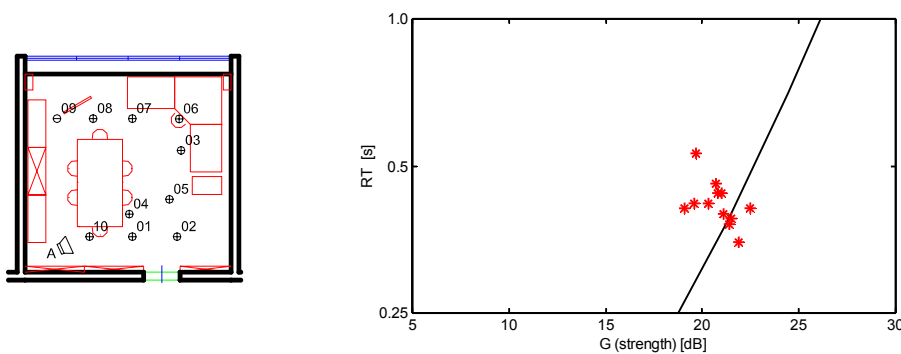

Figure 2: *G-RT-diagram measured in an office at 500 Hz. Office dimensions are 5.4×5.4×2.7 m. The ceiling has absorbing material. RT = 0.4 corresponds with α = 0.27.*

Actually, the method prescribing α-values as suggested for sports facilities, can be used in offices as well. The noise in an office is commonly less than in a sports facility and hence the demands don't have to be so severe. So, in our opinion, the architect has to design absorption coefficients in the order of 25% to attain a good acoustical quality with 20% as a minimum value.
Using the absorption coefficient as a design parameter means that RT-values in the order of 0.8 s are found for offices in the order of 400 m^3.
The design of open plan offices is too complicated for the average architect because two acoustical properties collide: speech intelligibility (the speaker must be understood by the persons listening) and speech privacy (a talk should *not* be heard). The intelligibility is benefited by high absorption coefficients; privacy requires low absorption. In fact it is impossible to solve both problems by absorption alone. Nevertheless absorption coefficients below 0.20 should be avoided, otherwise the speech intelligibility drops too much.
Room shape is another design parameter that has its influence. L- and U-shaped rooms reduce noise levels [5] and room height may help as well. Extra screening elements and even artificial noise (high ventilation levels, muzak, fountains, etc) are used by acoustic consultants to improve the speech privacy.

Restaurants

Big restaurants have the same properties and drawbacks as open plan offices, but higher noise levels and lower speech privacy can be allowed. Architects and restaurant managers sometimes seem to prefer low absorption values. In this case customers often will be shouting to the other people at the table. This is a normal human reaction but on the other hand: it doesn't help. If all customers in a restaurant should talk at a lower level (for instance 5 dB) it would decrease both the signal and the noise with the same amount and it wouldn't change anything.
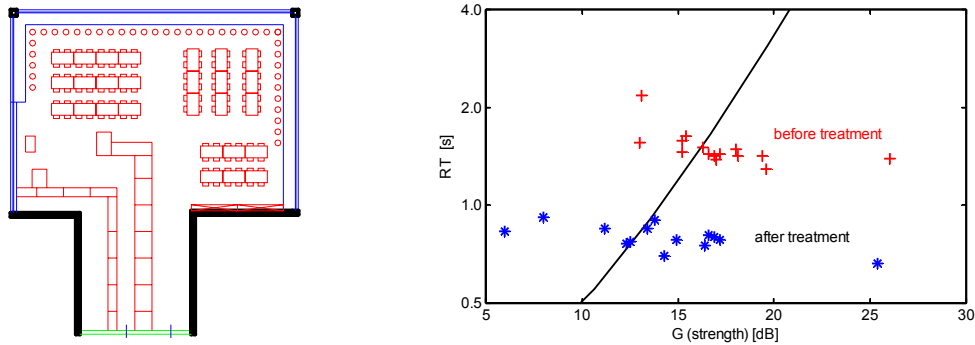

Figure 3: *G-RT-diagram for a restaurant before and after installing an absorptive ceiling.*

Nevertheless a good starting point for an architect is again $\alpha = 0.20$. It is illustrated in figure 3. The G and RT-values before treatment correspond with $\alpha = 0.14$. There were quite some complaints, so a new ceiling was installed. The material used was only "fair", so the absorption coefficient only increased to $\alpha = 0.20$. The situation has improved, but for a quiet restaurant higher values would be required.

Living rooms for mentally challenged people

One special branch of our research is to provide building design parameters for institutions for mentally challenged people. They differ from common living rooms as there live more people in a room [9]. Again the mean absorption coefficient is a very suitable to instruct the architect. The value, however, should be at least 0.30.
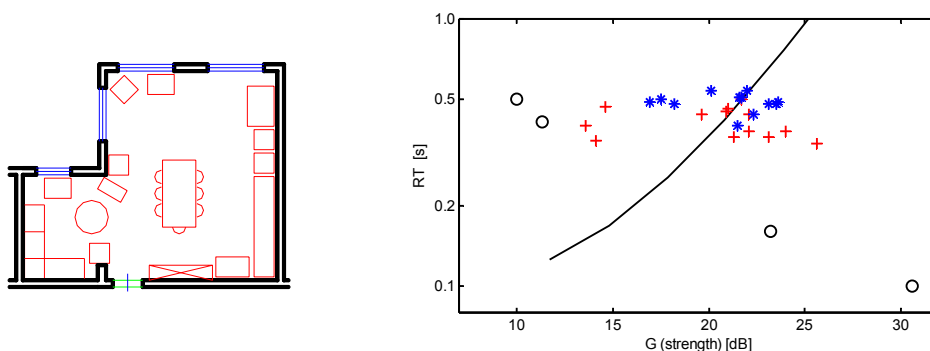

Figure 4: *G-RT-diagram measured in a living room at 500 Hz. Blue stars – empty room; Red crosses - Non equal absorption, sound source placed in the part with less absorption; Black circles - non equal absorption, with screening effect, sound source placed in the most absorptive part behind the screen.*

An extra solution may be the use of L-shaped and U-shaped rooms; ray tracing models predict an extra 3 dB "per corner" [5]. In measurements similar effects have been found, although they are a little bit less optimistic about the effects. Figure 4 gives the results for a (rather small) L-shaped room to illustrate the effects that occur. According to our measurements performed in the empty living room, where α was around 0.15, the influence of the corner was 3 dB on average. Addition of the absorption or furniture (α increased up to 0.30) in the room increased the influence of the corner to 6 dB. However, real acoustical improvement (to obtain the wanted signal to noise ratio) in such a multisource environment is found by the combination of reasonable location of the absorption plus screening elements. Then the measured sound reduction was 9 dB and more.

4 CONCLUSION

The preliminary study, as reported here, has highlighted the need for improving the guidelines for architects. Present guidelines are nearly always based on the reverberation time, which has some important drawbacks. From our research we can conclude that it is always recommended to measure or calculate the strength G as well and to present both values in a G-RT-diagram.

However, since G and RT not "building parameters", a translation to building practice is necessary. In practice the mean absorption coefficient appears an easy value as a starting point for an architect. When this value is lower than 0.20, the acoustical quality will nearly always be unsatisfactory. High absorption coefficients decrease noise levels (sports facilities, living rooms for mentally challenged people, etc.) but in classrooms high absorption coefficients lead to low sound pressure levels and speech intelligibility from teachers. The optimum value for a classroom lies somewhere around 0.25. Since measurement of the absorption coefficient is difficult, the reverberation time should be used in addition to measure the mean absorption coefficient when a room is finished.

The correlation between G-RT-values and common theory has been confirmed for rectangular rooms. Especially in L-shaped rooms extra sound reduction can be accomplished from the corners. Future studies are needed to understand the correlation between other parameters and criteria, as optimal values of parameters should be established.

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