COMPARATIVE LIFE CYCLE SOCIAL ASSESSMENT OF BUILDINGS: ACOUSTIC CRITERION

A. Pereira [1], H. Gervásio [1], P. Santos[1], L. Simões da Silva [1], A. Bettencourt [2]

[1] ISISE, Department of Civil Engineering, University of Coimbra, Coimbra, Portugal
{apereira@dec.uc.pt, hger@dec.uc.pt, pfsantos@dec.uc.pt, luisss@dec.uc.pt}
[2] CEARQ, Department of Architecture, University of Coimbra, Coimbra, Portugal
{antonio.bettencourt@iol.pt}

Abstract
In order to assess sustainability of buildings (either new or existing) environmental, economic and social criteria need to be considered. Within the evaluation of social performance in the use stage, guidance is provided by the standard EN 16309:2014, where the following performance categories are defined: (i) Accessibility; (ii) Adaptability; (iii) Health and Comfort; (iv) Impacts on the Neighbourhood; (v) Maintenance and Maintainability; and (vi) Safety and Security.
Contrary to the standards for the assessment of environmental and economic criteria, the qualitative approach recommended for social assessment does not enable an easy comparability of the results of assessments. Moreover, at the present time no application to real case study buildings have been performed, which makes its practical implementation and its understanding more complex.
Thus, the aim of this paper is to propose a methodology to perform a life cycle assessment of the social performance of buildings, focusing on the criterion of health and comfort. This criterion addresses different sub-criteria: in this paper the assessment is performed taking into account the sub-criterion of acoustic comfort. The buildings selected as case studies are schools for higher education. Three different buildings are analyzed and the results are compared aiming to obtain a ranking of the building acoustic performances.

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1 Introduction

Within the evaluation of social sustainability of buildings in the use stage, methods and requirements are provided in the standard EN 16309:2014 [1], while taking into account the building's functionality and technical characteristics. Contrary to the standards for the assessment of environmental and economic criteria, the qualitative approach recommended for social assessment does not enable an easy comparability of the results of assessments. Moreover, at the present time no application to real case study buildings have been performed, which makes its practical implementation and its understanding more complex. The purpose of the present paper is to focus on the assessment of the Health and Comfort criterion. This criterion includes different sub-criteria: i) Thermal characteristics; iii) acoustic characteristics; iv) indoor air quality characteristics; v) visual comfort and special characteristics. The acoustic sub-criterion is hereunder addressed for buildings used as schools for higher education.
Several attempts have been performed to provide acoustic classifications of buildings or parts of buildings, such as the one provided by Portuguese National Laboratory of Civil Engineering for

residential buildings [2]. Within European Union, other countries also use different classification schemes for evaluation of acoustic quality of dwellings ([3], [4]) and no uniformity is achieved either because different acoustic parameters are used to evaluate the acoustic performance of constructive solutions or because different requirements are defined. Cost Action TU 0901 has been working in order to achieve a harmonization of acoustic aspects such as classifications that can be applied to dwellings within European Union countries [5]. Other authors have also been investigating proposals to assess acoustic quality of specific spaces (e.g. exhibition rooms of museums [6]) based on a multi-criteria analysis. As far as the authors know for school buildings there is yet no acoustic objective classification proposal, therefore in this paper one such acoustic classification is provided for school buildings based on the recommendations of the standard EN 16309:2014. This standard only indicates that evaluation of the acoustic performance of constructive solutions should be performed. In order to rank the buildings acoustic quality a multi-criterial analysis is here adopted. In a first stage only three different spaces (typical classrooms, offices and atriums) of the building are analysed and weighting factors are obtained by providing a questionnaire to acoustic designers. The classification scheme is then applied to three case studies corresponding to schools for higher education and the results are compared aiming to obtain a ranking of the buildings' acoustic performances.

2 Acoustic classification proposal

In order to perform the assessment of the acoustic comfort for schools a hierarchic structure of acoustic performance of spaces and constructive solutions was defined, according to Figure 1. In the present paper only three different spaces were analysed: classrooms, offices and atriums.

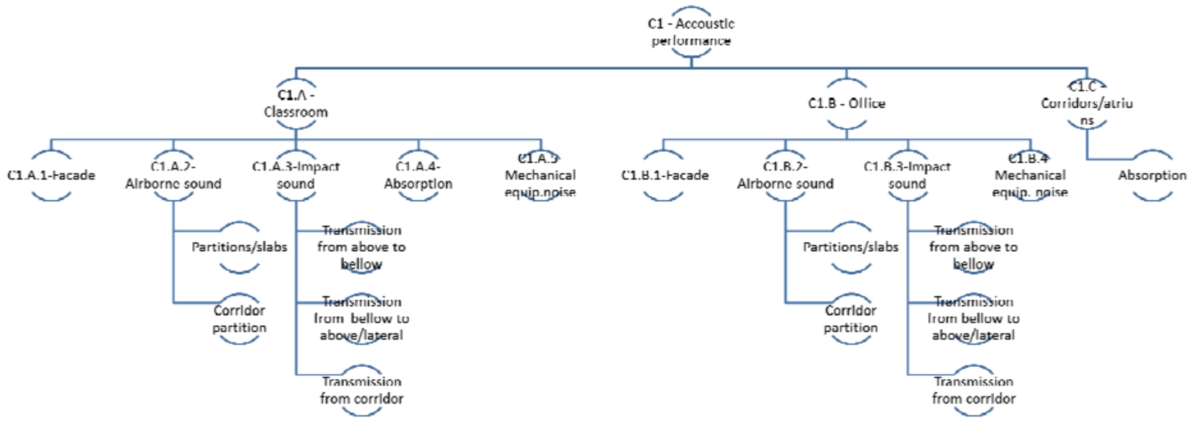


Figure 1. Hierarchic structure for the evaluation of acoustic performance of school buildings based on the analysis of classrooms, offices and corridors/atriums.

The acoustic classification of a school building according to the hierarchic structure defined in Figure 1 it is performed following these steps:

i) Establish a set of weighting factors for the different spaces;
ii) Establish a set of weights for the different requirements that contribute to obtain acoustic comfort inside each space (façade sound insulation; airborne sound insulation, impact sound insulation, sound absorption parameters and service equipment noise);
iii) Quantitatively evaluate acoustic performance of different building solutions;
iv) Define a score for assessment of the behaviour of the building solutions;
v) Obtain a global score for the acoustic performance of each building.

In order to establish a set of weighting factors for the different spaces (step i) a questionnaire was prepared and answered by a group of acoustic designers. The same procedure was followed to obtain the weighting factors for the different acoustic requirements that contribute to obtain acoustic comfort inside each space (step ii). The average values obtained are displayed in tables 1, 2 and 3.

Table 1: Weighting indicators for type of use.

Sub-criteria	**Type of space**	**Weighting indicator**
C1.A	Classrooms	58%
C1.B	Offices	30%
C1.C	Corridor	12%
	Sum	100%

Table 2: Weighting factors for classrooms.

Sub-criteria	**Acoustic requirement**	**Weighting indicator**		
		Exterior noise		
		Intermediate	**Low**	**High**
C1.A.1	Facade sound insulation	13%	8%	23%
C1.A.2 Airborne sound insulation	Airborne sound insulation - Partitions/slabs	16%	17%	14%
	Airborne sound insulation - Corridor	8%	8%	7%
C1.A.3 Impact sound insulation	Transmission from above to bellow	9%	9%	7%
	Transmission from bellow to above/lateral transmission	6%	6%	5%
	Impact sound insulation - Corridor	6%	6%	4%
C1.A.4	Sound absorption	35%	35%	33%
C1.A.5	Mechanical equipment noise	9%	12%	7%
	Sum	100%	100%	100%

Table 3: Weighting factors for offices.

Sub-criteria	**Acoustic requirement**	**Weighting indicator**		
		Exterior noise		
		Intermediate	**Low**	**High**
C1.B.1	Facade sound insulation	17%	11%	29%
C1.B.2 Airborne sound insulation	Airborne sound insulation - Partitions/slabs	25%	26%	23%
	Airborne sound insulation - Corridor	17%	16%	14%
C1. B.3 Impact sound insulation	Impact sound insulation - Transmission from above to bellow	12%	13%	11%
	Impact sound insulation - Transmission from bellow to above/lateral transmission	8%	8%	7%
	Impact sound insulation - Corridor	10%	10%	9%
C1.B.4	Mechanical equipment noise	11%	16%	8%
	Sum	100%	100%	100%

To perform step iii, the acoustic behaviour of constructive solutions may be evaluated in the design stage according to series of standards EN ISO 12354-1 [7] (airborne sound insulation), EN ISO 12354-2 [8] (impact sound insulation), EN ISO 12354-3 [9] (facade sound insulation), EN ISO 12354-5 [10] (noise from service equipment) and EN ISO 12354-6 [11] (sound absorption in enclosed spaces). In existing buildings measurements can also be performed. In order to evaluate the acoustic behaviour of constructive solutions a score scale was defined, aiming also to obtain information about acoustic quality. The score varies between 1 and 5, where 1 means that the solution provides poor acoustic performance and 5 a very good acoustic performance (see Table 9). The requirements established in the Portuguese acoustic code [12] were used as a reference to define the proposed scale (see tables 4-8).

Table 4: Score scale to classify sound insulation provided by constructive solutions.

Thresholds ($\Delta_1 = D^{sol}_{2m,\mathrm{nT,w}} - D^{req}_{2m,\mathrm{nT,w}}$, $\Delta_2 = D^{sol}_{\mathrm{nT,w}} - D^{req}_{\mathrm{nT,w}}$, $\Delta_3 = L^{req}_{\mathrm{nT,w}} - L^{sol}_{\mathrm{nT,w}}$)			**Score**
$\Delta_1 \le -4$	$\Delta_2 \le -4$	$\Delta_3 \le -4$	1
$-3 \le \Delta_1 \le -1$	$-3 \le \Delta_2 \le -1$	$-3 \le \Delta_3 \le -1$	2
$\Delta_1 = 0$	$\Delta_2 = 0$	$\Delta_3 = 0$	3
$1 \le \Delta_1 \le 3$	$1 \le \Delta_2 \le 3$	$1 \le \Delta_3 \le 3$	4
$\Delta_1 \ge 4$	$\Delta_2 \ge 4$	$\Delta_3 \ge 4$	5

Table 5: Score scale to classify sound absorption performance of classrooms (V<250 m^3).

Thresholds	**Score**
$T_{500,1000,2000} > 1.25 \times 0.15 \times \sqrt[3]{V}$	1
$0.15 \times \sqrt[3]{V} < T_{500,1000,2000} \le 1.25 \times 0.15 \times \sqrt[3]{V}$	2
$T_{500,1000,2000} = 0.15\sqrt[3]{V}$	3
$0.80 \times 0.15 \times \sqrt[3]{V} \le T_{500,1000,2000} < 0.15 \times \sqrt[3]{V}$	4
$T_{500,1000,2000} < 0.80 \times 0.15 \times \sqrt[3]{V}$	5

Table 6: Score scale to classify sound absorption performance of atriums/corridors.

Thresholds	**Score**
$A_{eq} > 0.25 \times A$	1
$A_{eq} \le 0.25 \times A$	5

Table 7: Score scale to classify sound level generated by service equipment.

Thresholds ($\Delta = L^{req}_{\mathrm{Ar,nT}} - L^{equipment}_{\mathrm{Ar,nT}}$)	**Score**
Δ≤-4	1
-3≤Δ≤-1	2
Δ=0	3
3≤Δ≤1	4
Δ≥4	5

Table 8: Requirements defined in the RRAE [12] for offices, classrooms and atriums/corridors.

Acoustic demand		Requirement
Facade	Intermediate-high exterior noise	$D_{2m,nT,w} \geq 33$ dB
	Low exterior noise	$D_{2m,nT,w} \geq 28$ dB
Airborne sound insulation	Emitting room-noisy space	$D_{nT,w} \geq 55$ dB
	Emitting room-quiet space	$D_{nT,w} \geq 45$ dB
	Emitting room-corridor	$D_{nT,w} \geq 30$ dB
Impact sound insulation	Emitting room-noisy space	$L_{nT,w} \leq 60$ dB
	Emitting room-quiet space	$L_{nT,w} \leq 65$ dB
	Emitting room-corridor	$L_{nT,w} \leq 60$ dB
Noise from service equipment	Continuous noise	$L_{Ar,nT} \leq 40$ dB(A)
	Intermittent noise	$L_{Ar,nT} \leq 35$ dB(A)
Sound absorption	Classrooms ($V \leq 250$ m^3)	$T_{500,1000,2000} \leq 0.15\sqrt[3]{V}$
	Corridors and atriums	$A_{500,1000,2000} \geq 0.25 A_{floor}$

The final score is obtained, by applying the following expression:

$$Score = \sum_{\substack{i=classroom,\\ office}} W_i \times \left(W^i_{D_{2m,nT,w}} \times S^i_{D_{2m,nT,w}} + W^i_{D_{nT,w}} \times S^i_{D_{nT,w}} + W^i_{L_{nT,w}} \times S^i_{L_{nT,w}} + W^i_{L_{Ar,nT}} \times S_{L_{Ar,nT}} + W^i_{Tr} \times S^i_{Tr} \right) + W_{Atrium} \times S_{Atrium} \quad (1)$$

where W_i is the weighting factor of the space; W^i and S^i is the weighting factor and the score of the constructive solutions. Table 9 defines the scale grade for buildings.

Table 9: Scale grade for the score values.

Score	1	2	3	4	5
Grade	Bad	Poor	Fair	Good	Very Good

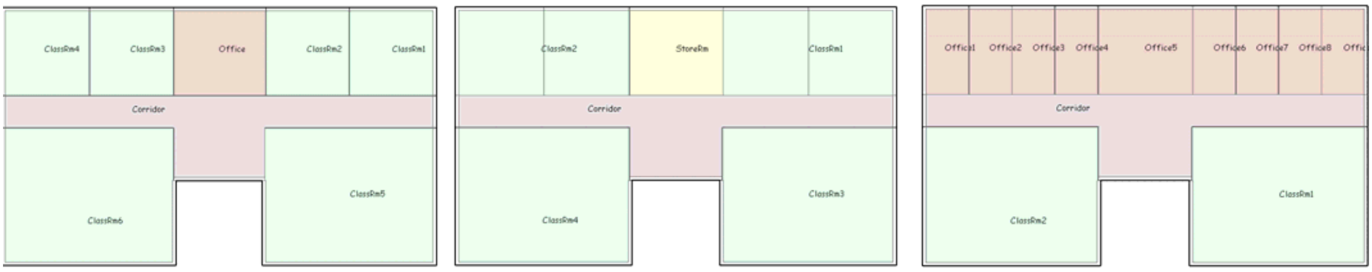
3 Case studies

1 Case studies

In order to make a comparative assessment of the three buildings, a representative fraction (part) of each building was selected, which are described in the following paragraphs. Each representative fraction includes classrooms, offices and other spaces.

The first building belongs to the University of Minho located in Guimarães (PT) and has three floors (see Figure 2). The gross floor area of each storey is 350.0 m^2 and the height of the building is 10.0 m. There is a central corridor on each floor giving access to the contiguous compartments. These compartments are mainly classrooms with different sizes/areas and offices, existing also one storeroom as showed in Figure 2b.

The relevant building components are briefly described in Table 10 and Table 11 including the acoustic properties. It is important to note that in this building there are no service equipments.



a) Floor 0 b) Floor 1 c) Floor 2

Figure 2. Floors' layouts of Building 1.

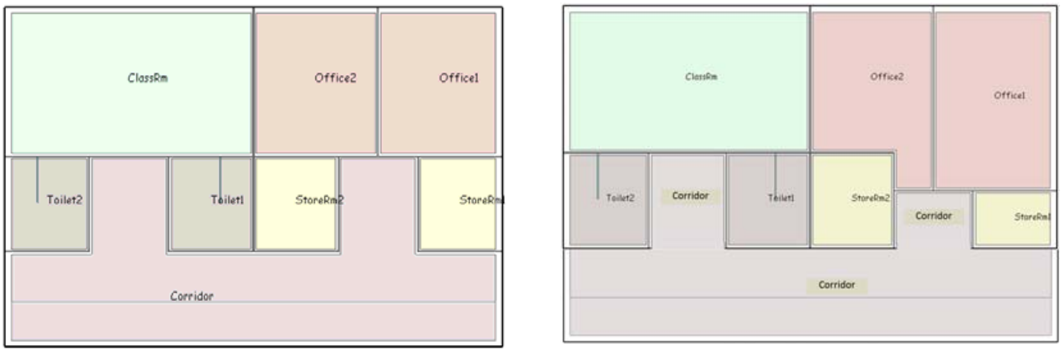
Table 10: Acoustic properties of main components: Building 1.

Component	**Description**	**R_w**	**$L_{n,w}$**
External walls	Reinforced Concrete (0.25m) with ETICS (0.04m) - m=650kg/m^2	63 dB	-
Windows	Dbl Clr 6/10/4mm air with iron frames	30 dB	-
Internal partition 1	Reinforced Concrete (0.20m)	62 dB	-
Internal partition 2	Hollow brick (0.11m) with 2 cm of mortar lining in each side (m=180kg/m^2)	42 dB	-
Internal door	Wood panel (m>20kg/m^2)	23 dB	-
Internal floors	Reinforced concrete (0.25m) with stone lining (650kg/m^2) and suspended ceiling (0.0125m)	63 dB	69 dB

Table 11: Acoustic properties of the linings: Building 1.

Component	**Classrooms**	**α_{500Hz}/A_{eq}**	**α_{1000Hz}/A_{eq}**	**α_{2000Hz}/A_{eq}**
Walls	Plastered and painted	0.03	0.03	0.04
Ceilings	Plasterboard	0.07	0.06	0.05
Floor	Wood parquet	0.04	0.05	0.05
Windows	Glass	0.06	0.05	0.05
Door	Wood	0.08	0.08	0.08
Chairs/tables	Typical chairs/tables of classrooms	0.03	0.04	0.06
Component	**Corridor**	**α_{500Hz}**	**α_{1000Hz}**	**α_{2000Hz}**
Walls	Plastered and painted	0.03	0.03	0.04
Ceilings	Plasterboard	0.07	0.06	0.05
Floor	Stone	0.01	0.01	0.02

Figure 3 illustrates the selected representative zone of the Building 2 for the indoor environmental assessment regarding health and comfort criteria. This building belongs to the Polytechnic Institute of Setubal located in Setubal (PT) and has two floors. The gross floor area of each storey is 150.0 m^2 and the major height of the building is 7.5 m. There is a corridor on each floor giving access to the contiguous compartments. These compartments are occupied as classrooms, offices, storerooms and toilets.



a) Floor 0 b) Floor 1

Figure 3. Floors' layouts of Building 2.

The relevant building components are briefly described in Table 12 and

Table 13 including the obtained acoustic insulation parameters. In the building there are no service equipments.

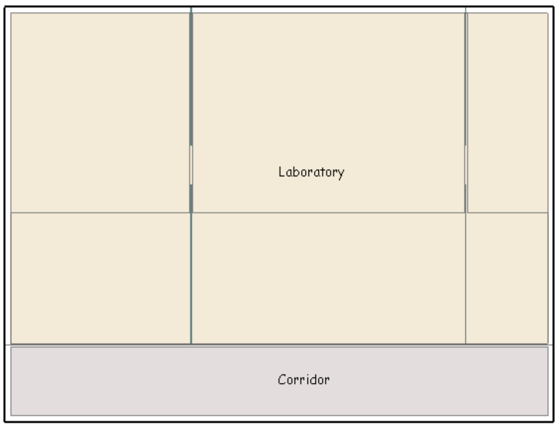
Table 12: Acoustic properties of main components: Building 2.

Component	**Description**	**R_w**	**$L_{n,w}$**
External walls	Reinforced Concrete (0.15m) with ETICS(0.04) + mineral wool(0.04) + hollow brick (0.07)	52 dB	-
Windows	Dbl Clr 8/8/8mm air with iron frames	31 dB	-
Internal partition 1	Reinforced Concrete (0.15m)	52 dB	-
Internal partition 2	Hollow brick (0.15m) with 2 cm of mortar lining in each side	45 dB	-
Internal partition 3	Hollow brick (0.20m) with 2 cm of mortar lining in each side	47 dB	-
Internal partition 4	Hollow brick (0.11m) with 2 cm of mortar lining in each side	42 dB	
Internal door	Wood panel (m>20kg/m^2)	23 dB	-
Internal floors 1	Reinforced concrete (0.25m) with stone lining (0.02m) and suspended ceiling (0.0125m)	63 dB	69 dB
Internal floors 2	Reinforced concrete (0.25m) with linoleum (0.003m) and suspended ceiling (0.0125m)	63 dB	56 dB
Ground floor1	Reinforced concrete (0.15m) with stone lining (0.02m)	52 dB	80 dB
Ground floor 2	Reinforced concrete (0.15m) with linoleum (0.003m)	52 dB	67 dB

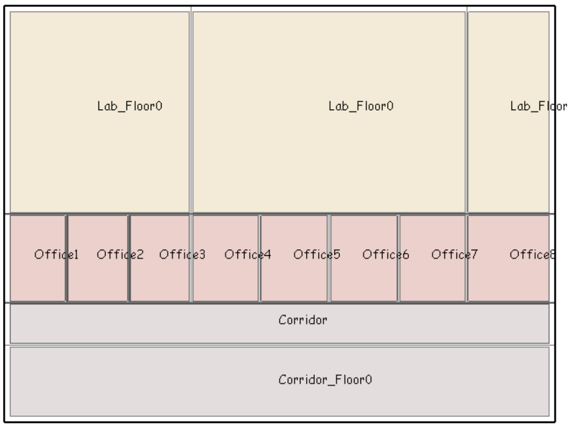
Table 13: Acoustic properties of the linings: Building 2.

Component	**Classrooms**	α_{500Hz}/**Aeq**	α_{1000Hz} /**Aeq**	α_{2000Hz} /**Aeq**
Walls	Plastered and painted	0.03	0.03	0.04
Walls	Stone Panelling	0.04	0.04	0.04
Ceilings	Plasterboard	0.07	0.06	0.05
Floor	Linoleum	0.05	0.04	0.10
Windows	Glass	0.06	0.05	0.05
Door	Wood	0.08	0.08	0.08
Chairs/tables	Typical chairs and tables of classrooms	0.03	0.04	0.06
Component	**Corridor**	α_{500Hz}	α_{1000Hz}	α_{2000Hz}
Walls	Stone panelling	0.01	0.01	0.02
Walls	Plastered and painted	0.03	0.03	0.04
Ceilings	Plasterboard	0.07	0.06	0.05
Floor	Stone	0.01	0.01	0.02

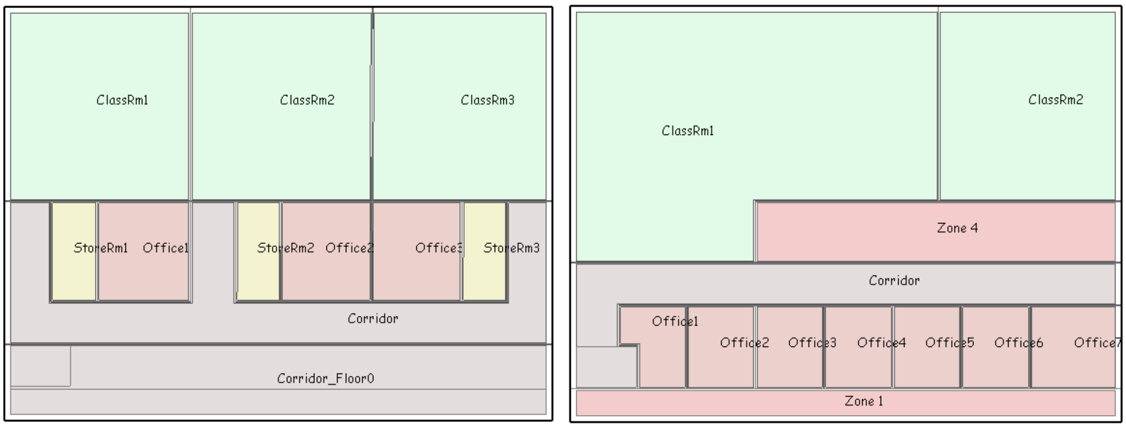
General views of Building 3 are illustrated in Figure 4. This building belongs to the University of Aveiro located in Aveiro (PT) and has four floors. The gross floor area of each storey is 530.0 m^2 and the height of the building is 12.75 m. The ground floor is mainly occupied by a laboratory, which has a double storey high as illustrated in Figure 4a and Figure 4b. Besides the top part of the laboratory, the first floor has eight offices and a balcony access corridor. Notice that the ground floor corridor has a triple storey high as displayed in Figure 4a, b and c. In the second floor there are 3 classrooms, 3 offices, 3 storerooms and a corridor (Figure 4c). In the top floor there is a central corridor, which has natural daylight provided by an adjacent unoccupied semi-exterior compartment with a large skylight, labelled in Figure 4d as Zone 4. Moreover there are seven small offices and two classrooms.



a) Floor 0



b) Floor 1



c) Floor 2 c) Floor 3

Figure 4. Floor's layouts: Building 3.

The relevant building components are briefly described in Table 14 and Table 15 including the obtained acoustic insulation parameters. Note that corridors have linings similar to those applied in Building 1 (see Table 11) It is important to note that in the building there are no service equipment.

Table 14: Acoustic properties of main components: Building 3.

Component	**Description**	R_w	$L_{n,w}$
External walls 2	Curtain wall	36 dB	-
Interior windows	Glass 6/10/4	30 dB	
Internal partition 1	Hollow brick (0.15m) with 2 cm of mortar lining in each side	45 dB	-
Internal partition 2	Hollow brick (0.20m) with 2 cm of mortar lining in each side	47 dB	-
Internal partition 3	Single plaster panel (12.5 + 48 + 12.5)	36 dB	-
Internal door	Wood panel ($m>20kg/m^2$)	23 dB	-
Internal floors 1	Reinforced concrete (0.20m) with stone lining (0.02m) and suspended ceiling with mineral wool	67 dB	70 dB
Internal floor 2	Reinforced concrete (0.20m) with linoleum and suspended ceiling with mineral wool	67 dB	57 dB

Table 15: Acoustic properties of the linings: Building 3.

Component	**Classrooms**	α_{500Hz}/Aeq	α_{1000Hz} /Aeq	α_{2000Hz} /Aeq
Walls	Plastered and painted	0.03	0.03	0.04
Ceilings	Plasterboard	0.07	0.06	0.05
Floor	Linoleum	0.05	0.04	0.10
Floor	Resin epoxy	0.03	0.03	0.04
Windows	Glass	0.06	0.05	0.05
Door	Wood	0.08	0.08	0.08
Chairs/tables	Typical chairs and tables of classrooms	0.03	0.04	0.06

In order to apply the proposed acoustic classification to the above described buildings it was necessary to perform a selection of spaces of similar use to be analysed. Note that the constructive solutions and linings are similar within the same building. Therefore the spaces with solutions displaying worst acoustic performance were selected to perform the analysis. In the analysis of the selected spaces we may have different solutions as separation elements. Here again the worst solution was chosen to be scored. It is important to bear in mind that in acoustics it is the worst solution that defines the acoustic behaviour inside a space. The acoustic parameters were then obtained using the procedures required in the series of ISO standards 12354. These parameters and the corresponding score achieved either for the constructive solution integrated in the building or for the space are displayed in tables 16-18.

Table 16: Acoustic classification of classrooms.

	C1.A-Classroom																
	C1.A.1		C1.A.2.1		C1.A.2.2		C1.A.3.1		C1.A.3.2		C1.A.3.3		C1.A.4		C1.A.5		
CLASSIFICATION	D2m,nT,w	N2m,nTw	DnT,w	NDnT,w	DnT,w	NDnT,w	L'nT,w	NL'nT,w	L'nT,w	NL'nT,w	L'nT,w	NL'nT,w	Tr	NTr	Lar,nT	NLar,nT	C1.A-FINAL
Building 1	36	4	38	1	35	5	55	5	-	5	-	5	2.75	1	-	5	2,83
Building 2	41	5	53	5	32	4	59	5	-	5	-	5	1.94	1	-	5	3,52
Building 3	33	3	33	1	40	5	-	5	50	5	42	5	3.26	1	-	5	2,71

Table 17: Acoustic classification of offices.

	C1.B-Office														
	C1.B.1		C1.B.2.1		C1.B.2.2		C1.B.3.1		C1.B.3.2		C1.B.3.3		C1.B.3.3		
CLASSIFICATION	D2m,nT,w	N2m,nTw	DnT,w	NDnT,w	DnT,w	NDnT,w	L'nT,w	NL'nT,w	L'nT,w	NL'nT,w	L'nT,w	NL'nT,w	Lar,NT	Lar,NT	C1.B-FINAL
Building 1	-	5	41	1	30	3	-	5,00	-	5	-	5	-	5	3,64
Building 2	-	5	44	2	35	5	-	5,00	-	5	47	5	-	5	4,24
Building 3	-	5	33	1	32	4	-	5,00	-	5	-	5	-	5	3,81

Table 18: Acoustic classification of corridors/atriums.

	C1.C Atrium/Corridor		
	C1.C.1		
CLASSIFICATION	Aeq	NAeq	C1.B-FINAL
Building 1	0,29	1	1,00
Building 2	0,28	1	1,00
Building 3	0,37	1	1,00

Table 19: Acoustic classification of buildings.

CLASSIFICATION	FINAL SCORE
Building 1	2,82
Building 2	3,39
Building 3	2,79

The final acoustic classification of the building is displayed in Table 19. These scores range from poor to fair acoustic qualities. These results were expected because the buildings were designed having has a reference the first Portuguese acoustic code where the acoustic requirements were low. It is observed that higher requirements are currently established according to the national code in force.

2 Conclusions

In this paper an acoustic classification of spaces integrated in school buildings was provided in order to assess acoustic quality. Based on questionnaires answered by acoustic designers the weighting indicators were obtained. The procedure was applied to the analysis of three existing Portuguese schools for higher education. The buildings display quite similar classifications although Building 2 has a better score. It would be interesting to compare real building user's opinions with the obtained score in order to validate this classification. It is also important to mention that this classification should be performed by an acoustic designer as the selection of spaces to be analysed is of crucial importance.

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