BRITISH STANDARD

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Building Acoustics — Estimation of acoustic performance of buildings from the performance of elements —

Part 6: Sound absorption in enclosed spaces

The European Standard EN 12354-6:2003 has the status of a British Standard

ICS 91.120.20

British Standards

National foreword

This British Standard is the official English language version of EN 12354-6:2003.

The UK participation in its preparation was entrusted by Technical Committee B/209, General building codes, to Subcommittee B/209/18, Sound insulation, which has the responsibility to:

- aid enquirers to understand the text;
- present to the responsible international/European committee any enquiries on the interpretation, or proposals for change, and keep the UK interests informed;
- monitor related international and European developments and promulgate them in the UK.

A list of organizations represented on this subcommittee can be obtained on request to its secretary.

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Acoustique du bâtiment - Calcul de la performance acoustique des bâtiments à partir de la performance des éléments - Partie 6: Absorption acoustique des pièces et espaces fermés

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CEN members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration. Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the Management Centre or to any CEN member.

This European Standard exists in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CEN member into its own language and notified to the Management Centre has the same status as the official versions.

CEN members are the national standards bodies of Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Luxembourg, Malta, Netherlands, Norway, Portugal, Slovakia, Spain, Sweden, Switzerland and United Kingdom.

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Foreword

This document (EN 12354-6:2003) has been prepared by Technical Committee CEN/TC 126 “Acoustic properties of building products and of buildings”, the secretariat of which is held by AFNOR.

This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by June 2004, and conflicting national standards shall be withdrawn at the latest by June 2004.

This document is the first version of a standard which forms a part of a series of standards specifying calculation models in building acoustics:

- *Part 1: Airborne sound insulation between rooms*
- *Part 2: Impact sound insulation between rooms*
- *Part 3: Airborne sound insulation against outdoor sound*
- *Part 4: Transmission of indoor sound to the outside*
- *Part 5: Sound levels due to service equipment*
- *Part 6: Sound absorption in enclosed spaces*

Although this part covers the most common types of enclosed spaces in buildings it cannot yet cover all variations of such spaces. It sets out an approach for gaining experience for future improvements and developments of the standard.

The accuracy of this standard cannot be specified in detail until wide ranging comparisons with field data have been made, which can, in turn, only be gathered over a period of use of the prediction model. To help the user in the meantime, indications of the accuracy have been given, based on earlier comparable prediction models. It is the responsibility of the user (i.e. a person, an organisation, the authorities) to consider the consequences of the accuracy, inherent in all measurement and prediction methods, to specify requirements for input data and/or apply a safety margin to the results or to apply some other correction.

Annex A is normative, annexes B, C, D and E are informative.

According to the CEN/CENELEC Internal Regulations, the national standards organizations of the following countries are bound to implement this European Standard: Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Luxembourg, Malta, Netherlands, Norway, Portugal, Slovakia, Spain, Sweden, Switzerland and the United Kingdom.

1 Scope

This European Standard describes a calculation model to estimate the total equivalent sound absorption area or reverberation time of enclosed spaces in buildings. The calculation is primarily based on measured data that characterise the sound absorption of materials and objects. Calculations can only be carried out for frequency bands.

This European Standard describes the principles of the calculation model, lists the relevant quantities and defines its applications and restrictions. It is intended for acoustical experts and provides the framework for the development of application documents and tools for other users in the field of building construction, taking into account local circumstances.

The model is based on experience with predictions for rooms, such as rooms in dwellings and offices, and common spaces in buildings, such as stairwells, corridors and rooms containing machinery and technical equipment. It is not intended to be used for very large or irregularly-shaped spaces, such as concert halls, theatres and factories.

2 Normative references

This European Standard incorporates by dated or undated reference, provisions from other publications. These normative references are cited at the appropriate places in the text and the publications are listed hereafter. For dated references, subsequent amendments to or revisions of any of these publications apply to this European Standard only when incorporated in it by amendment or revision. For undated references the latest edition of the publication referred to applies (including amendments).

EN ISO 354, *Acoustics - Measurement of sound absorption in a reverberation room (ISO 354:2003).*

ISO 9613-1, *Acoustics - Attenuation of sound during propagation outdoors - Part 1: Calculation of the absorption of sound by the atmosphere.*

3 Relevant quantities

3.1 Building performance

3.1.1

quantities to express building performance
sound absorption in enclosed spaces can be expressed in terms of the equivalent absorption area or the reverberation time in accordance with prEN ISO 3382-2. These quantities are determined in frequency bands (one-third octave bands or octave bands)

3.1.2

equivalent sound absorption area of a room A
hypothetical area of a totally absorbing surface without diffraction effects which, if it were the only absorbing element in the room, would give the same reverberation time as the room under consideration

NOTE Equivalent sound absorption area of a room is expressed in m^2.

3.1.3

reverberation time T
time required for the sound pressure level to decrease by 60 dB after the sound source has stopped

NOTE 1 Reverberation time is expressed in s.

NOTE 2 The definition of T with a decrease by 60 dB of the sound pressure level may be fulfilled by linear extrapolation of a shorter evaluation range.

NOTE 3 Where a decay curve is not monotonic the reverberation time is defined by the times at which the decay curve first reaches 5 dB and 25 dB below the initial level, respectively. In the case of uncertainty this reverberation time should be labelled T_{20}.

3.2 Element performance

3.2.1
quantities to express element performance
sound absorption of elements in accordance with EN ISO 354 can be expressed as the equivalent sound absorption area or the sound absorption coefficient. These quantities are determined in one-third octave bands and can also be expressed in octave bands

NOTE Also a single number rating for the element performance can be obtained from the frequency band data in accordance with EN ISO 11654 [7], for instance $_{w}$(M). Such single number ratings may be used for comparing or specifying the required performance of products, but they cannot be used directly to calculate the performance in situ.

3.2.2
equivalent sound absorption area of an object A_{obj}
difference between the equivalent sound absorption area with and without the object (test specimen) in the test room

NOTE Equivalent sound absorption area of an object is expressed in m^2.

3.2.3
sound absorption coefficient $_{s}$
equivalent sound absorption area of a test specimen divided by the area of the test specimen

NOTE 1 For plane absorbers with both sides exposed, this relates to each side as an average value over both sides.

NOTE 2 This quantity applies only to a flat absorber or a specified array of objects, and not to single objects.

3.2.4
other relevant data
for calculations additional information may be necessary, e.g.:

¾ area of the room boundary elements;

¾ volume and shape of the enclosed space;

¾ amount and nature of objects and fittings in the enclosed space;

¾ number of people assumed to be present in the room

3.3 Other terms and quantities

3.3.1
absorption by air A_{air}
equivalent absorption area of the sound attenuation by air

3.3.2
empty room volume V
volume of the enclosed space without the objects and fittings present

3.3.3
object volume V_{obj}

volume of the smallest regular shaped envelope for an object, ignoring small elements that protrude through that envelope

NOTE An example of small protruding elements which can be ignored, are the legs of a table.

3.3.4
object fraction

ratio of the sum of the volumes of all objects to the volume of the empty space

3.3.5
object array

specific array of objects for which the absorption is expressed by a sound absorption coefficient ${}_{\mathrm{s}}$ related to the surface area covered by the array.

4 Calculation models

4.1 General principles

For the calculation of the equivalent sound absorption area and reverberation time in enclosed spaces it is assumed that the sound field is diffused. This means that the dimensions of the enclosed space are similar (see 4.6) and the absorption is distributed over the space; the presence of sound scattering objects relaxes these restrictions. The effect of absorption by surfaces, by objects - including persons -, by object arrays and by air is taken into account.

NOTE 1 For other situations, such as irregularly shaped spaces and irregular absorption distribution, guidance for improved calculation models is given in annex D. In irregularly shaped spaces, such as stairwells or rooms filled with machinery, it is assumed that the sound pressure level and hence absorption better characterises the performance than reverberation time.

The model can be used to calculate the building performance in frequency bands, based on acoustic data for the elements in frequency bands. The calculation is normally performed in octave bands in the frequency range from 125 Hz to 4 000 Hz.

NOTE 2 The calculations can be extended to higher or lower frequencies. However, particularly for the lower frequencies no information is available at present on the accuracy of calculations for these extended frequency regions.

A list of symbols used in the models is given in annex A.

4.2 Input data

The equivalent absorption area and the reverberation time can be determined from:

¾ absorption coefficient of surface i: ${}_{\mathrm{s,i}}$;

¾ area of surface i: S_{i};

¾ equivalent absorption area of object j: $A_{\mathrm{obj,j}}$;

¾ absorption coefficient of object array k: ${}_{\mathrm{s,k}}$;

¾ area of surface covered by the object array k: S_{k};

¾ volume of empty enclosed space: V;

- volume of object j or object array k: $V_{\mathrm{obj,j}}$, $V_{\mathrm{obj,k}}$.

The acoustic data on the materials, objects and object configurations involved should be taken primarily from standardized laboratory measurements in accordance with EN ISO 354. However, they may also be deduced in other ways, using theoretical calculations, empirical estimations or field measurement results. Data sources used shall be clearly stated.

The input data for calculations in octave bands can be taken as the arithmetic mean value of the corresponding one-third octave band values.

NOTE Using the arithmetic mean value of one-third octave band values as input for calculations in octave bands can be inaccurate for absorbers other than broad band absorbers.

Information on the sound absorption by some materials and surface treatments is given in annex B.

Information on the sound absorption by some typical objects is given in annex C.

4.3 Determination of the total equivalent absorption area

The total equivalent sound absorption area for an enclosed space follows from:

$$A = \sum_{\mathrm{i}=1}^{n} \alpha_{\mathrm{s,i}} \; S_{\mathrm{i}} + \sum_{\mathrm{j}=1}^{o} A_{\mathrm{obj,j}} + \sum_{\mathrm{k}=1}^{p} \alpha_{\mathrm{s,k}} \; S_{\mathrm{k}} + A_{\mathrm{air}} \tag{1}$$

where

n is the number of surfaces i;

o is the number of objects j;

p is the number of object arrays k.

The equivalent absorption area for air absorption follows from:

$$A_{\mathrm{air}} = 4 \, m \, V \, (1 - \quad) \tag{2}$$

where

m is the power attenuation coefficient in air, in Neper per metre;

V is the volume of the empty enclosed space, in cubic metres;

is the object fraction.

The object fraction follows from:

$$\Psi = \frac{\sum_{\mathrm{j}=1}^{o} V_{\mathrm{obj,j}} + \sum_{\mathrm{k}=1}^{p} V_{\mathrm{obj,k}}}{V} \tag{3}$$

The attenuation of sound by transmission through air is specified in ISO 9613-1 as a function of temperature, humidity and frequency. For sound transmission in rooms the relevant values determined in accordance with that standard for common conditions are given in Table 1. If other specific conditions apply, the values for the power attenuation coefficient shall be determined in accordance with ISO 9613-1. If no conditions are specified it is recommended that the values for 20 °C and 50 % - 70 % humidity are used.

If the calculations are restricted to the 1 000 Hz octave band as the highest frequency and to rooms with volumes less than 200 m^3, the absorption by air can be neglected and equation (1) shall be used with $A_{\text{air}} = 0$ m^2.

For hard, irregularly shaped objects such as machinery, storage cupboards or office furniture the equivalent absorption area may be important, but will not normally be available from measurements. For the purpose of this standard the equivalent absorption area of such a hard object can be estimated from its volume by:

$$A_{\text{obj}} = V_{\text{obj}}^{2/3} \tag{4}$$

where

V_{obj} is the volume of the hard objects.

NOTE This is an empirical equation used to obtain reliable results for spaces containing a relatively large number of objects as may be found in rooms containing technical equipment.

4.4 Determination of reverberation time

The reverberation time is determined from the total equivalent sound absorption area, as calculated by 4.3, the volume of the empty enclosed space and the object fraction:

$$T = \frac{55{,}3}{c_{\text{o}}} \frac{V\,(1 \quad \Psi)}{A} \tag{5}$$

where

c_{o} is the speed of sound in air, in metres per second.

NOTE For the ratio 55,3/c_{o} to be 0,16 as assumed in EN ISO 140-4 [8] the speed of sound has to be taken as 345,6 m/s.

Table 1 — Power attenuation coefficient in air *m* in octave bands, depending on temperature and humidity

	m in 10^{-3} Neper per metre, for octave bands with centre frequency in Hz						
	125	250	500	1k	2k	4k	8k
10 °C, 30 % - 50 % humidity	0,1	0,2	0,5	1,1	2,7	9,4	29,0
10 °C, 50 % - 70 % humidity	0,1	0,2	0,5	0,8	1,8	5,9	21,1
10 °C, 70 % - 90 % humidity	0,1	0,2	0,5	0,7	1,4	4,4	15,8
20 °C, 30 % - 50 % humidity	0,1	0,3	0,6	1,0	1,9	5,8	20,3
20 °C, 50 % - 70 % humidity	0,1	0,3	0,6	1,0	1,7	4,1	13,5
20 °C, 70 % - 90 % humidity	0,1	0,3	0,6	1,1	1,7	3,5	10,6

NOTE These values are deduced from the Tables with the atmospheric-absorption attenuation coefficient in decibels per kilometre in ISO 9613-1 for 1/3 octave bands, by dividing the values in those Tables by 4,343 (=10 lg e). The values for the octave bands are those for the centre 1/3 octave band below 1 kHz and those for the lower 1/3 octave band above 1 kHz. The values are linearly averaged over the humidity within the indicated range.

4.5 Interpretations

¾ the model is applicable to regularly shaped rooms in buildings with a reasonable distribution of absorbing material and some scattering of objects, both hard or absorbing, such as would be found in normal rooms in dwellings and offices. In such rooms, the absorption by air can be neglected and the volume fraction will typically be $< 0,05$ for empty rooms and 0,05 0,2 for furnished rooms;

¾ in rooms containing technical equipment or machinery, the volume fraction occupied by objects, even hard objects, can be quite important as can the air absorption. However, if the volume fraction is very large the free space can probably not be considered as a single space and thus the model may not be valid; see annex D;

¾ hard objects or object arrays are only of importance if their dimensions are larger than the wavelength, so objects with dimensions of less than 1 m can normally be neglected;

¾ in common spaces in buildings such as a stairwell or an entrance hall, the dimensions are such that the estimation of the reverberation time will be less reliable. In such spaces it may be appropriate for any requirements to specify the amount of absorption rather than the reverberation time.

4.6 Limitations

The calculation model for the equivalent absorption area is by definition independent of the type of enclosed space, though the relationship with the resulting sound pressure levels will depend on the type and shape of the enclosed space.

The calculation model for the reverberation time is restricted to enclosed spaces with:

¾ regular shaped volumes: no dimension should be more than 5 times any other dimension;

¾ evenly distributed absorption: absorption coefficient should not vary by more than a factor of 3 between pairs of opposite surfaces, unless some sound scattering objects are present;

¾ not too many objects: the object fraction should be less than 0,2.

If these assumptions are not met, the reverberation time can often be longer than estimated. Indications on how to determine the reverberation time in such situations are given in annex D.

5 Accuracy

The accuracy of the prediction model depends on many factors: the accuracy of the input data, the fit of the situation to the model, the type of materials, elements and objects involved, the geometry of the situation and the workmanship. It is therefore not possible to specify the accuracy of the predictions for all situations and applications. Data on the accuracy will have to be gathered for future use by comparing the results of calculations to the model with accurate field measurement results in a variety of situations. However, from limited practical experience, it has been observed that for situations with a low diffusivity (due to irregular room shape, irregular absorption distribution, few scattering objects or low modal density), the actual reverberation time could be up to twice the predicted reverberation time. Increased diffusivity, for instance by having more scattering objects, will decrease this difference substantially.

In applying predictions it is advisable to vary the input data, especially for complicated situations and with atypical elements with uncertain input data. The resulting variation in the results gives an impression of the expected accuracy for these situations.

Annex A
(normative)

List of symbols

Table A.1 — List of symbols

Symbol	Physical quantity	Unit
A	total equivalent sound absorption area in an enclosed space	m^2
A_{obj}	equivalent sound absorption area of an object	m^2
$A_{obj,j}$	equivalent sound absorption area of object j	m^2
$A_{obj,k}$	equivalent sound absorption area of object configuration k	m^2
$A_{obj,x}$, $A_{obj,y}$, $A_{obj,z}$ $A_{opj,central}$	equivalent sound absorption area of objects near surfaces at respectively x = 0, x = L, y = 0, y = B, z = 0, z = H and in the central area of the room	m^2
$A_{x = L}$,$A_{y = B}$, $A_{z = H}$	equivalent sound absorption area of surface at x = L, y = B, z = H, etc.	m^2
A_{air}	equivalent sound absorption area by air	m^2
A_x,A_y,A_z, A_d	equivalent sound absorption area for sound fields grazing to surfaces perpendicular to respectively the x-, y- and z-axis and the diffuse sound field	m^2
A_s	equivalent sound absorption area of surfaces and objects in subspace *s*	m^2
A'_x,A'_y,A'_z, A'_d	scattering sound absorption area for coupling between sound fields from grazing field x, y and z to diffuse and diffuse to grazing fields	m^2
A^*_x,A^*_y,A^*_z, A^*_d	effective sound absorption area for sound fields grazing to surfaces perpendicular to respectively the x-, y- and z-axis and the diffuse sound field	m^2
A^*_{xyzd}	effective sound absorption area in an enclosed space below f_t	m^2
C	dimensionless parameter for absorbing material (= / $_o f$)	-
c_o	speed of sound in air	m/s
d	thickness of a layer of absorbing material	m
f	frequency	Hz
f_{ref}	reference frequency (= 1 000 Hz)	Hz
f_t	transition frequency	Hz
i	index for absorbing surfaces	-
j	index for absorbing objects, index of subspace	-
k	index for absorbing object array, index for sources, index for subspaces	-
k_o	wave number (= 2 f/c_o)	m^{-1}
$L_{p,s}$	sound pressure level in subspace s	dB re 20 Pa

continued

Table A.1 continued

Symbol	Physical quantity	Unit
$L_{\mathrm{p,x}}$	sound pressure level for grazing sound field x; the same with index y, z and d for grazing sound field y and z and diffuse sound field	dB re 20 Pa
$L_{\mathrm{W,k}}$	sound power level of source k	dB re 1 pW
L, B, H	length, width and height of a rectangular enclosed space	m
l_{ref}	reference length (= 1 m)	m
m	power attenuation coefficient in air	$(\mathrm{Np})\mathrm{m}^{-1}$
$\mathrm{N_x, N_y, N_z}$	relative number of modes grazing to surfaces perpendicular to resp. the x-, y- and z-axis	-
n	number of absorbing surfaces, number of subspaces k	-
o	number of absorbing objects	-
p	number of absorbing object arrays	-
p_{o}	reference sound pressure level; $p_o = 20$ Pa	Pa
r	air flow resistivity	Pa s/m^2
r	pressure-reflection coefficient for a plane sound wave, incident at an angle	-
r_{k}	distance from source k to the reception point in a subspace	m
s	number of subspaces in an enclosed space	-
S_{i}	area of surface i	m^2
S_{k}	area of surface covered by object array k	m^2
$S_{\mathrm{s,j}}$	open area connecting subspace *s* with subspace j	m^2
T	reverberation time	s
$T_{\mathrm{x}}, T_{\mathrm{y}}, T_{\mathrm{z}}\ T_{\mathrm{d}}$	reverberation time for modes in x- , y- and z-direction and diffuse field of an enclosed space	s
T_{eff}	effective reverberation time in enclosed space considering modes in three directions	s
V	volume of empty enclosed space	m^3
V_{s}	volume of subspace s	m^3
V_{obj}	volume of an object or object configuration	m^3
$V_{\mathrm{obj,j}}$	volume of object j	m^3
$V_{\mathrm{obj,k}}$	volume of object configuration k	m^3
W_{s}	sound power, injected into subspace s	W
W_{o}	reference sound power; W_o = 1 picoWatt	W
w_{s}	sound energy density in subspace *s*	J/m^3
x, y, z	distance in three directions of a rectangular enclosed space	m

continued

Table A.1 *concluded*

Symbol	Physical quantity	Unit
Z'	$_oc_o$ normalised surface impedance	-
Z'_c	$_oc_o$ normalised characteristic impedance of the absorbing material	-
s	absorption coefficient	-
s,i	absorption coefficient of surface i	-
s,k	absorption coefficient of specified array of objects k	-
$\overline{\ }_s$	average absorption coefficient for subspace s	-
	absorption coefficient for a plane sound wave, incident at an angle	-
	propagation coefficient in the absorbing material	m^{-1}
x = 0	scattering coefficient for surface at x=0; the same with index for surfaces at x = L, y = 0, y = B, z = 0, z = H respectively	-
	angle of incident of plane wave	rad
o	density of air	kg/m^3
	attenuation factor for various attenuation effects for direct sound propagation like screening and radiation directivity	-
	object fraction	-

Annex B
(informative)

Sound absorption of materials

B.1 Examples

Absorption coefficients for some common surfaces in buildings, as measured in accordance with EN ISO 354, are given in Table B.1. These values can be considered as typical minimum values.

Table B.1 — Typical values for the absorption coefficient

Material	**Sound absorption coefficient $_s$ in octave bands, centre frequency in Hz**					
	125	250	500	1 000	2 000	4 000
concrete, plastered brick	0,01	0,01	0,01	0,02	0,02	0,03
brickwork, unplastered	0,02	0,02	0,03	0,04	0,05	0,07
hard floor coverings (e.g. PVC, parquet) on heavy floor	0,02	0,03	0,04	0,05	0,05	0,06
soft floor covering on heavy floor; 5 mm	0,02	0,03	0,06	0,15	0,30	0,40
soft floor covering on heavy floor; 10 mm	0,04	0,08	0,15	0,30	0,45	0,55
wooden floor, parquet on battens	0,12	0,10	0,06	0,05	0,05	0,06
windows, glass facade	0,12	0,08	0,05	0,04	0,03	0,02
doors (wood)	0,14	0,10	0,08	0,08	0,08	0,08
net curtain; 0 mm - 200 mm in front of hard surface[1]	0,05	0,04	0,03	0,02	0,02	0,02
curtain, < 0,2 kg/m^2; 0 mm – 200 mm in front of hard surface; typical minimum [1]	0,05	0,06	0,09	0,12	0,18	0,22
curtain, woven material 0,4 kg/m^2; folded or ruffled > 1:3, 0-200 mm in front of hard surface; typical maximum	0,10	0,40	0,70	0,90	0,95	1,00
large openings (smallest dimension > 1 m)	1,00	1,00	1,00	1,00	1,00	1,00
air grid, 50 % open area	0,30	0,50	0,50	0,50	0,50	0,50
NOTE These data are based on publications used in Austria, Denmark and the Netherlands.						
[1] in front of a window the values of the combination can increase to the values for such a window alone.						

B.2 Calculation

The sound absorption coefficient of a layer of porous material placed directly on a hard wall can be estimated from knowledge of the flow resistance of the material and the thickness of the layer. The flow resistance is measured in accordance with EN 29053 [3].

For a diffuse sound field the absorption coefficient $_s$ may be determined from:

$$_s = \int_0^{/2} \sin 2 \quad d$$

$$= 1 \quad \left| r \right|^2 \qquad \text{(B.1}$$

$$r = \frac{Z' \cos \quad 1}{Z' \cos \quad + 1}$$

where

is the angle of incidence, in radians;

is the absorption coefficient for a plane sound wave, incident at an angle ;

r is the pressure-reflection coefficient for a plane sound wave, incident at an angle ;

Z' is the c normalised surface impedance of the layer.

The normalised impedance of the layer for locally reacting material placed directly on a hard wall may be determined from:

$$Z' = Z'_c \coth \quad d \qquad \text{(B.2}$$

where

is the propagation coefficient in the absorbing material, in radians per metre;

d is the thickness of the layer, in metres;

Z'_c is the $_o c_o$ normalised characteristic impedance of the absorbing material.

For various absorbing materials the normalised material impedance W' and the propagation constant can be deduced from the flow resistance r of the material by empirical relationships using C and the wave number k_o as parameters :

$$C = \frac{r}{_o f}$$

$$\text{(B.3}$$

$$k_o = \frac{2 \pi f}{c_o}$$

where

r is the air flow resistivity, in Pascal seconds per square metre;

f is the frequency, in Hertz;

$_o$ is the density of air (1,2 kg/m^3), in kilograms per cubic metre;

c_o is the speed of sound in air (343 m/s), in metres per second.

In the relations given, the time dependence of time varying quantities is assumed as $e^{-i2 \ f t}$.

For fibrous material these relationships are [1], [4]:

$$Z'_{\mathrm{c}} = \left(1 + 0{,}0571\ C^{\ 0{,}754}\right) \quad \mathrm{i} \ \left(0{,}087\ C^{\ 0{,}732}\right)$$

(B.4a)

$$\gamma = \mathrm{k_o} \left(0{,}189\ C^{\ 0{,}595}\right) + \mathrm{ik_o} \left(1 + 0{,}0978\ C^{\ 0{,}700}\right)$$

For open-cell foams these relationships are [2]:

$$Z'_{\mathrm{c}} = \left(1 + 0{,}114\ C^{\ 0{,}369}\right) \quad \mathrm{i} \ \left(0{,}0985\ C^{\ 0{,}758}\right)$$

(B.4b)

$$\gamma = \mathrm{k_o} \left(0{,}168\ C^{\ 0{,}715}\right) + \mathrm{ik_o} \left(1 + 0{,}136\ C^{\ 0{,}494}\right)$$

Each of these relationships has its own range of validity for the parameter C. For high values of C these relationships lead to physically incorrect results. For such values a better estimation may be obtained from theory by [4]:

$$Z'_{\mathrm{c}} = \sqrt{1{,}11 \quad \mathrm{i} \quad 0{,}12\,C}$$

(B.4c)

$$= \mathrm{ik_o} \ 1{,}33\, Z'_{\mathrm{c}}$$

For open-cell foam and fibrous material, results for continuous values of C are obtained by using the equations as follows:

$C < 0{,}25$: equations B.4b

$0{,}25 \quad C \quad 80$: equations B.4a

$C > 80$: equations B.4c

These type of predictions can also be applied to multi-layered absorbing elements or absorbing materials backed by an airspace; see the Bibliography [4].

Annex C
(informative)

Sound absorption of objects

For some common objects and configurations of objects the equivalent absorption area and sound absorption coefficient measured in accordance with EN ISO 354 are given in Tables C.1 and C.2. These values can be considered as typical values.

Table C.1 — Typical values for the equivalent absorption area for some common objects

Object	**Equivalent absorption area A_{obj} in octave bands, centre frequency in Hz**					
	125	250	500	1 000	2 000	4 000
single chair, wood	0,02	0,02	0,03	0,04	0,04	0,04
single chair, upholstered	0,10	0,20	0,25	0,30	0,35	0,35
single person in a group, sitting or standing, 1 per 6 m^2 area; typical minimum	0,05	0,10	0,20	0,35	0,50	0,65
single person in a group, sitting, 1 per 6 m^2 area; typical maximum	0,12	0,45	0,80	0,90	0,95	1,00
single person in a group, standing, 1 per 6 m^2 area; typical maximum	0,12	0,45	0,80	1,20	1,30	1,40

NOTE These data are based on publications used in Austria, Denmark and the Netherlands.

Table C.2 — Typical vales for the sound absorption coefficient for some common specified arrays of objects

Array of objects	**Sound absorption coefficient $_{\text{s}}$ in octave bands, centre frequency in Hz**					
	125	250	500	1 000	2 000	4 000
chairs in a row at 0,9m – 1,2m; wood/plastic	0,06	0,08	0,10	0,12	0,14	0,16
chairs in a row at 0,9m – 1,2m; upholstered; typical minimum	0,10	0,20	0,30	0,40	0,50	0,50
chairs in a row at 0,9m – 1,2m; upholstered; typical maximum	0,50	0,70	0,80	0,90	1,0	1,0
persons sitting in a row at 0,9m – 1,2m (audience); typical minimum	0,20	0,40	0,50	0,60	0,70	0,70
persons sitting in a row at 0,9m – 1,2m (audience); typical maximum	0,60	0,70	0,80	0,90	0,90	0,90
children in a hard furnished class room, 1 per m^2 area	0,10	0,20	0,25	0,35	0,40	0,40

NOTE These data are based on publications used in Austria, Denmark and the Netherlands.

Annex D
(informative)

Estimation for irregular spaces and/or absorption distribution

D.1 Introduction

If the enclosed space has a non-regular distribution of absorption, has irregular shapes or is filled to a large extent with machinery and equipment, the prediction of reverberation time according to the calculation model in clause 4 can either be incorrect or irrelevant. This annex indicates possible means of improving predictions in such situations. The two main situations considered are (a) rectangular spaces with irregular absorption distribution and (b) irregularly shaped spaces, either as a result of the design or resulting from filling the empty space with a large number of objects (object fraction well in excess of 0,2).

D.2 Irregular absorption distribution

An essentially rectangular space with irregular absorption distribution is quite common. In many offices absorption is only applied to the ceiling, all other surfaces being fairly reflective. Though various proposals have been presented in literature to deal with this situation, none of them seems to work adequately in all situations. A reasonable solution is to divide the sound field into parts that graze the different surfaces and a part that is non-grazing [5]. The different effect of absorbing materials for these different sound fields and the effect of diffusing elements of mixing the sound fields is taken into account by considering the balance of power between the sound fields. In this annex a practical estimation is provided, based on that model but making use of absorption data measured in accordance with standard methods.

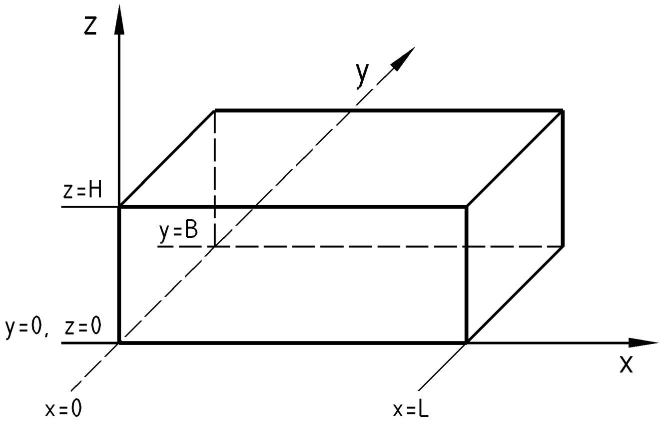

Figure D.1 — Definition of dimensions for a rectangular space

The room dimensions are defined as in Figure D.1 for the room with volume $V = L \times B \times H$ m^3. For the higher frequencies the total sound field is divided into three fields, grazing the surfaces perpendicular to the axis x, y and z, and a diffuse field. For each of these fields the effective absorption and corresponding reverberation time is determined. The importance of each of these sound fields is determined by the number of modes in those fields deduced from the room dimensions. For the lower frequencies the total sound field is considered with a reduced absorption effect due to the lack of diffusion in the room at those frequencies.

The transition between high and low frequency is determined by comparing the octave band mid frequency with the transition frequency given by:

$$f_t = \frac{8{,}7\, c_{\mathrm{o}}}{V^{1/3}} \qquad \text{(D.1)}$$

The equivalent sound absorption area A of a surface is deduced from absorption data as found in 4.3 considering only the specific surface and neglecting any objects. The equivalent sound absorption area of the relevant objects A_{obj} is also deduced from absorption data as in 4.3. The absorption of the room surfaces and the absorption by the various objects is applied to the sound fields considered as described in this annex. Additionally a scattering coefficient can be attributed to the room surfaces that indicates the fraction of the energy reflected diffusely; its value could range from 0,0 to 1,0. Even if only a few data on this coefficient are currently available, a global estimation can be used to get an impression of the effect of scattering on the results in specific situations.

NOTE 1 The scattering coefficient takes into account irregularities in the plane surfaces. For hard plane surfaces a typical value will be 0,05 or less, but for walls with recesses as found in a facade the value at mid and higher frequencies can take typical values of 0,4 to 0,6.

The relative mode number as given by equation D.2 indicates the contribution of each sound field:

$$N_{\mathrm{x}} = 0{,}14 + 1{,}43 \;\frac{(B+H)}{2c_{\mathrm{o}}} + \frac{\pi f}{c_{\mathrm{o}}^2} BH \;\; \frac{c_o^3}{4\,\pi f^2 V}$$

$$N_{\mathrm{y}} = 0{,}14 + 1{,}43 \;\frac{(L+H)}{2c_{\mathrm{o}}} + \frac{\pi f}{c_{\mathrm{o}}^2} LH \;\; \frac{c_{\mathrm{o}}^3}{4\,\pi f^2 V} \qquad \text{(D.2)}$$

$$N_{\mathrm{z}} = 0{,}14 + 1{,}43 \;\frac{(L+B)}{2c_{\mathrm{o}}} + \frac{\pi f}{c_{\mathrm{o}}^2} LB \;\; \frac{c_{\mathrm{o}}^3}{4\,\pi f^2 V}$$

The equivalent sound absorption area for the grazing sound fields A_{x}, A_{y} and A_{z} and the equivalent sound absorption area A_{d} for the diffuse field due to the room surfaces and air absorption may be determined from equations D.3a-d:

$$A_{\mathrm{x}} = \frac{c_o^2}{2f^2 L^2}\left(A_{\mathrm{x}=0} + A_{\mathrm{x}=\mathrm{L}}\right)\left(f / f_{\mathrm{ref}}\right)^{1/3} + A_{\mathrm{y}=0} + A_{\mathrm{y}=\mathrm{B}} + A_{\mathrm{z}=0} + A_{\mathrm{z}=\mathrm{H}} \sqrt{2}\left(f / f_{\mathrm{ref}}\right)^{1/3} + \pi m V \qquad \text{(D.3a)}$$

$$A_{\mathrm{y}} = \frac{c_{\mathrm{o}}^2}{2f^2 B^2}\left(A_{\mathrm{y}=0} + A_{\mathrm{y}=\mathrm{B}}\right)\left(f / f_{\mathrm{ref}}\right)^{1/3} + A_{\mathrm{x}=0} + A_{\mathrm{x}=\mathrm{L}} + A_{\mathrm{z}=0} + A_{\mathrm{z}=\mathrm{H}} \sqrt{2}\left(f / f_{\mathrm{ref}}\right)^{1/3} + \pi m V \qquad \text{(D.3b)}$$

$$A_z = \frac{c_o^2}{2f^2 H^2}\left(A_{z=0} + A_{z=\mathrm{H}}\right)\left(f / f_{\mathrm{ref}}\right)^{1/3} + A_{x=0} + A_{\mathrm{x}=\mathrm{L}} + A_{\mathrm{y}=0} + A_{\mathrm{y}=B} \sqrt{2}\left(f / f_{\mathrm{ref}}\right)^{1/3} + \pi m V \qquad \text{(D.3c)}$$

$$A_{\mathrm{d}} = \left(A_{\mathrm{x}=0} + A_{\mathrm{x}=\mathrm{L}} + A_{\mathrm{y}=0} + A_{\mathrm{y}=\mathrm{B}} + A_{\mathrm{z}=0} + A_{\mathrm{z}=\mathrm{H}}\right) + 4\, m\, V \qquad \text{(D.3d)}$$

where

$A_{x=0}$, $A_{x=L}$ is the equivalent sound absorption area of surface x = 0 and x = L respectively, in square metres.

NOTE 2 The indexes y and z indicate the same quantities associated with the surfaces perpendicular to the y-axis and z-axis.

f_{ref} is the reference frequency, in Hz; f_{ref} = 1 000 Hz.

The different sound fields are coupled by the diffusing effects of surfaces and the diffusing and absorbing effects of objects. This is expressed in the scattering sound absorption area A'_{x}, A'_{y}, A'_{z} and A'_{d} for each sound field as may be determined from equations D.4a-d:

$$A'_{\mathrm{x}} = LH(\,\delta_{\mathrm{y}=0} + \delta_{\mathrm{y}=\mathrm{B}}\,) + LB\,(\,\delta_{\mathrm{z}=0} + \delta_{\mathrm{z}=\mathrm{H}} + A_{\mathrm{obj,y}} + A_{\mathrm{obj,z}} + A_{\mathrm{obj,central}} \tag{D.4a}$$

$$A'_{\mathrm{y}} = BH(\,\delta_{\mathrm{x}=0} + \delta_{\mathrm{x}=\mathrm{B}}\,) + LB(\,\delta_{\mathrm{z}=0} + \delta_{\mathrm{z}=\mathrm{H}} + A_{\mathrm{obj,x}} + A_{\mathrm{obj,z}} + A_{\mathrm{obj,central}} \tag{D.4b}$$

$$A'_{\mathrm{z}} = BH(\,\delta_{\mathrm{x}=0} + \delta_{\mathrm{x}=\mathrm{B}}\,) + LH(\,\delta_{\mathrm{y}=0} + \delta_{\mathrm{y}=\mathrm{H}} + A_{\mathrm{obj,x}} + A_{\mathrm{obj,y}} + A_{\mathrm{obj,central}} \tag{D.4c}$$

$$A'_{\mathrm{d}} = \sum_{\mathrm{all}} A_{\mathrm{obj}} + N_{\mathrm{x}}A'_{\mathrm{x}} + N_{\mathrm{y}}A'_{\mathrm{y}} + N_{\mathrm{z}}A'_{\mathrm{z}} \tag{D.4d}$$

where

$_{\mathrm{x}=0}$, $_{\mathrm{x}=\mathrm{L}}$ is the scattering coefficient of surface x = 0 and x = L respectively;

A_{obj} is the equivalent sound absorption area of an object, in square metres;

$A_{\mathrm{obj,x}}$ is the equivalent sound absorption area of those objects associated with surfaces at x = 0 and x = L, in square metres;

$A_{\mathrm{obj,central}}$ is the equivalent sound absorption area of those objects in the central space, in square metres.

NOTE 3 The indexes y and z indicate the same quantities associated with the y-axis and z-axis.

The effective sound absorption area for each sound field may be determined from equation D.5a-b:

$$A_{\mathrm{d}}^{*} = \frac{A_{\mathrm{d}} + A'_{\mathrm{d}} \quad N_{\mathrm{x}}A'^{2}_{\mathrm{x}} / (A_{\mathrm{x}} + A'_{\mathrm{x}}) \quad N_{\mathrm{y}}A'^{2}_{\mathrm{y}} / (A_{\mathrm{y}} + A'_{\mathrm{y}}) \quad N_{\mathrm{z}}A'^{2}_{\mathrm{z}} / (A_{\mathrm{z}} + A'_{\mathrm{z}})}{1 + N_{\mathrm{x}}A'_{\mathrm{x}} / (A_{\mathrm{x}} + A'_{\mathrm{x}}) + N_{\mathrm{y}}A'_{\mathrm{y}} / (A_{\mathrm{y}} + A'_{\mathrm{y}}) + N_{\mathrm{z}}A'_{\mathrm{z}} / (A_{\mathrm{z}} + A'_{\mathrm{z}})} \tag{D.5a}$$

$$A_{\mathrm{x}}^{*} = \frac{A_{\mathrm{x}} + A'_{\mathrm{x}}}{1 + A'_{\mathrm{x}} / A_{\mathrm{d}}^{*}};\ A_{\mathrm{y}}^{*} = \frac{A_{\mathrm{y}} + A'_{\mathrm{y}}}{1 + A'_{\mathrm{y}} / A_{\mathrm{d}}^{*}};\ A_{\mathrm{z}}^{*} = \frac{A_{\mathrm{z}} + A'_{\mathrm{z}}}{1 + A'_{\mathrm{z}} / A_{\mathrm{d}}^{*}} \tag{D.5b}$$

The effective sound absorption area for the total field A^*_{xyzd} for low frequencies ($f < f_\mathrm{t}$) may be determined from equation D.6a:

$$A^*_{\mathrm{xyzd}} = \left(\overline{A_{\mathrm{x}=0}} + \overline{A_{\mathrm{x}=\mathrm{L}}} + \overline{A_{\mathrm{y}=0}} + \overline{A_{\mathrm{y}=\mathrm{B}}} + \overline{A_{\mathrm{z}=0}} + \overline{A_{\mathrm{z}=\mathrm{H}}} \right) + \sum A_{\mathrm{obj}} + 4\,mV \qquad \text{(D.6a)}$$

by reducing the effectiveness of the absorption of the surfaces denoted as $\overline{A}$ for each index x, y and z by

$$\overline{A} = A\mathrm{e}^{\ A/S} \qquad \text{(D.6b)}$$

where A and S are the equivalent sound absorption area and surface area of the surface considered respectively.

The reverberation time for each sound field x, y, z and d is given by equation D.7:

$$T_{\mathrm{x}} = \frac{55{,}3}{c_\mathrm{o}} \frac{V\,(1 \qquad)}{A^*_{\mathrm{x}}};\ T_y = \frac{55{,}3}{c_\mathrm{o}} \frac{V\,(1 \qquad)}{A^*_{\mathrm{y}}};\ T_z = \frac{55{,}3}{c_\mathrm{o}} \frac{V\,(1 \qquad)}{A^*_{\mathrm{z}}};\ T_d = \frac{55{,}3}{c_\mathrm{o}} \frac{V\,(1 \qquad)}{A^*_{\mathrm{d}}} \qquad \text{(D.7)}$$

The relative sound level at t = 0 s for each sound field x, y, z and d may be determined from:

$$L_{\mathrm{p,d}} = \quad 10\lg \left(1 + N_{\mathrm{x}} \frac{A^*_{\mathrm{d}}}{A^*_{\mathrm{x}}} + N_y \frac{A^*_{\mathrm{d}}}{A^*_{\mathrm{y}}} + N_z \frac{A^*_{\mathrm{d}}}{A^*_{\mathrm{z}}} \right) \qquad \text{(D.8a)}$$

$$L_{\mathrm{p,x}} = L_{\mathrm{p,d}} + 10\lg \left(N_{\mathrm{x}} \frac{A^*_{\mathrm{d}}}{A^*_{\mathrm{x}}} \right);\ L_{\mathrm{p,y}} = L_{\mathrm{p,d}} + 10\lg \left(N_{\mathrm{y}} \frac{A^*_{\mathrm{d}}}{A^*_{\mathrm{y}}} \right);\ L_{\mathrm{p,z}} = L_{\mathrm{p,d}} + 10\lg \left(N_{\mathrm{z}} \frac{A^*_{\mathrm{d}}}{A^*_{\mathrm{z}}} \right) \qquad \text{(D.8b)}$$

If the differences between the four reverberation times from equation D.7 are small, the diffuse field reverberation time can be considered as an adequate estimation for the situation under consideration. If not, the reverberation time is probably longer and the decay curve will no longer be monotonic. A more realistic estimate of T_{20} can then be calculated from the average of the effective reverberation times from equation D.9a for the higher frequency range. This estimate of the reverberation time cannot however be shorter than that for the diffuse field.

$$T_{\mathrm{estimate}} = \frac{\left(T_{\mathrm{x}} + T_{\mathrm{y}} + T_{\mathrm{z}} + T_{\mathrm{d}} \right)}{4} \quad T_{\mathrm{d}} \qquad \text{(D.9a)}$$

For the lower frequencies ($f < f_\mathrm{t}$) the estimation is given by equation D9b:

$$T_{\mathrm{estimate}} = \frac{55{,}3}{c_\mathrm{o}} \frac{V\,(1 \qquad)}{A^*_{\mathrm{xyxd}}} \qquad \text{(D.9b)}$$

D.3 Irregularly shaped spaces

With very irregularly shaped spaces or narrow spaces the reverberation time will not be constant over the whole space, as will be the case with many and/or large objects in a regularly shaped space. However, for situations with a large amount of machinery and equipment, it is not the reverberation time that is particularly important, but the sound pressure levels in the different parts of the room. These sound pressure levels will depend on the distribution and the sound power of the sources as well as the distribution of absorption. In such cases, an estimate of the sound pressure levels can be based on an approach where the total space is divided into regular sub-spaces. The sound pressure level is estimated in each sub-space by the direct sound from the sources in that sub-space and the contribution from the sound power distribution over all sub-spaces [6]. The sound power distribution follows from the sound power injected into the reverberant field by the sources in each sub-space, the equivalent sound absorption area for each sub-space and the power balance between all connected sub-spaces.

NOTE This approach could be used for prEN 12354-5 [9] and will be developed along the lines indicated below, either in future versions of part 6 or in prEN 12354-5 [9].

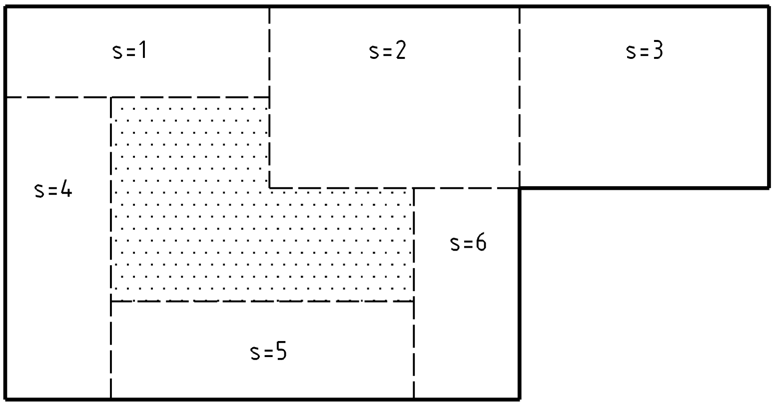

Figure D.2 — Illustration of an irregular shaped space and its division into sub-spaces s = 1 through s = 6.

The equivalent sound absorption area in each sub-space with volume V_s is calculated according to 4.3, with the assumption that = 1 for all open surfaces S_{sj} between *s* the sub-space considered and the n connected sub-spaces j. The following relation holds for each sub-space *s* in which there are k sound sources with sound power level $L_{W,k}$:

$$W_s = c_o w_s A_s \quad \sum_{j\;\;s}^{n} c_o w_j S_{sj} \qquad \text{(D.10a)}$$

with

$$W_s = (\,1 \quad \bar{}_s\,) W_o \sum_{k} 10^{L_{W,k}/10} \qquad \text{(D.10b)}$$

where

W_s is the sound power injected into the reverberant field by sources in subspace s, in Watts;

W_o is the reference sound power in Watts, W_o = 1 picoWatt;

w_s is the sound energy density in subspace *s*, in Joules per cubic metre;

A_s	is the equivalent sound absorption area in subspace s of surfaces, openings, objects and air, in square metres;
$S_{s,j}$	is the open connecting area between subspace s and subspace j, in square metres;
n	is the number of subspaces k, connected to subspace *s*;
$L_{W,k}$	is the sound power level of source k in subspace *s*, in dB re 1 picoWatt;
$_s$	is the average absorption coefficient for subspace s, taking into account all absorption (i.e. surfaces, openings, objects, air).

The sound energy density w_s in each subspace is found by solving equation D.10a with given sound power levels and absorption, for instance by matrix inversion. The sound pressure level, $L_{p,s}$, at positions in each subspace is found from this by taking into account the direct sound transmission to the reception point from the sources k at distance r_k and the appropriate attenuation factors resulting from effects such as screening and radiation directivity:

$$L_{p,s} = 10 \lg \frac{\rho_o c_o}{p_o^2} \; 4 c_o w_s + \sum_k \frac{W_o}{4\pi r_k^2} \chi_k \; 10^{L_{W,k}/10} \tag{D.11}$$

where

$L_{p,s}$	is the sound pressure level in subspace s, in dB re 20 Pascal;
p_p	is the reference sound pressure, in Pascal; p_o = 20 Pascal;
r_k	is the distance between source k and the reception point in subspace k, in metres;
$_k$	is an attenuation factor describing various attenuation effects during sound propagation such as screening and radiation directivity from source k to the reception point.

Annex E
(informative)

Calculation example

A room has the dimensions (length, width, height) of 4,54 x 2,73 x 2,40 = 29,75 m^3.

The floor and ceiling are made from concrete, one wall (long wall) and the two sidewalls (short walls) are made from unplastered brickwork and the remaining surface is a glass facade. The floor has a hard floor covering. Consider the octave band of 1 000 Hz.

Case 1: bare, empty room

According to annex B the absorption coefficient for the surfaces are $_{\text{floor}}$ = 0,05, $_{\text{ceiling}}$ = 0,02, $_{\text{wal l}}$ = 0,04, $_{\text{sidewall}}$ = 0,04 and $_{\text{façade}}$ = 0,04. Considering the 1 000 Hz octave band and the volume, the air absorption can be neglected (A_{air} = 0 m^2). With these data equation (1) leads to an equivalent absorption area of A = 12,39 0,05 + 12,39 0,02 + 10,90 0,04 + 10,90 0,04 + 6,55 0,04 + 6,55 0,04 = 2,26 m^2, rounded to A = 2,3 m^2. With equation (5) the resulting reverberation time becomes T = 0,16 . 29,75 / 2,26 = 2,1 s.

NOTE In this case A_{air} = 0,12 m^2 at normal conditions, so the reverberation time would be 2,0 s.

Case 2: case 1 with (hard) objects

Bringing a table (0,15 m^3), a desk (0,60 m^3), two chairs (2x 0,05 m^3) and two cupboards (2x 0,65 m^3) into the room, the volume fraction becomes = 0,072, while the absorption by these hard objects is estimated as $\sum A_{\text{obj}} = 0{,}15^{2/3} + 0{,}60^{2/3} + 2 \quad 0{,}05^{2/3} + 2 \quad 0{,}65^{2/3} = 2{,}77$ m^2.

Thus the equivalent absorption area becomes A = 2,26+2,77 = 5,03 m^2, rounded to A = 5,0 m^2, and the reverberation time follows as T = 0,16 . 29,75 (1-0,072)/5,03 = 0,9 s.

Case 3: case 1 with one absorbing wall

One long wall is lined for 90 % of its area with absorbing material with an absorption coefficient of $_{\text{s}}$ = 0,85. Thus the equivalent absorption becomes
A = 12,39 0,05 + 12,39 0,02 + (1,09 0,04 + 9,81 0,85) + 10,90 0,04 + 6,55 0,04 + 6,55 0,04 = 10,21 m^2, rounded to A = 10,2 m^2.

With equation (5) the resulting reverberation time becomes T = 0,16 . 29,75 / 10,21 = 0,5 s.

Since two opposite walls differ significantly in absorption and there are no scattering objects, this case is in fact outside the application limits of the model. An indication of the reverberation time could in this situation be derived from annex D. According to D.2 the reverberation times for the four sound fields would in this case, without additional scattering by surfaces or objects, become (equation D.3) A^*_{x} = 13,69 m^2; A^*_{y} = 2,04 m^2; A^*_{z}=13,22 m^2 and A^*_{d} = 10,21 m^2. The corresponding reverberation times (eq. D.6) are T_{x} = 0,35 s; T_{y} = 2,34 s; T_{z} = 0,36 s and T_{d} = 0,47 s, giving an effective reverberation time of T_{eff} = 0,9 s (equation D.8). Since T_{y} is about five times longer than the shortest time, this is likely to be a better estimate of the real reverberation time (T_{20}) in this case.

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