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Functions for noise reduction in acoustic standards: evaluating reverberation time, mean absorption coefficient, and a novel approach

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Abstract

Contemporary European acoustic standards frequently utilize dimensioning functions based on either reverberation time or mean absorption coefficient. For spaces with the primary goal of noise reduction, achieving consistent overall sound pressure level (SPL) reduction, regardless of room sizes and shapes is evidently desirable.

The conditions under which reverberation time and mean absorption coefficient approaches align with the objective of consistent SPL reduction are analyzed. Generally, both approaches fall short of achieving consistency in case of varying ground surface or room shape, i.e. length, width and height relations. Additionally, in large rooms, constant or room height-dependent reverberation time functions may lead to extensive absorption areas, complicating the installation of acoustical treatments and degrading their economic efficiency. A dimensioning function, providing consistent SPL reduction independently of room size and shape, is derived based on diffuse field theory. This function is multiplied by a linear function of room height and length, to alleviate accuracy limitations of diffuse field theory in case of varying room shapes. Finally, simulations systematically varying room sizes and shapes demonstrate that the novel dimensioning function significantly outperforms existing approaches in achieving consistent SPL reduction.

1.INTRODUCTION

European standards on roomacoustics as well as labour protection regulations employ various mathematical functions to dimension room acoustic measures. The basic objective of this work is to analyze dimensioning functions in order to support standardization bodies in making informed decisions about the implications of such functions on the achievement of goals like sound pressure level reduction and calculation of adequate absorption areas. In the following paragraphs a short classification of such functions for spaces with a need for sound pressure level (SPL) reduction like offices, industry halls, work rooms, canteens is provided.

1. Reverberation time as a function of room height is used in standards like the Austrian B-8115-3 [1] as well as scandinavian standards for open plan offices [2]. Additionally, as argued in chapter 2, the German DIN 18041[3][4] can be considered belonging to this class.
2. Constant reverberation time target values are frequently used in standards for open plan offices like [2][5][6][7].
3. The mean absorption coefficient α_m is frequently used in labour protection regulations for noisy rooms like industry halls [5] and predecessor versions of national standards like [8].

Similar to α_m, target values defined as a fraction of the ceiling area can be found in standards on open plan offices [2][5][6][7] in order to provide some basic absorption in case the specific use of the space (e.g. call center, collaborative work) is not yet defined.

4. The DL2, the SPL decay in case of distance doubling [5] can be found in standards on industry halls [5][9]. Similarily, the $D_{2,S}$ an adapted version DL2 for speech signals is used in open plan offices [2][6].

The above introductory overview is in no way complete. Additionally, standards focused on spaces intended for audibility over longer distances like plenary rooms and classrooms are not considered. This paper focuses on the room height dependent functions in the Austrian ÖNORM B8115-3, 2023 [1] and the German DIN 18041, 2016 [3][4] (referred to simply as "ÖNORM" and "DIN" hereafter) as representatives of the class 1, and the mean absorption degree as used in [5] and [8] as representative of class 3 functions mentioned above. Note, however, that the obtained results can be qualitatively applied to standards in other countries having similar formulas with possibly slightly different parameter settings.

2. SUMMARIZING ÖNORM AND DIN FORMULAS

ÖNORM and DIN distinguish between Group A spaces, such as classrooms and lecture halls, where good speech intelligibility over greater distances is required, and Group B spaces, such as workshops and call centers, where good speech intelligibility over shorter distances suffices. Group B, which this article exclusively addresses, is subdivided into classes with varying requirements for acoustic quality. In DIN, for instance, quality classes include less noisy spaces like cafeterias in Group B3 or noisy workshops in Group B5. ÖNORM defines the reverberation time (T) as $T = c_1 \cdot h/h_{ref}$, where h is the room height, constant c_1 determines quality classes A-D, and h_{ref} represents a reference room height of 3.5m. DIN defines the ratio of equivalent sound absorption area (A) and room volume (V) as $A/V = (c_2+c_3 \cdot \log(h))^{-1}$, with constants c_2 and c_3 defining quality classes B1-B5. By using Sabine's reverberation time formula, A/V can be expressed as T: $T = 0.16 \cdot (c_2+c_3 \cdot \log(h))$. Thus, the formulas for dimensioning the target values in both norms are of similar nature, dependent only on room height. Unlike ÖNORM, DIN limits the maximum room volume to 5000m3. *Both standards declare a reduction of the mean sound pressure level as their primary objective for Group B spaces.*

In the previous versions of ÖNORM and DIN, the mean sound absorption coefficient (α_m) was used for rooms aiming at noise reduction: $\alpha_m = A/S$, where S represents the total room surface area. In DIN 18041, 2004 [10] it is recommended to double the existing equivalent sound absorption area if a reduction in sound pressure level ΔL by at least 3 dB is achieved through additional sound absorbers as compared to the untreated room. According to [10], ΔL can be estimated using the diffuse field method, formulated as follows:

$$\Delta L = 10 \cdot \log\left(\frac{A_1}{A_0}\right) = 10 \cdot \log\left(\frac{T_0}{T_1}\right) = 10 \cdot \log\left(\frac{\alpha_{m,1}}{\alpha_{m,0}}\right) \quad (1)$$

where A_1 denotes the total equivalent sound absorption area after installation of sound absorbers, and A_0 represents the equivalent sound absorption area in the original room. Equivalently, T_0 and T_1 stand for the reverberation time, and $\alpha_{m,0}$ and $\alpha_{m,1}$ for the mean absorption coefficient before and after the acoustic treatment. According to [10], $\alpha_{m,1}$ should not exceed 0.35 to avoid too large absorption areas deteriorating economic efficiency. In ÖNORM B8115, 2005 [8], $\alpha_{m,1} \geq 0.25$ is recommended for the 250Hz octave band, and $\alpha_{m,1} \geq 0.3$ for the 500Hz-4000Hz octave bands for non-empty spaces with fittings.

3. DIFFUSE FIELD THEORY REVISITED: HEIGHT-DEPENDENT FORMULAS OR MEAN ABSORPTION COEFFICIENT FOR NOISE REDUCTION?

The new versions of ÖNORM and DIN do not mention reasons why formulas dependent solely on room height were adopted for rooms aiming at noise reduction. This chapter relates the approaches of ÖNORM and DIN and their predecessor versions to the SPL reduction achieved through norm-compliant dimensioning, calculated according to formula (1).

Let's assume an acoustician is tasked with planning two arbitrary Group-B rooms of the *same quality class* but with differing geometry, size, and A_0. The primary objective of ÖNORM and DIN for Group B spaces is *mean SPL reduction*. Consequently, it is evident to anticipate that with norm-compliant dimensioning, the two rooms of the same quality class would exhibit an identical or at least similar SPL reduction. From this expectation, the following goal can be derived:

- With norm-compliant dimensioning Group B rooms of the same quality class should exhibit an ideally identical average SPL reduction, irrespective of room size, shape and A_0.

To comprehend how different dimensioning formulas align with this goal, two cases are distinguished:

- Case 1: Both original rooms feature acoustically identical materials/surfaces on average, i.e., identical $\alpha_{m,0}$: In this instance, according to (1) the two rooms will experience the same SPL reduction (i.e., fulfill the goal) if an $\alpha_{m,1}$ is prescribed, as is the case in ÖNORM 2005 [8] with $\alpha_{m,1}$ = 0.3. For the height dependent formulas of ÖNORM and DIN different geometries will cause different SPL reductions for the two considered spaces.
- Case 2: Both original rooms have the same reverberation time T_0 and the same room height, or an identical T_1/T_0 ratio emerges randomly due to the target value function and room properties: In this scenario, the two rooms will experience the same SPL reduction if dimensioned according to the formulas of ÖNORM or DIN. ÖNORM 2005 with $\alpha_{m,1}$ = 0.3 will cause different SPL reductions.

Thus, whether α_m or reverberation time target values in standards induce homogeneous SPL reductions depends on the initial condition of the untreated rooms. A straightforward explanation, as in Case 1 with α_m and identical SPL reduction in case of acoustically identical materials on average, however, is not provided in Case 2 with reverberation time as the target value.

Table 1 shows the analyzed example rooms. Parameters are systematically varied to demonstrate the tendencies of the target value formulas regarding ΔL. In rooms 1-3 and hall 1-3, the floor area is increased by a factor of 4, while the height remains constant at h=3.5 and h=7m, respectively. In rooms cube, shoebox, flat, and corridor, the volume remains constant while the room proportions are altered, from cube with identical length, width and height to strongly eccentric shapes in the case of the flat room and the corridor. For ÖNORM, target values of Class B with c_1=0.55, for DIN target values of Class B4 with c_2=2.69 and c_3=4.13 are used.

The central part of Table 1 shows Case 1, the favorable case for α_m target values, with a constant $\alpha_{m,0}$ = 0.1 for all rooms. With a target value α_m = 0.3 for ÖNORM 2005 [8], as expected according to (1), an identical SPL reduction of 4.77dB is achieved for all rooms. Comparing rooms of different floor areas and the same height (rooms 1-3, hall 1-3), DIN and ÖNORM yield a constant A_1/V or T_1, thus $\alpha_{m,1}$ and ΔL increases with the floor area. Additionally, for Cube, shoebox, flat and corridor, different SPL reductions occur in case of ÖNORM and DIN.

The lower part of Table 1 shows the favorable Case 2 for ÖNORM [1] and DIN [3], starting from reverberation times T_0 that yield a constant SPL reduction for ÖNORM for each room-group (Room1-3, Hall1-3, Cube..Corridor). For rooms of different floor areas and the same height (rooms 1-3, hall 1-3), DIN yields identical reductions. Due to the logarithmic dependency on room height the DIN formula differs from ÖNORM, thus different SPL reductions occur for DIN when varying room proportions (Cube, Shoebox, Flat, Corridor). As expected according to (1), different SPL reductions are obtained with a target value α_m = 0.3 for ÖNORM 2005.

In summary, while scenarios exist that result in identical SPL reduction for ÖNORM and DIN, these are not easily understandable and constructible, unlike with α_m and the rationale of acoustically identical materials on average. By solely using room height as single parameter to describe a room, two out of three dimensions are neglected. Due to this lack of information, it is difficult to find balanced target values for a wide range of room sizes and length/width/height proportions with the ÖNORM and DIN formulas. For both approaches, α_m and the room height dependent functions in ÖNORM and DIN, the goal of identical SPL reduction is achieved only in special scenarios that specifically fit a certain function, and not in the general case.

	Varying ground surface			Varying ground surface			Varying room proportions			
Room	**Room1**	**Room2**	**Room3**	**Hall1**	**Hall2**	**Hall3**	**Cube**	**Shoebox**	**Flat**	**Corridor**
Length [m]	10	20	40	18	36	72	8	14	18	42
Width [m]	7	14	28	10	20	40	8	8,5	11,38	4,515
Height [m]	**3,5**	**3,5**	**3,5**	**7**	**7**	**7**	8	4,3	2,5	2,7
Ground surface [m²]	70	280	1120	180	720	2880	64	119	205	190
Volume V [m³]	245	980	3920	1260	5040	20160	**512**	**512**	**512**	**512**
Total surface [m²]	259	798	2716	752	2224	7328	384	432	557	630
Case 1: $\alpha_{m,0}$	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1
ÖNORM Class B, A_1 [m²]	72,6	290,4	1161,7	186,7	746,8	2987,3	66,4	123,4	151,8	151,7
T_1 [s]	0,55	0,55	0,55	1,10	1,10	1,10	1,26	0,68	0,55	0,55
$\alpha_{m,1}$	0,28	0,36	0,43	0,25	0,34	0,41	0,17	0,29	0,27	0,24
ΔL [dB]	4,48	5,61	6,31	3,95	5,26	6,10	2,38	4,56	4,36	3,81
DIN Class B4, A_1 [m²]	52,3	209,3	837,3	206,8	827,1	3308,4	80,4	100,3	128,1	123,3
T_1 [s]	0,76	0,76	0,76	0,99	0,99	0,99	1,04	0,83	0,65	0,68
$\alpha_{m,1}$	0,20	0,26	0,31	0,27	0,37	0,45	0,21	0,23	0,23	0,20
ΔL [dB]	3,05	4,19	4,89	4,39	5,70	6,55	3,21	3,66	3,62	2,91
ÖNORM 2005, A_1 [m²]	77,7	239,4	814,8	225,6	667,2	2198,4	115,2	129,5	167,0	189,1
T_1 [s]	0,51	0,67	0,78	0,91	1,23	1,49	0,72	0,64	0,50	0,44
$\alpha_{m,1}$	0,30	0,30	0,30	0,30	0,30	0,30	0,30	0,30	0,30	0,30
ΔL [dB]	**4,77**	**4,77**	**4,77**	**4,77**	**4,77**	**4,77**	**4,77**	**4,77**	**4,77**	**4,77**
A_1^* Class 4.77dB [m²]	77,7	239,3	814,6	225,5	667,0	2197,8	115,2	129,4	166,9	189,1
T_1 [s]	0,51	0,67	0,78	0,91	1,23	1,50	0,72	0,64	0,50	0,44
$\alpha_{m,1}$	0,30	0,30	0,30	0,30	0,30	0,30	0,30	0,30	0,30	0,30
ΔL [dB]	**4,77**	**4,77**	**4,77**	**4,77**	**4,77**	**4,77**	**4,77**	**4,77**	**4,77**	**4,77**
A_1^* form factor, 4.77dB [m²]	86,2	240,5	775,9	255,6	678,1	2106,2	172,8	140,3	164,1	177,5
T_1 [s]	0,46	0,66	0,82	0,80	1,21	1,56	0,48	0,59	0,51	0,47
$\alpha_{m,1}$	0,33	0,30	0,29	0,34	0,30	0,29	0,45	0,33	0,29	0,28
ΔL [dB]	5,22	4,79	4,56	5,31	4,84	4,59	6,53	5,12	4,70	4,49
Case 2: T_0 optimized	1,70	1,70	1,70	3,20	3,20	3,20	3,00	1,61	1,31	1,31
$\alpha_{m,0}$	0,09	0,12	0,14	0,08	0,11	0,14	0,07	0,12	0,11	0,10
ÖNORM class B, A_1 [m²]	72,6	290,4	1161,7	186,7	746,8	2987,3	66,4	123,4	151,8	151,7
T_1 [s]	0,55	0,55	0,55	1,10	1,10	1,10	1,26	0,68	0,55	0,55
$\alpha_{m,1}$	0,28	0,36	0,43	0,25	0,34	0,41	0,17	0,29	0,27	0,24
ΔL [dB]	**4,98**	**4,98**	**4,98**	**4,72**	**4,72**	**4,72**	**3,86**	**3,86**	**3,86**	**3,86**
DIN class B4, A_1 [m²]	52,3	209,3	837,3	206,8	827,1	3308,4	80,4	100,3	128,1	123,3
T_1 [s]	0,76	0,76	0,76	0,99	0,99	0,99	1,04	0,83	0,65	0,68
$\alpha_{m,1}$	0,20	0,26	0,31	0,27	0,37	0,45	0,21	0,23	0,23	0,20
ΔL [dB]	3,56	3,56	3,56	5,16	5,16	5,16	4,69	2,96	3,13	2,96
ÖNORM 2005, A_1 [m²]	77,7	239,4	814,8	225,6	667,2	2198,4	115,2	129,5	167,0	189,1
T_1 [s]	0,51	0,67	0,78	0,91	1,23	1,49	0,72	0,64	0,50	0,44
$\alpha_{m,1}$	0,30	0,30	0,30	0,30	0,30	0,30	0,30	0,30	0,30	0,30
ΔL [dB]	5,28	4,14	3,44	5,54	4,23	3,39	6,25	4,06	4,28	4,82
A_1^* class 4.77dB [m²]	69,2	276,6	950,6	188,9	755,8	2564,8	81,9	151,0	187,1	187,1
T_1 [s]	0,58	0,58	0,67	1,09	1,09	1,28	1,02	0,55	0,45	0,45
$\alpha_{m,1}$	0,27	0,35	0,35	0,25	0,34	0,35	0,21	0,35	0,34	0,30
ΔL [dB]	**4,77**	**4,77**	4,11	**4,77**	**4,77**	4,06	**4,77**	4,73	**4,77**	**4,77**
A_1^* form factor, 4.77dB [m²]	76,8	278,0	905,4	214,1	768,4	2457,9	122,8	163,8	184,0	175,6
T_1 [s]	0,52	0,57	0,71	0,96	1,07	1,34	0,68	0,51	0,45	0,48
$\alpha_{m,1}$	0,30	0,35	0,33	0,28	0,35	0,34	0,32	0,38	0,33	0,28
ΔL [dB]	5,22	4,79	3,90	5,31	4,84	3,87	6,53	5,09	4,70	4,49

Table 1: Room descriptions, target values and SPL reduction according to diffuse field theory

Aside from the goal of homogeneous SPL reduction, the formulas of DIN and ÖNORM tend to either undersize small or oversize large rooms, which can lead to absorption areas that are economically difficult to justify and can hardly be implemented in practice due to insufficient space for sound absorbers. Figure 1 illustrates this basic property of height dependent formulas exemplary for ÖNORM and a room height of 3.5m and 8m: α_m increases monotonically with floor surface. Calculated with the Sabine formula $\alpha_m > 0.5$ for class A and large ground surfaces. For class B or the Eyring Formula values are lower, the basic tendency of the formula, however, remains the same.

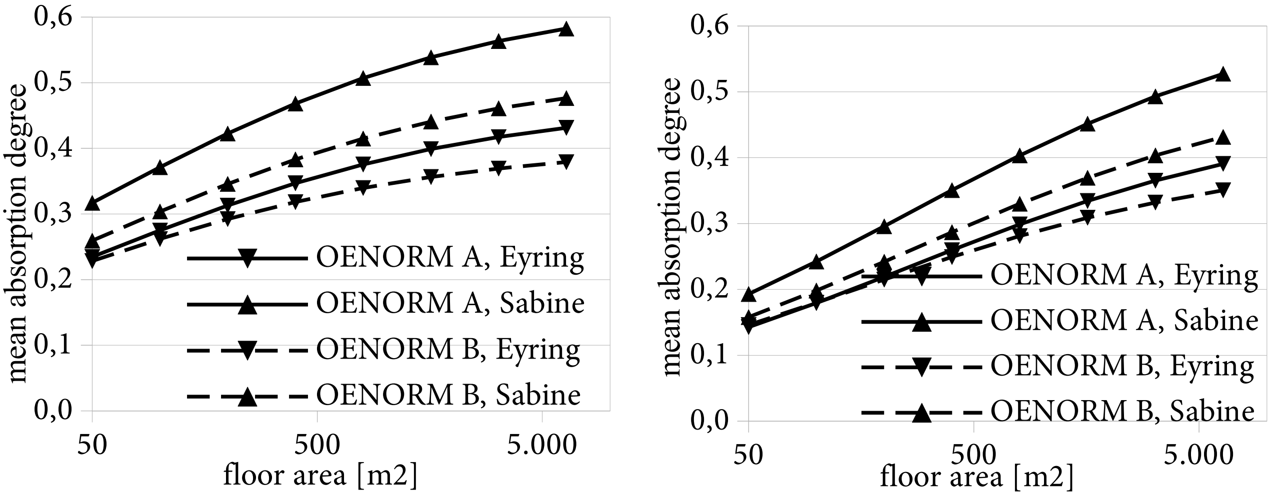

Figure 1: α_m as a function of floor area, ÖNORM Class A and B, Sabine and Eyring formulas. Left figure: height = 3.5m, right figure: height = 8m

Considering Table 1, using the Sabine formula, ÖNORM Class B results in $\alpha_{m,1} > 0.4$ for room 3 and hall 3. DIN exhibits similar tendencies, but Class B4 generally yields lower $\alpha_{m,1}$ than ÖNORM Class B. The volume restriction to 5000m3 (hall 3, Table 1 exceeds this limit but is included in order to show the tendency of the formula) limits the applicability of the standard but also avoids too high $\alpha_{m,1}$ for large and high rooms. Room 1 is potentially under-dimensioned in the case of DIN with $\alpha_{m,1} = 0.2$, T_1 0.76s. For higher/lower quality classes or lower/higher absorption areas A_0, the aforementioned differences would be more or less pronounced.

It is widely known that Equation (1) only inaccurately predicts SPL reduction in reality. SPL decay curves do not converge to a target value, as assumed in diffuse field theory, but instead have a negative slope with increasing distance from the source [9] even in the middle and far sound field. Therefore, simulations with geometrical acoustics using the example rooms listed in Table 1 will be conducted in Chapter 5 to achieve more realistic results. In the following chapter an alternative model will be presented, capable of representing different room shapes with higher accuracy and, according to diffuse field theory, calculating the required absorption area such that identical SPL reductions are achieved not only for individual cases but for the general case, regardless of room geometry and A_0.

4. AN ALTERNATIVE MODEL

In Chapter 3, the conditions for height-dependent formulas and α_m to achieve identical SPL reduction were analyzed. It was found that with these formulas, the goal of geometry-independent identical SPL reduction is only achieved in specific cases. For the subsequent approach, multiplying A_0 by a constant k and assuming a diffuse sound field (1), it can be shown that the SPL reduction ΔL is identical for any room, independently of room properties:

$$A_1 = k \cdot A_0 \;\Rightarrow\; \Delta L = 10 \cdot \log\left(\frac{A_1}{A_0}\right) = 10 \cdot \log\left(\frac{k \cdot A_0}{A_0}\right) = 10 \cdot \log(k) \qquad (2)$$

In equation (2), A_0 can be simplified resulting in a constant ΔL. $A_1 = k \cdot A_0$ thus represents the necessary absorption area according to the diffuse field theory to achieve ΔL independently of room geometry and A_0. For k=2, the expression exactly matches the formula of DIN 18041-2004[10]. Thus, contrary to the other standards, only DIN 18041-2004 achieves the goal of geometry-independent level reduction, assuming a diffuse sound field. Similar to ÖNORM and DIN, quality classes could be defined with such an approach, e.g., Quality Class ΔL = 4 dB. The term $10^{\Delta L/10}$ then reduces to the aforementioned constant k:

$$\Delta L = 10 \cdot \log\left(\frac{A_1}{A_0}\right) \Rightarrow A_1 = A_0 \cdot 10^{\Delta L/10}, \quad \Delta L = 4\,dB \quad \Rightarrow \quad A_1 = k \cdot A_0, k = 10^{4/10} \tag{3}$$

Equivalently to DIN 18041-2004, the target absorption area A_1 depends on A_0. Thus, like [10], unrealistically high absorption areas A_1 can arise for high target values for ΔL or high initial values for A_0. Therefore, it is necessary to limit the maximum A_1:

$$A_1^* = MIN\left(\alpha_{max} \cdot S, A_0 \cdot 10^{\Delta L/10}\right) \tag{4}$$

The term $\alpha_{max} \cdot S$ multiplies the room surface area by a maximum sound absorption coefficient, which, for the subsequent considerations, as in DIN 18041-2004, is set to 0.35. Thus, A_1^* is restricted to 0.35·S. Below this threshold, A_1^* is calculated so that ΔL is achieved.

As mentioned earlier, the accuracy of diffuse field theory according to equation (1) is strongly limited. Generally, ΔL tends to be overestimated in non-eccentric rooms (S/V small, e.g., cube) and underestimated in eccentric rooms (S/V large, h/l<<0.3, e.g., large, flat rooms). Therefore, in order to level out the inaccuracies of (1), A_1^* can be multiplied by a form factor, a linear function with slope h/l:

$$A_1^* form\,factor = A_1^* \cdot \left(c_4 + c_5 \cdot \frac{h}{l}\right) \tag{5}$$

The bracketed term represents the form factor, which reduces A_1^* with increasing room-eccentricity. For the subsequent simulations, constants c_4 and c_5 are set are set as follows: c_4=0.9 and c_5 = 0.5. For nested, e.g. L- or U-shaped rooms, the room length l can be calculated as the average of the total longitudinal sides. A_1^* form factor contains significantly more information about the room than the usual functions, thus fundamentally enabling a more precise calibration according to room size and proportion. Analyses regarding the parameter settings of this model are subject to future investigations. Obviousely, the form factor could also be multiplied with α_m or reverberation time functions to incorporate room proportions into the sizing formula.

Table 1 contains the values for A_1^* and A_1^* with form factor. As expected, for Case 1, A_1^* results in identical level reductions for all rooms. For A_1^* scenarios ΔL was set to a target value of 4.77 dB, thus the SPL reductions are identical to the ÖNORM 2005 scenario with $\alpha_{m,1}$ = 0.3. The form factor adjusts A_1^* as a function of room proportions, resulting in slightly different SPL reductions for A_1^* form factor, according to diffuse field theory. For Case 2, A_1^* is restricted to 0.35·S in the Room 3, Hall 3, and Shoebox scenarios, hence lower SPL reductions are obtained in these rooms as compared to the target value of 4.77 dB. Otherwise, according to the diffuse field theory, the target value of 4.77 dB is also achieved for Case 2.

5. SIMULATION

For simulations, CATT Acoustic [11] is utilized. The base area and proportions of simple, empty, cuboid-shaped rooms are varied according to Table 1. In order to be able to derive general conclusions, scenarios are kept simple without specific fittings. The scattering coefficient of room surfaces is generally set to 75%. [12] shows that high scattering coefficients yield realistic results if simulating empty rooms. The absorption degree of room surfaces without sound absorbers is set such that $\alpha_{m,0}$ according to Table 1 is achieved. For simulations with sound absorbers to achieve norm-compliant target values, the absorption coefficient of the ceiling, one longitudinal wall, and the adjacent front wall are increased to yield an A_1 according to Table 1.

Simulation Settings: 500,000 to 2 million rays, depending on room size. The TUCT [11] simulation method "Map Measures" yields an energy-equivalent sound pressure level (L_{eq}) per quadrant of the "Audience Plane," a plane parallel to the base at a height of 1.7m. Quadrants are cubes with side lengths of 0.5m for smaller rooms and up to 2m for larger rooms. An omnidirectional point sound source with a sound power of 101dB is located near the absorbing end wall at the height of the Audience Plane. In the context of this work frequency-dependent aspects are uninteresting, hence L_{eq} is analyzed for the 1000Hz octave band only (significantly above the Schroeder frequency of all rooms). Air absorption is considered but has minimal effects at 1000Hz.

Subsequent metrics are used to determine SPL differences among rooms:

- $\overline{\Delta L}$ [dB] is defined as the difference in the energetic average L_{eq} with and without norm-conformant acoustical treatment. Average L_{eq} is calculated energetically across all quadrants of the Audience Plane with a distance from the source greater than 2m.

- Δmax [%]: Let ΔL_{max} be the maximum SPL reduction of a formula (ÖNORM, DIN, A_1^*, etc.) and room-group (Room1-3, Hall1-3, Cube-Box-Flat-Corridor) and, equivalently, ΔL_{min} the minimum SPL reduction: $\Delta_{max} = 100 \cdot (\Delta L_{max} - \Delta L_{min}) / \Delta L_{max}$ Normalizing the SPL reduction shows the effect of the standardisation functions on ΔL differences between rooms independently of the absolute SPL reduction (e.g., DIN Group B4 generally causes smaller absolute ΔL than ÖNORM Group B).

$\overline{\Delta L}$ [dB], Case 1	Room1	Room2	Room3	Hall1	Hall2	Hall3	Cube	Shoebox	Flat	Corridor
ÖNORM	5,1	6,8	8,2	4,3	5,9	7,3	2,1	5,3	5,4	5,0
DIN	3,3	4,8	6,0	4,8	6,4	7,9	2,9	4,1	4,4	3,8
α_m = 0.3, A_1*	5,3	5,5	5,5	5,3	5,3	5,5	4,4	5,6	6,0	6,5
A_1* form-factor	6,1	5,5	5,8	6,0	5,3	5,5	6,8	6,1	6,0	6,1

Table 2: Case 1, SPL Reduction in tabular form

$\overline{\Delta L}$ [dB], Case 2	Room1	Room2	Room3	Hall1	Hall2	Hall3	Cube	Shoebox	Flat	Corridor
ÖNORM	5,5	5,9	6,5	5,3	5,4	5,7	3,4	4,4	4,8	5,1
DIN	3,9	4,0	4,3	5,9	5,9	6,3	4,2	3,3	3,9	3,8
α_m = 0.3	5,9	4,7	4,1	6,3	4,8	3,9	5,7	4,7	5,5	6,5
A_1*	5,3	5,6	**5,1**	5,4	5,4	**4,7**	4,3	5,6	6,2	6,4
A_1* mit Formfaktor	5,8	5,6	**4,8**	6,0	5,5	**4,5**	6,0	6,2	6,1	6,1

Table 3: Case 2, SPL Reduction in tabular form

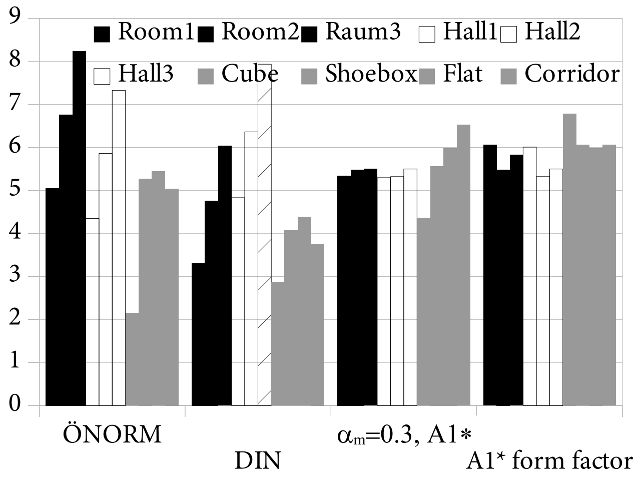

Figure 2: Case 1, $\overline{\Delta L}$ [dB]

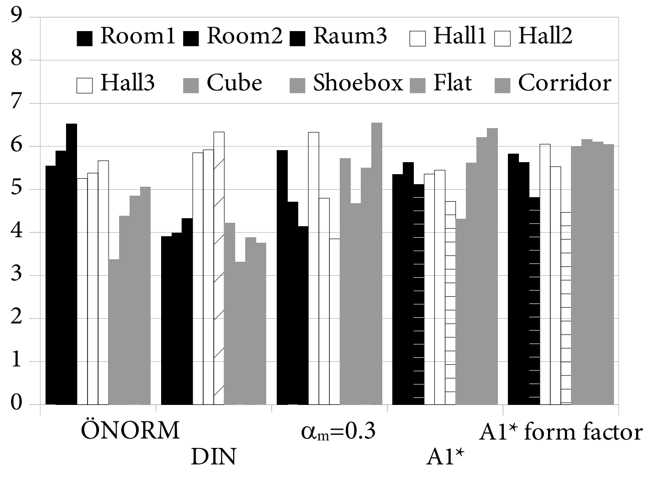

Figure 3: Case 2, $\overline{\Delta L}$ [dB]

	Case 1			Case 2		
Δ_{max} [%]:	**Room 1-3**	**Hall 1-3**	**Cube, .. Corridor**	**Room 1-3**	**Hall 1-3**	**Cube, .. Corridor**
ÖNORM	49	41	61	15	7	33
DIN	54	39	35	10	8	22
α_m = 0.3	18	4	33	30	39	29
A_1*	18	4	33	9	13	33
A_1* Formfactor	12	11	12	17	26	3

Table 4: Case 1 and Case 2, Δ_{max} [%]

Figure 2 depicts the same simulation results as Table 2: Case 1 based on $\alpha_{m,0}$ = 0.1, i.e. the favorable case for α_m as shown in Table 1. For Room1-3 and Hall1-3, the scenarios with increasing floor space, the results indicate that $\overline{\Delta L}$ for α_m, A_1^*, and A_1^* with form factor is approximately identical (e.g., A_1^*, Hall1 5.3 dB, Hall3 5.5 dB, $\overline{\Delta L}$ difference 0.2 dB). DIN and ÖNORM exhibit significant differences (e.g., ÖNORM, Hall1 4.3 dB, Hall3 7.3 dB, $\overline{\Delta L}$ difference 3 dB). For Hall 3, the DIN was included in the simulations in order to understand the tendency of the formula, but marked separately with oblique hatching in figure 2 because its room volume is well above the 5000m3 limit of the DIN. Similarly, significant differences are visible for DIN and ÖNORM when varying the proportions of rooms (e.g., ÖNORM, Cube 2.1 dB, Flat 5.4 dB, $\overline{\Delta L}$ difference 3.3 dB). Differences in $\overline{\Delta L}$ are also evident for α_m and A_1^* when varying room proportions, indicating the inaccuracy of the diffuse field model. For the cube, the form factor results in a comparatively high A_1, thus A_1^* with form factor leads to balanced SPL reductions. The $\overline{\Delta L}$ difference for cube and flat is only 0.8 dB.

Table 4 and the Δ_{max} metric illustrate that, compared to the other approaches, the normalized maximum deviations within a room-group (Room1-3, Hall1-3, Cube..Corridor) are significantly lower for A_1^* with form factor. Compared to A_1^*, A_1^* with form factor causes slightly higher differences when varying the base area but is much more balanced when varying room proportions. DIN and ÖNORM show higher Δ_{max} than the other approaches. Due to the normalizaton, Δ_{max} also shows that DIN and ÖNORM yield similar results when varying the base area.

The favorable Case 2 for ÖNORM and DIN (see Table 1) is presented in Table 3 and Figure 3. As expected, $\overline{\Delta L}$ is more balanced within a room-group for DIN and ÖNORM in Case 2 as compared to Case 1, whereas α_m causes significant $\overline{\Delta L}$ differences. The A_1^* formula results in relatively balanced SPL reductions for Room1-3 and Hall1-3, although for Room3 and Hall3, the limit of 0.35·S is exceeded (bars with horizontal hatching), resulting in lower $\overline{\Delta L}$ for these rooms. When varying room proportions, A_1^* with form factor again compensates for the inaccuracies of the diffuse field model, leading to homogeneous SPL reductions for cube, shoebox, flat and corridor.

The normalized Δ_{max} metric in the right half of Table 4 demonstrates the aforementioned results independently of the absolute SPL reduction. Contrary to Case 1, DIN and ÖNORM show lower Δ_{max} than α_m. Again, Δ_{max} is lowest for A_1^* with form factor. Compared to A_1^*, A_1^* with form factor causes slightly higher differences when varying the base area but is much more balanced when varying room proportions.

6. SUMMARY, LIMITATIONS, OUTLOOK

Using well-known methods for diffuse sound fields, the conditions under which the room height dependent reverberation time formulas in [3] and [1], as well as α_m [5][8] achieve identical sound level reductions, irrespective of room geometry, have been analyzed. As explained in Chapter 3, against his expectations, an acoustician planning arbitrary rooms of the same quality class with the aim of noise reduction according to [1][3], will generally achieve different SPL reductions. This is demonstrated in Table 1 for example rooms systematically varying the base area or the length/width/height proportions of a room. Additionally, room height dependent reverberation time formulas tend to either undersize small rooms or oversize large rooms, which can lead to economically questionable high absorption areas for large rooms that can hardly be practically installed due to insufficient space for sound absorbers. Similarly to room height dependent reverberation time formulas, α_m achieves identical SPL reduction irrespective of the room geometry only in special cases. However, the condition of acoustically identical surfaces of the original room to cause identical SPL reduction is straightforward to comprehend for α_m, and the aforementioned space problem for absorbers in the case of reverberation time-based formulas is avoided.

A diffuse field theory based model similar to [10], calculating the required equivalent sound absorption area A_1^* to achieve a desired target SPL reduction irrespective of room properties, is presented. Additionally, to compensate for the inaccuracies of the diffuse field theory in case of different room proportions, A_1^* is multiplied with a form factor dependent on the room height to length ratio. Geometric acoustics simulations demonstrate that the A_1^* formula with form factor is significantly better at achieving balanced equivalent sound absorption areas and SPL reductions for a wide range of room sizes, geometries, and proportions than height dependent formulas or α_m.

The A_1^* approach is optimal given the assumption that identical SPL reduction, independent of room geometry, is desirable. This assumption should, however, be discussed in standardization committees. For example, would a lower SPL reduction in larger rooms be desirable, as a sound source of the same sound power in a larger room causes a lower average sound pressure level? On the other hand, large industrial halls often contain more and noisier machines than small workshops. Furthermore, the A_1^* formula implies that A_0 must be estimated. This allows ambiguities in room acoustic planning that would need to be avoided in standards by precisely defined rules for estimating A_0. In any case, further simulations with geometric acoustics systematically investigating the balance of sound pressure level reduction and target absorption areas for a wide range of room proportions and sizes are desirable and necessary in view of future revisions of room acoustic standards.

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