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Reverberation time in sports halls: Analysis of a large database of in-situ measurements and simulations according to absorption positions

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ABSTRACT

School gymnasia and sports halls are generally spaces with high noise and low acoustical treatment. This can lead to uncomfortable acoustic conditions for teachers and students. Building standards have been developed so as to protect the users from discomfort as well as possible health hazards due to prolonged noise exposure in these kinds of spaces. The Swiss and several other European countries' building standards use a maximal reverberation time (as a function of the hall volume) as an acoustic requirement.

In this paper, we review and compare 12 standards/recommendations from different countries and gather the reverberation times for 52 sport halls from scientific papers and our own in-situ measurements. The measurements results are compared to the German DIN 18041:2016 standard (also used by Italy and Switzerland), as a function of the presence and positions of absorbing surfaces.

Results show that none of the halls with an absorbing ceiling and reflecting walls comply with the standard, but that most of the halls with absorbing ceiling and absorbing materials on the lower sections of all four walls fulfil the standard requirements, regardless of the volume of the hall.

Furthermore, the shortcomings of predicting the reverberation time of sport halls using either diffuse-field methods (Sabine, Eyring, …) or acoustic simulations (ray-tracing) are discussed.

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1. INTRODUCTION

School Gymnasia and sport halls are large spaces with high reverberation time (T_r) and noisy environments. Research shows that poor acoustic conditions are one of the parameters which users find the most annoying [13,18], as well as being a potential health hazard (stress, hearing, vocal efforts) for frequent users (teachers, trainers) [15]. Sound absorbing materials must then be used to lower the reverberation time and the noise levels in these halls. Building regulations addressing reverberation times in sport halls have been around for a long time, at least since 1989 [17], and also the recommendation that the lower part of two adjacent walls should be absorbing [20].

Despite this, in construction projects today, acousticians are often asked to justify the costs of acoustic treatments and builders are wary of putting absorbing materials on the lower parts of the walls. Moreover, the task of justifying these acoustic treatments with accurate modelling is quite difficult, due to the fact that calculating the acoustic fields in large halls with non-diffuse sound fields with either statistical methods (Sabine, Eyring) or ray-tracing methods are subject to large errors.

First, the different acoustic descriptors used to describe the sound fields in scientific papers and standards are presented. Then, nine building standards from different countries are presented and compared. We then present our own T_r measurement results from six halls with information regarding the acoustic treatment. We also integrate a database of T_r measurement results from scientific papers and compare them to the German DIN 18041:2016 standard[1]. Three empirical regression models for the T_r in sport halls are calculated from the database according to the position of absorbing surfaces (none, ceiling, ceiling and walls). Finally, the difficulties with the calculation of T_r of halls in the planning phase are discussed.

2. DESCRIPTORS

Reverberation time (T_r) is the most common descriptor used to characterize the indoor acoustics of sport halls in literature. It is the easiest descriptor to measure, has high reproducibility [6], and is well correlated with the subjective perception of the users [25]. On the other hand, the reverberation time is not easy to predict accurately in the design phase, as sport halls usually have non-diffuse sound fields (sound absorption often being confined on one surface). Furthermore, the single number quantity T_r will not necessarily reflect the acoustic conditions of the hall, as parallel reflecting surfaces (especially walls) lead to concave decay curves [7,11]. For these reasons other descriptors have been proposed in literature [9,11], such as:
Sound level and noise exposure (L_{Aeq}, L_{Amax}, $L_{ex,8h}$,…) which are dependent on both the acoustics of the halls and the sound sources. They are the descriptors most directly correlated with the health hazards of the noisy environment in sport halls (stress, hearing loss [10]) and are well correlated to the discomfort felt in these spaces. On the other hand, sound level is very dependent on the number of students in the hall and, although to a lesser degree, on the activities taking place [13]. For this reason, a sound level limit cannot be used as criteria in the design phase.
More rarely, the Speech Transmission Index (STI) is used as a descriptor for the rating of a sports hall in literature, as it correlates well with vocal efforts needed to convey information. A lack of intelligibility is pointed out as the reason for high vocal efforts and learning difficulties [18].
Mean absorption (α_{mean}) is a very easy descriptor to use during the design phase of a new sports hall, as it directly affects the choices of materials without the need for simulations. But the downside to this descriptor is that it does not take into account the positions of the absorbing surfaces, which will have a strong effect on the overall acoustic conditions of the halls. For example, a hall with absorbing treatment on the high part of the walls has a much longer reverberation time for the users than if the same treatment is on the lower part of the walls. Other less common parameters (G sound strength, C50 Clarity) are also proposed as alternatives to T_r [9,12] because they are more reliably calculated in simulations.

[1] DIN 18041:2016 was adopted as the Swiss and the Italian standard in 2020 [22,23]. The old Swiss standard was based on old German standard DIN 18041:2004 [26]

3. STANDARDS AND RECOMMENDATION

Nine building standards/recommendations addressing the room acoustics of sport halls are analysed**.** They are all based on a requirement for the maximum reverberation time in the sport hall that is to be fulfilled. A comparison of the different maximum reverberation times from the each of the studied standards is shown in Figure 2. All reverberation time requirements are dependent on the volume of the hall (except the British BB93 standard, based on floor area, which is not shown in Figure 2). The Dutch and Polish standards are the strictest, followed by the German. The French and the old German standards are more lenient and the Portuguese standard is by far the most permissive. There is a large discrepancy between the different standards. For example, regarding a triple court sports hall (typically $V = 12\ 000\ m^3$), the mean for the maximum reverberation times is 2.6 s ± 0.8 s.
Due to the requirement being a maximum reverberation time, the respect of the standards can easily be checked with in-situ measurements, with the source and receptor points being at head level (usually 1.5 m). The sound field at this height is therefore determinant in whether the standards' requirements are fulfilled.

4. IN SITU REVERBERATION TIME MEASUREMENTS

The reverberation times as well as information about the positions of sound absorbing surfaces were gathered for 52 halls. Table 1 shows a summary of the number of halls analysed and their sources. Results from our own measurements in Switzerland are presented in Section 4.1. Results from both our measurements and the ones found in literature are presented in Section 4.2. The reverberation times are compared to the German standard requirements.
Large two- and three-court halls are usually equipped with dividers between courts which can be raised or deployed to separate the hall into different configurations (see Figure 1). The German standard specifies that the reverberation time requirements must be fulfilled for all the configurations (for the whole hall with dividers raised and for each partition with the dividers lowered).

Figure 1. Dividers in sport halls. Left: Curtain. Right: Skyfold acoustic partition

4.1 Swiss reverberation time database

Reverberation times were measured in six different sport halls in Switzerland. In accordance with the German/Swiss standard, multiple reverberation times in one sports hall were measured when it was possible to partition the hall by raising or lowering dividers. As a result, the T_r for 17 configurations were measured in the six halls (the configurations are described in more detail in [36]). In the Swiss database, 14 configurations have absorption on the ceiling and the walls (82%), two have absorption on the ceilings only (12%), and one configuration has no absorbing surfaces (6%).

Figure 4 shows the T_r for the halls from our measurements as a function of volume and the locations of sound absorbing materials (colour of markers), as well as the maximum T_r requirement from the German standard. Nine hall configurations comply with the standard, all of which have absorption on the ceiling and the lower parts of all four walls, whereas none of the halls without absorbing walls meet the standard. There are five hall configurations which have absorbing ceilings and walls, but that do not meet the standard (two are in hall B, one is in hall D and two are in hall F).

Hall B is a two court hall (V = 9300 m^3) and has an absorbing ceiling and absorbing panels on the lower part of the two short walls (with the two long walls parallel and reflecting). None of hall B's configurations comply with the standard.

Hall D is a three court hall (V = 12 300 m^3) and has an absorbing ceiling and absorbing panels on the lower part of all four walls. Only 1 out of the 6 measured configurations does not comply with the standard, which corresponds to the middle court when the dividers are down. This leads to a court with two parallel reflective surfaces (dividers), which leads to flutter echoes and higher reverberation times compared to the single courts at the extremities, which have three absorbing walls (see Figure 5).

The last two configurations that do not comply with the standard are in hall F, which is also a three-court hall (V = 16 300 m^3) with an absorbing ceiling, as well as absorbing panels on the lower part of all four walls and on the upper part of the dividers. The triple court and the two single courts at the extremities fulfil the standard's requirements, whereas the middle court with dividers deployed (same as hall D) and the double court with only 1 of the dividers deployed do not. The T_r in these two configurations barley exceed the requirements. It is important to note that considerable constructive measures were introduced to reduce the reverberation time in hall F. This shows that despite excellent acoustic treatment, middle courts of triple halls will generally not be able to meet the standards. The only solution seems to be having absorbing materials on the lower sections of the dividers.

Table 1. Summary and sources of the halls from the Swiss and international database

Database	No. Halls	No. Configurations	Reference
Swiss	6	17	[36]
UK	9	9	[1]
Jordan	11	11	[3]
UK	1	1	[7]
UK	3	3	[9]
Portugal	14	14	[13]
Italy	6	6	[15]
USA	2	2	[19]
Total	52	63	

4.2 International reverberation database

The Swiss and international reverberation time databases from scientific papers [36,1,3,7,9,15,19] and the corresponding information about the absorbing surfaces and hall sizes are presented in Figure 3 (halls from literature smaller than 1000 m^3 were discarded).

The joint database of our T_r measurement results and those found in literature consists of 63 configurations in 52 halls. 18 configurations have absorbing panels on the ceiling and the walls (29%), 7 have absorbing ceilings only (11%), 1 hall has absorbing walls only (1%) and 37 halls have no absorbing surfaces (59%). Logarithmic regression curves are shown for each group of halls.

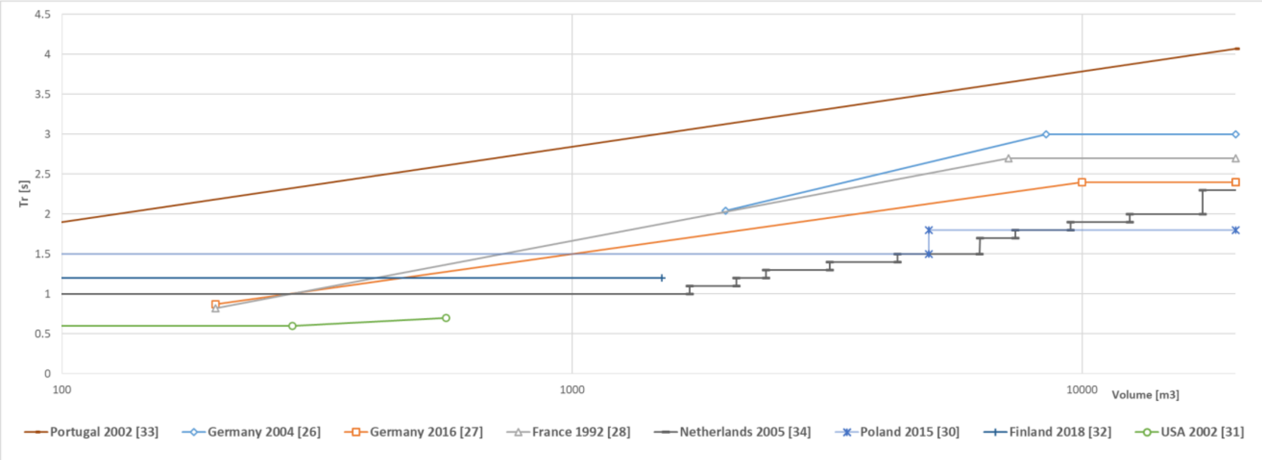

Figure 2. Comparison of the different maximum reverberation time requirements from the standards analysed as a function of volume. The British BB93 standard is not shown as the maximum T_r is a function of area

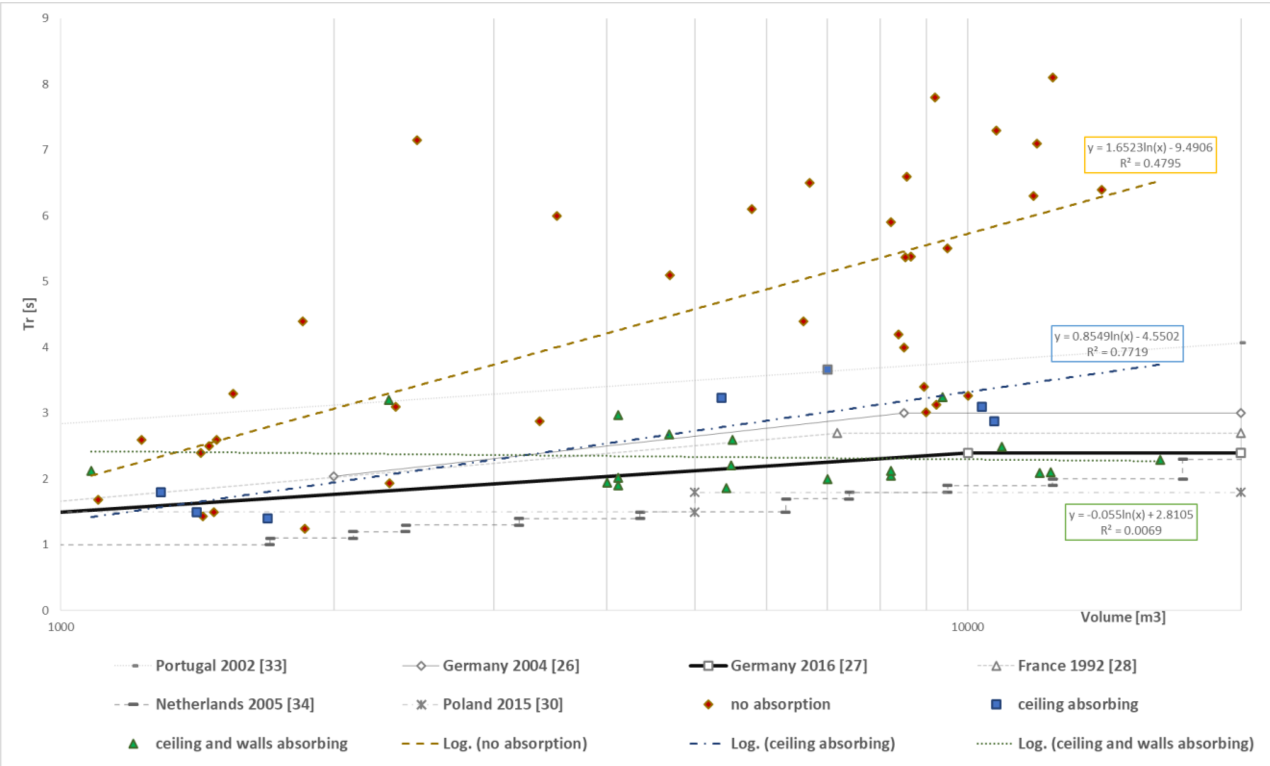

Figure 3. T_r measurement results from the Swiss and international database, consisting of 63 configurations in 52 sport halls. The results are split into groups according to the absorbing surfaces in the halls (no absorption, absorption on ceiling or absorption on ceiling and walls) and regression lines are fitted to each group. The requirements for the maximal T_r in sport halls from various standards are also shown.

Table 2. Set of standards which have a maximum reverberation time as the requirement for sport halls

Country	Standard	Requirement (Maximum T_r)		Comment
Germany 2004 [26]	DIN-18041:2004	1.2 (-2.49+1.27 Log(V)) 3.00 s	*2000 m^3 <V <8500 m^3* *V ≥ 8500 m^3:*	Also the old Swiss standard (SIA181:2006)
Germany 2016 [27]	DIN-18041:2016	1.2 (0.75 Log(V)-1) 2.40 s	*200 m^3 < V < 10'000 m^3* *V ≥ 10'000 m^3:*	Also current Swiss (SIA181:2020) and Italian (UNI 11532-2:2020) Standard
France 1992 [28]	NF P90-207 : 1992	0.14 $V^{(1/3)}$ 2.7 s	V < 7173 m^3 V ≥ 7173 m^3	Additionally : $D_{2,s}$ > 4 dB
Poland 2015 [30]	PN-B-02151-4:2015-06	1.5 s 1.8 s	*V < 5000 m^3* *V ≥ 5000 m^3*	
USA 2002 [31]	ANSI S12.60-2002	0.6 s 0.7 s	*V < 283 m^3* *284 m^3 < V < 566 m^3*	
Finland [32]	A-Y-o-r-ä 2018	1.2 s	*V < 1500 m^3*	
Portugal 2002 [33]	Decreto-Lei n.º 129/2002, artigo 9.1	0.15 $V^{(1/3)}$		0.12 $V^{(1/3)}$ if P.A system present
Netherlands 2005 [34]	NOC NSF-US1-BF1 : 2005	Maximum T_r given for 12 typical gym dimensions (see Figure 2)		
UK 1993 [35]	Building bulletin 93	1.5 s 2-(530-S)/500 2.0 s	*S < 280 m^2* *281 m^2 < S < 530 m^2* *S > 531 m^2*	Based on area of sports hall

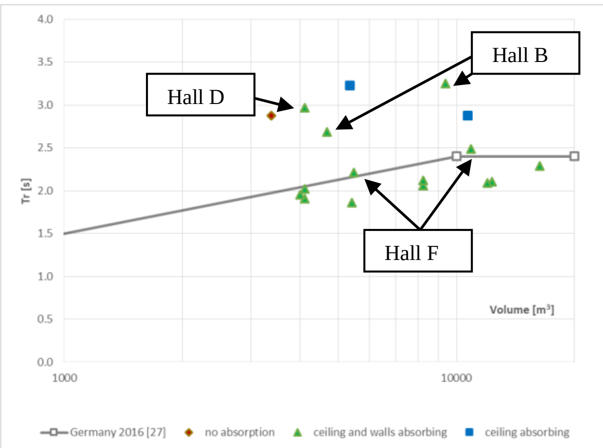

Figure 4. Reverberation times for the 17 hall configurations from the Swiss database according to the positions of acoustic surfaces. The labelled halls are discussed in Section 4.1. The black line represents the German standard maximum reverberation time requirements.

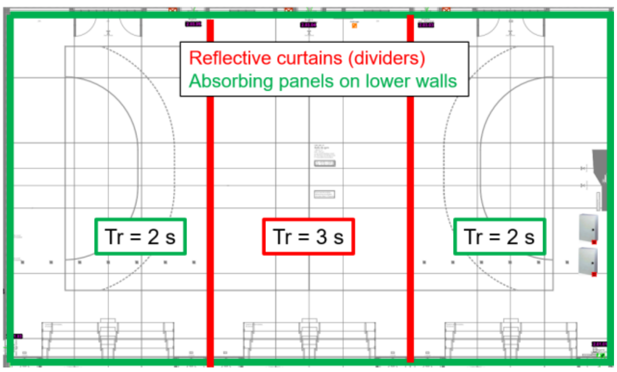

Figure 5: Example of a three-court hall with dividers where only the middle court does not meet the German standard.

4.3 Discussion of international database

15 of the 63 configurations (24%) fulfil the German standards' requirements. Considering only the halls larger than 3000 m^3 (normal size for hall with one basketball court), 10 out of 44 configurations (23 %) fulfil the requirements (furthermore, none of the halls bigger than 3000 m^3 comply with the stricter Polish and Dutch standards).

The database shows that the only way to fulfil the German standards' requirements for halls larger than 3000 m^3 is to have absorption on the ceiling and the lower part of all four walls. In the database, five halls have absorbing materials on the ceiling and on the upper parts of the walls, but none of them meet the requirement. None of the halls studied have absorbing surfaces on the lower part of only two adjacent walls. Therefore, it cannot be determined whether these halls would fulfil the German standard requirements.

Future work comparing the reverberation times in halls with absorbing surfaces on the lower parts of either two adjacent walls or all four walls would be very useful in optimising the design of halls.

The regression line for halls with no absorption (orange dotted line) shows that without any absorption the reverberation time increases relative to 1.6 times the log of the volume. The graph also shows that if left without acoustic treatment, the reverberation time in large sport halls (V > 10 000 m^3) will vary from 6 s to 8 s!

The regression line for halls with absorption on the ceiling only (blue dotted line) shows that the reverberation time increases relative to 0.8 times the log of the volume. Moreover, it shows that halls with absorbing ceilings comply the old German standard 50 % of the time.

The regression line for halls with both ceiling and walls absorbing (blue dotted line) shows that the reverberation times in these halls does not depend on the volume (the increase in volume and the increase in absorption area seem to cancel each other out).

The dispersion of the T_r values for halls with similar volume within each group can be explained by the difference in hall shapes, absorption performance of the materials, different T_r measurement methods and technicians as well as the detail in geometry in each of the halls.

5. REVERBERATION TIME PREDICTION

Building planners often need convincing to integrate absorbing surfaces on the ceiling and the lower part of the walls. Indeed, the economic and practical drawbacks of absorbing surfaces, especially on the lower part of the hall's walls will often push them to seek other solutions. The prior part of this work shows that without absorbing walls on the ceiling and the lower part of all four walls there is a high risk of not complying with any of the standards (except for the Portuguese standard, where an absorbing ceiling seems to be enough). But most often the planners will request simulations or calculations to prove or optimise the absorbing surfaces.

Thus, acousticians are expected to accurately calculate the reverberation time in sport halls and to find the least amount of absorbing materials to integrate into a project to meet the required standard.

There are two main methods for calculating the reverberation time in sport halls; statistical methods (for example Sabine equation), or geometrical methods (for example ray-tracing in 3D models). The calculation methods, as we will see, are relatively accurate for halls with diffuse sound fields (either absorbing surfaces on ceilings and lower walls, or no absorbing surfaces at all), but are quite unreliable for halls with inhomogeneous absorbing surfaces (absorbing ceiling only) [7].

5.1 Statistical methods

Statistical methods are the quickest and easiest methods to calculate the reverberation time in sport halls. One needs to plug the hall's volume, sound absorption surface areas and sound absorption coefficients into one of the corresponding equations (Sabine, Eyring, Knudsen, etc). Absorption coefficients can indeed be found easily, but often come with a high level of (measurement and selection) uncertainty.

Statistical methods are accurate for halls with diffuse sound fields and exponential decay of sound, which are conditions found in spaces where the absorbing surfaces are homogeneously distributed or in spaces with high diffusion. However, halls with absorption on the ceiling and reflective walls do not have diffuse sound fields. The multiple reflexions of sound in the lower part of the hall are not taken into account in the statistical method [17], but they will be measured in situ (parallel reflective surfaces at the source and receiver height). Because of this, statistical methods will tend to largely underestimate the T_r in halls with non-diffuse sound fields.

5.2 Ray Tracing

The more sophisticated ray-tracing methods allow the input of the positions and absorption coefficients of the different surfaces, as well as the positions of the sources and the receivers, and can thus model the specific conditions in which in-situ measurements are performed (source and the receiver are at head height). This is especially an advantage for modelling halls with non-diffuse sound fields where the sound field at head height is defining for both the T_r measurement results and the subjective experience of the users.

Ray tracing methods require absorbing and scattering coefficients. One of the main difficulties with ray-tracing simulations of sport halls with non-diffuse sound fields (absorption on ceiling only) is that the reverberation time results are extremely sensitive to the scattering coefficients attributed to the lower parts of the walls. Even though a standard exists for measuring scattering coefficients [37], there are very few available resources [21], in particular due to the difficulties in obtaining reasonable data for a wide frequency range and the lack of laboratories available that measure scattering coefficients.

If the scattering coefficients for the lower part of the walls are too high the simulations will underestimate the reverberation time (rays will be prematurely sent to the absorbing ceiling). If on the contrary the scattering coefficients are too low, the reverberation time results will depend greatly on the chosen absorption coefficients of the lower walls [6,14]. Experience is thus very helpful when choosing scattering and absorption coefficients to achieve realistic and satisfactory results.

6. CONCLUSIONS

Nine building standards from several countries addressing the room acoustics of sport halls are analysed. The requirements from these standards are all based on a maximal reverberation time. It is observed that there is a large discrepancy of the value between the standards.

A database of the reverberation times from 52 halls (six from our own measurements and 46 from scientific literature) are analysed as a function the locations of sound absorbing materials and are compared to the standards' requirements. Only 23% of halls larger than 3000 m^3 (which is the typical size for a hall with one basketball court) fulfil the German DIN 18041:2016 standards' requirements. Analysis of the database shows that only halls with absorption on the ceiling and the lower part of all four walls fulfil the requirements. In the database, none of the four halls larger than 3000 m^3 and with only absorption on the ceiling fulfil the standards' requirements. Unfortunately, the database does not contain any halls with absorption on the ceiling and on the lower part of only two adjacent walls. Further work would be useful to determine this could be a sufficient acoustic treatment to fulfil the standards' requirements. It is also shown that in large halls (V > 10 000 m^3) with 3 basketball courts, the reverberation times of the middle courts with dividers down never fulfil the requirements (even if all other configurations of the same hall do). This is because the lower parts of the dividers are never absorbing. Three empirical regression models for T_r are calculated from the database according to the position of absorbing surfaces. The regression line for halls with no absorption increases relative to 1.6 times the log of the volume. The regression line for halls with absorption on the ceiling only shows that the reverberation time increases relative to 0.8 times the log of the volume. The regression line for halls with both ceiling and walls absorbing shows that the reverberation times in these halls does not depend on the volume (the increase in volume and the increase in absorption area seem to cancel each other out).

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