Relating Dimensioning Functions in Room Acoustic Standards for Noise Control to their Goals: A Classification and Simulation Analysis

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1. Introduction

Dimensioning functions in room acoustic standards on noise control are usually simple formulas specifying a certain desired reverberation time, mean absorption coefficient or DL_2. The Sound Pressure Level (SPL) reduction achieved by such functions depends on size, shape, fitting density and absorption of the considered space. Thus the consequences of dimensioning functions in roomacoustic standards on noise control are often hard to understand for standardization committees. The aim of this paper is to shed light on the question how dimensioning functions relate to room properties and the desired SPL-reduction goal.

Dimensioning functions should be simple to understand and apply, resulting reverberation times should be monotonically increasing with room volume. Furthermore, suggested equivalent absorption areas should be neighter too low causing underdimensioning of rooms nor too high causing overdimensioning, i.e. unnecessarily high costs and potential problems in finding enough space on room-bounderies for the installation of sound absorbers. In addition to the above requirements, the following stability criterion should hold: *SPL reduction should be homogenous and balanced for a broad spectrum of room geometries and absorption areas. Otherwise the effect of acoustical treatments on noise control is hard to predict, given that size, geometry and absorption of spaces vary extensively.*

Note that standardization committees tend to over-emphasize questions like „should reverberation time or mean absorption coefficient be used“. Preferably, dimensioning functions should be selected based on a conscious definition of SPL reduction goals and an understanding how room-parameters and functions relate to SPL reduction goals. In order to meet the above mentioned stability criterion, it is obvious that functions having more information on room properties have higher potential to achieve stability for a broad variety of room geometries as compared to functions with little room-information. Recent standards propose constant reverberation time functions or functions depending only on the room height [1][2][3][4]. Obviously these functions have less information on room geometry as compared to classical formulas in older standards [5] [6] using room surface (S) or volume (V).

2. A classification of common functions

Table 1 shows dimensioning functions and their effect on SPL in the diffuse field. Knowing Sound power of the source L_w and Absorption area A of the room, SPL can simply be calculated using formula 1 [7]:

$$SPL = L_w - 10 \cdot \log\left(\frac{A}{4}\right) \qquad (1)$$

„Two room scenarios“ are shown in order to consider different room geometries and levels of absorption, the two factors influencing SPL. Absorption level is defined by the mean absorption coefficient $\alpha_{m,0}=A_0/S$, index 0 indicating the untreated room. Propositional logics tells us that there exist four cases to distinguish: the two rooms have (1) different geometry and $\alpha_{m,0}$, (2) different geometry and identical $\alpha_{m,0}$, (3) identical geometry and different $\alpha_{m,0}$, (4) identical geometry and $\alpha_{m,0}$. Case 1 is the generic, realistic case, case 2-4 are special cases for illustration purpose. Sound power of sources is non predictable, and thus set constant in Table 1.

The following functions are investigated in this paper:

- mean absorption coefficient $\alpha_m = A/S = constant$
- Reverberation Time $T= f(h)$ *with room height h*. As an example for this type of functions Class B ÖNORM 8115-3, 2023 [2] is used: $T = 0.55 \cdot h/h_{ref}$, h_{ref} represents a reference room height of 3.5m. Note that DIN 18041, 2016 [1] uses a similar room height dependent function.
- Absorption area after the acoustical treatment $A_1^* = A_0 \cdot k$, with constant k. See [5][8][9] and section 3.

Let SPL_{Ri} define the mean absolute SPL for room i. Let ΔSPL_{Ri} define the difference of mean SPL in room i caused by an acoustical treatment according to some dimensioning function and the untreated room.

Assume the task is to dimension two arbitrary rooms according to an acoustic standard with the objective of SPL reduction. It is intuitively evident to anticipate that with norm-compliant dimensioning, the two rooms should exhibit either (1) identical or at least similar absolute mean SPL, i.e. $|SPL_{R1} - SPL_{R2}|=0$ or (2) identical or at least similar mean SPL reduction $|\Delta SPL_{R1} - \Delta SPL_{R2}|=0$[1]. Assume a sound source of identical sound power in two rooms with the same level of absorption but different size (i.e. case 2 scenario, identical $\alpha_{m,0}$). Obviously, the sound source will cause a lower SPL in the larger space, naturally having a higher A_0, as compared to the smaller space, see formula 1. We cannot expect acoustical treatments to perfectly equalize this natural, room size-based SPL-difference; i.o.w. above expectation (1) $|SPL_{R1} - SPL_{R2}| = 0$ is naive and unrealistic[2]. A reasonable minimum requirement on dimensioning functions concerning SPL-stability, however, is that the natural SPL difference of two untreated rooms caused by their difference in size is not amplified by the acoustical treatment – i.e. larger rooms should not be

[1]Probably all field engineers have been asked these questions by their customers: “what’s the noise level after the treatment” (1), or “how many dB less noise will we have”(2). Though these questions are partly naive, they are obvious and perfectly match the task.

[2]Natural, room size based mean SPL differences can easily exceed 10dB. Such a goal would not even be desirable as it would lead to the proposal of unreasonably low or high A_1 in many scenarios.

Table 1: Two-Room Scenarios relating dimensioning functions to absorption area and room geometry

		Case 1A: $\alpha_{m,0}$ and geometry different		**Case 1B: $\alpha_{m,0}$ and geometry different, $\alpha_{m,0}$ swapped**		**Case 2: $\alpha_{m,0}$ identical, geometry different**		**Case 3: $\alpha_{m,0}$ different, geometry identical**		**Case 4: $\alpha_{m,0}$ and geometry identical (trivial)**	
	Class	**Room 1**	**Room 2**	**Room 1**	**Room 2**	**Room 1**	**Room 2**	**Room 1**	**Room 2**	**Room 1**	**Room 2**
l [m]		10	20	10	20	10	20	10	10	10	10
b [m]		7	14	7	14	7	14	7	7	7	7
h [m]		3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
Volume V [m³]		245	980	245	980	245	980	245	245	245	245
Total Surface S [m²]		259	798	259	798	259	798	259	259	259	259
L_w Source [dB]		100	100	100	100	100	100	100	100	100	100
α_m without treatment		0.05	0.2	0.2	0.05	0.2	0.2	0.05	0.2	0.2	0.2
A_0 [m²]		12.95	159.6	51.8	39.9	51.8	159.6	12.95	51.8	51.8	51.8
SPL [dB]		94.90	83.99	88.88	90.01	88.88	83.99	94.90	88.88	88.88	88.88
α_m konstant	**A**	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
A_1 [m²]		77.70	239.40	77.70	239.40	77.70	239.40	77.70	77.70	77.70	77.70
SPL [dB]		87.12	82.23	87.12	82.23	87.12	82.23	**87.12**	**87.12**	**87.12**	**87.12**
Δ SPL [dB]:		7.78	1.76	1.76	7.78	**1.76**	**1.76**	7.78	1.76	**1.76**	**1.76**
T = const * h [s]	**A**	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55
A_1 [m²]		72.61	290.44	72.61	290.44	72.61	290.44	72.61	72.61	72.61	72.61
α_m		0.28	0.36	0.28	0.36	0.28	0.36	0.28	0.28	0.28	0.28
SPL [dB]		87.41	81.39	87.41	81.39	87.41	81.39	**87.41**	**87.41**	**87.41**	**87.41**
Δ SPL [dB]:		7.49	2.60	1.47	8.62	**1.47**	**2.60**	7.49	1.47	**1.47**	**1.47**
A_1*, A_1 [m²]	**B**	25.84	318.44	103.35	79.61	103.35	318.44	25.84	103.35	103.35	103.35
α_m		0.10	0.40	0.40	0.10	0.40	0.40	0.10	0.40	0.40	0.40
SPL [dB]		91.90	80.99	85.88	87.01	85.88	80.99	91.90	85.88	**85.88**	**85.88**
Δ SPL [dB]:		**3.00**	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**

overdimensioned as compared to smaller rooms. Subsequently, two goals are defined according to above optional expectations:

- Goal1: the natural SPL difference of two untreated rooms caused by their difference in size is not increased by the acoustical treatment; larger rooms should not be overdimensioned as compared to smaller rooms:

$$\Delta SPL_{large\text{-}Room} \leq \Delta SPL_{small\text{-}Room}$$

- Goal2: $|\Delta SPL_{R1} - \Delta SPL_{R2}|$ *should be as small as possible.* Note that computing ΔSPL eliminates the natural *SPL* difference due to the size and absorption of the untreated rooms as well as differences in sound power of sources.

Note that especially goal1 should be subject to discussion, it might be argued that goals taking room size into account are not desirable[3]. Table1 illustrates which function has the potential to fulfil goal1 or 2 in diffuse field scenario 1,2,3 allowing a classification. Case 4, the trivial case with identical geometry and absorption, is listed in the table only for the sake of completeness. In this case all functions fulfill goals 1 and 2 in the diffuse field. Highlighted with black background in Table 1 if both rooms have identical Δ*SPL* or identical *SPL*.

An input-parameter based classification of functions:

- *Class A: A_1 depends on room geometry but not on A_0.* Functions like α_m *= constant*, *T= f(h), T= f(V)* belong to this class. Because both rooms have identical geometry, Class A functions cause identical SPL in two room scenario3. Additionally, because of identical (A_1–A_0) difference, goal 2 is achieved for α_m *= constant* in scenario 2. In summary, however, class A functions fulfil goal 2 only in special cases. Note that because of its tendency to overdimension larger spaces the *T=f(h)* function violates goal 1 in scenario 2: ΔSPL ist 2.6dB for the larger room 2 as compared to 1.47dB for room 1 in scenario 2. Class A functions decrease the natural SPL difference in Case1A scenarios but increase natural SPL difference in Case1B, if the larger room2 has a smaller $\alpha_{m,0}$ as compared to room1: e.g case 1a: without treatment $SPL_{R1} - SPL_{R2}=94.9\text{-}83.99=10.91dB;$ T=f(h): $SPL_{R1} - SPL_{R2}=6.02dB.$ Case 1b: without treatment $SPL_{R1} - SPL_{R2}=1.13dB;$ T=f(h): $SPL_{R1} - SPL_{R2}=7.17dB.$
- *Class B: A_1 depends on A_0 but not on room geometry.* Contrary to Class A, in case of Class B functions like A_1^* $|SPL_{R1} - SPL_{R2}|$ is identical with and without acoustical treatment, e.g. case1a 10,91dB. As shown in table 1, contrary to class A functions, A_1^* results in identical ΔSPL for all cases 1-4 in the diffuse field, i.e. goal 1 and 2 are fulfilled in the general case. The reason for this is shown in [8] and formula 2: A_0 can be simplified resulting in a constant ΔSPL, independently of A_0 and room geometry.

$$A_1^{*}=k\cdot A_0 \;\Rightarrow$$
$$\Delta SPL=10\cdot\log\left(\frac{A_1}{A_0}\right)=10\cdot\log\left(\frac{k\cdot A_0}{A_0}\right)=10\cdot\log(k) \quad (2)$$

- *Class C: A_1 depends on room geometry and A_0.* See section 3 for such a function.

Another goal for SPL-stability might be defined as follows: „Two rooms should have the same ΔSPL for identical source/receiver distances, independently of geometry and A_0. The well known DL_2 [7] supports this goal. Investigation of this function is, however, out of scope for this paper.

[3] Due to the room-size based natural SPL difference, it could be argued that functions should overdimension smaller spaces as compared to larger spaces to achieve homogenous SPL. Considering for instance production halls, however, larger spaces often have more machines with higher sound power as compared to smaller spaces. We conclude that the latter considerations are irrelevant in the context of standardisation as dimensioning functions have to be applicable to all room geometry and absorption situations and the number and sound power of sources is unpredictable. Rather, to stay neutral, it could be argued that SPL reduction should be identical or at least similar for the two differently-sized spaces, i.e. goal 2.

Though all functions basically achieve SPL-stability in some 2-room scenarios, their stability and applicability for a broad range of geometries and absorption areas varies. For the diffuse field case this is shown above. For more realistic cases section 4 shows simulation results systematically varying room geometry and absorption.

3. Details on the A_1^* formula

Formula 2 shows why the A_1^* function fulfils the stability criterion when aiming at goal 2 (ΔSPL). This section summarizes some constraints and extensions for the A_1^* function [8][9]. Quality classes can be defined with such an approach, e.g., Quality Class ΔSPL = 4 dB. The term $10^{\Delta L/10}$ then reduces to the aforementioned constant k:

$$\Delta SPL = 10 \cdot \log\left(\frac{A_1}{A_0}\right) \Rightarrow A_1 = A_0 \cdot 10^{\Delta SPL/10}$$

$$\Delta SPL = 4\,dB \quad \Rightarrow \quad A_1* = k \cdot A_0, k = 10^{4/10} \qquad (3)$$

The target absorption area A_1 depends on A_0. Thus undesirably high/low absorption areas A_1 can arise for high/low target values for ΔSPL or high/low initial values of A_0. Therefore, it is necessary to limit the minimum and the maximum A_1:

$$\alpha_{min} \cdot S \; < \; A_1^* \; < \; \alpha_{max} \cdot S \quad (4)$$

The absorption coefficients α_{min} and α_{max} are set to 0.15 and 0.35 for subsequent simulations. Between these constraints A_1^* is calculated so that ΔSPL is achieved.

It is well known that the accuracy of diffuse field theory is strongly limited. Generally, ΔSPL 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). To compensate these inaccuracies A_1^* is multiplied by a form factor, a linear function with slope h/l:

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

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 as follows: c_4=0.9 and c_5 = 0.5. See [8] and [9] for more details. A_1^* with form factor can be considered a class C function depending on A_0 and room geometry.

4. SIMULATION

For simulations, CATT Acoustic [10] is utilized. In order to be able to derive general conclusions, scenarios are kept simple using empty, cuboid-shaped rooms without specific fittings. The scattering coefficient of room surfaces is generally set to 75%. [11] 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 2 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 2. Table 2 shows simulated case 2 scenarios, i.e. two room scenarios with identical $\alpha_{m,0}$ (α_m without acoustical treatment) and different geometry – see section 1. In case of Room1-3 scenarios the ground surface is varied, room height is kept constant. In case of the cube, shoebox, flat-room, corridor scenarios length, width, height proportions are varied and volume ist kept constant. The bottom lines in table 2 show $\alpha_{m,1}$ (α_m with acoustical treatment) as computed by the considered functions.

Table 2 : simulation scenarios, case 2

	Varying ground surface			Varying room proportions			
Room	**Room1**	**Room2**	**Room3**	**Cube**	**Shoebox**	**Flat**	**Corr.**
Length [m]	10	20	40	8	14	18	42
Width [m]	7	14	28	8	8.5	11.4	4.5
Height [m]	**3.5**	**3.5**	**3.5**	8	4.3	2.5	2.7
Floor [m²]	70	280	1120	64	119	205	190
V [m³]	245	980	3920	**512**	**512**	**512**	**512**
S [m²]	259	798	2716	384	432	557	630
$\alpha_{m,0}$	0.1	0.1	0.1	0.1	0.1	0.1	0.1
T=f(h),$\alpha_{m,1}$	0.28	0.36	0.43	0.17	0.29	0.27	0.24
A_1^* ,$\alpha_{m,1}$ = 0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
A_1^* formf. $\alpha_{m,1}$	0.33	0.3	0.29	0.45	0.33	0.29	0.28

Simulation Settings: 500000 to 2 million rays, depending on room size. The TUCT [10] 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 1m 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 analysed for the 1000Hz octave band only (significantly above the Schroeder frequency of all rooms). Air absorption is considered but has minimal effects at 1000Hz. The ΔSPL class for the A_1^* function is set to 4.77 dB. This results into identical A_1 as compared to α_m = 0.3. Thus A_1^* and α_m are combined in in table 2 and figure 1.

Subsequent metrics are used to determine SPL differences among rooms: Average SPL ($\overline{SPL}$) is calculated energetically across all L_{eq} in quadrants of the Audience Plane with a distance from the source greater than 2m. $\overline{\Delta SPL}$ [dB] is defined as the $\overline{SPL}$ difference with and without norm-compliant acoustical treatment.

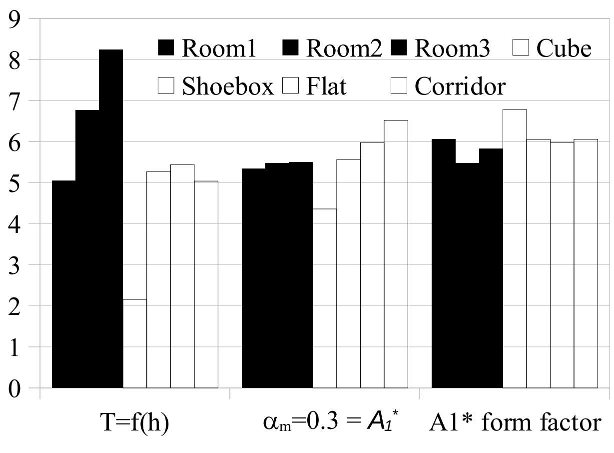

Figure 1: Case 2 scenarios, goal 2 $\overline{\Delta SPL}$ [dB]

Figure 1 shows $\overline{\Delta SPL}$ for case 2. For Room1-3, the scenarios with increasing floor space, $\overline{\Delta SPL}$ is nearly constant for α_m,

A_1^*, and A_1^* with form factor. The T=f(h) formula exhibits significant differences (e.g. Room1 5dB, Room3 8.15 dB, $\overline{\Delta SPL}$ difference 3.15 dB); larger rooms experience higher $\overline{\Delta SPL}$ than smaller rooms. Thus goals 1 and 2 are violated. Differences in $\overline{\Delta SPL}$ 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 more balanced SPL reductions. The $\overline{\Delta SPL}$ difference for cube and flat is only 0.8 dB.

Table 3 : simulation, case 3 scenarios

	without treatment	T=F(H)	$\alpha_{m,1}$ = 0.3	A_1^* = A_1^* Formfactor
$\alpha_{m,1}$, $\alpha_{m,0}$ = 0.05	0.05	0.36	0.3	0.15
$\alpha_{m,1}$, $\alpha_{m,0}$ = 0.1	0.1	0.36	0.3	0.3
$\alpha_{m,1}$, $\alpha_{m,0}$ = 0.2	0.2	0.36	0.3	0.35

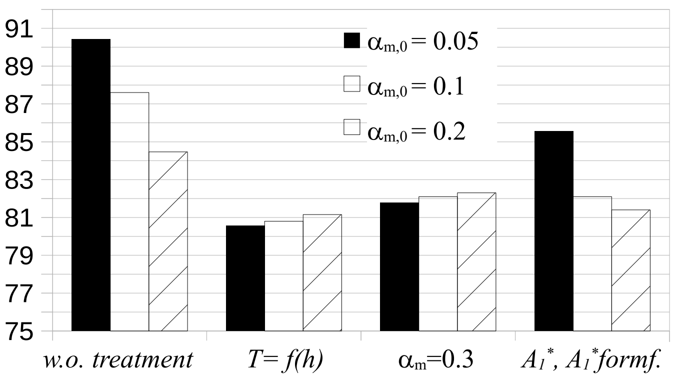

Figure 2: Case 3 scenarios, $\overline{SPL}$ [dB]

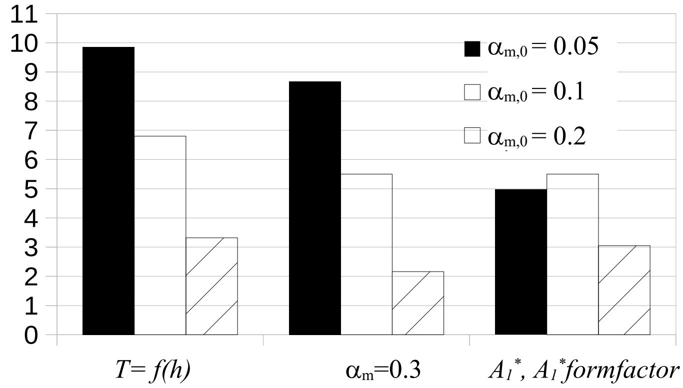

Figure 3: Case 3 scenarios, ΔSPL [dB]

Table 3 and figures 2,3 show simulated case 3 scenarios with varying $\alpha_{m,0}$ but identical room geometry. Room2 (see table2) is used with $\alpha_{m,0}$ set to 0.05, 0.1, 0.2, respectively. T=f(h) and α_m = 0.3 compute A_1 based on room geometry thus $\overline{\alpha_{m,1}}$ and $\overline{SPL}$ stay nearly constant when altering $\alpha_{m,0}$. $\overline{\Delta SPL}$ decreases as $\alpha_{m,0}$ increases for T=f(h) and α_m = 0.3, see figure 3. A_1^* computes A_1 based on $\alpha_{m,0}$, thus SPL decreases with increasing $\alpha_{m,0}$ and $\overline{\Delta SPL}$ should stay constant. For the $\alpha_{m,0}$ = 0.05 and the $\alpha_{m,0}$ = 0.1 scenario the target of a constant $\overline{\Delta SPL}$ of 4.77dB is roughly achieved. In case of $\alpha_{m,0}$ = 0.2 the A_1 computation is upper-bounded by 0.35·S thus $\overline{\Delta SPL}$ is lower.

5. Conclusions and Limitations

The first part of this paper proposes an input parameter based classification of dimensioning functions for acoustic standards on noise control. The first class of functions takes room-geometry into account but not the absorption of the original room. Commonly used functions like mean absorption coefficient or reverberation time as a function of room height or volume belong to this class. Comparing spaces with different ground surface sizes we find that functions only using the room height may result in overdimensioning of larger spaces, which is considered non desirable. Mean absorption coefficient does not show this behaviour.

The second class of functions takes the absorption of the original room into account but not room-geometry. For the A_1^* function multiplying the equivalent absorption area of the untreated room by a constant, we find that identical SPL reduction is achieved independently of room geometry and absorption of the untreated room in diffuse sound fields.

Consequently, as an example for a third class of functions taking room geometry and absorption in to account, the "A_1^* with form factor" function including room height and length is proposed.

Simulations are performed varying ground surface and length/width/height proportions of rooms. Essentially, above mentioned findings based on simple diffuse field formulas are confirmed by simulation. A_1^* with form factor shows higher homogeneity in SPL reduction in case of varying room proportions as compared to the other formulas.

Limitations of this paper: additional simulation-scenarios are necessary. Matching additional functions like DL_2 to SPL reductions goals, room geometry and absorption area would be interesting. Finally, the SPL reduction goals mentioned in this paper as should be subject to discussion.

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