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ACOUSTICAL CHARACTERIZATION OF PORTUGUESE LIBRARIES

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This paper presents the acoustical characterization of the main reading room of 28 public libraries in Portugal. *In situ* measurements were held regarding the interior sound pressure levels (background noise, with and without the HVAC equipment working), the Noise Criteria and Noise Rating values (NC/NR), the objective speech intelligibility using the Rapid Speech Transmission Index (RASTI) and Reverberation Time (125 to 4k Hz). Two groups of libraries were formed (*Classic* and *Modern* libraries) regarding their interior layout and date of construction and differences were checked. Regression models among the architectural and acoustical parameters were established. The acoustical performance of these spaces concerning the current Portuguese legislation is analyzed and a short set of design goals are presented to help acoustical consultants to achieve a good environment in this type of building.

1. Introduction

The main reading rooms of public libraries are special places where the acoustics can be a very important matter. Low noise is a must. These spaces are characterized by a large open area, sometimes with a tall ceiling, and with walls and floor made with very sound reflective materials.

The goal of this work was to check the overall acoustic conditions of these spaces by the use of objective acoustic parameters concerning their interior conditions: Reverberation Time (*RT*), Rapid Speech Transmission Index (RASTI), background sound levels and sound pressure levels of their HVAC equipment (and NC/NR noise curves).

The among-room variations of acoustic objective parameters can be viewed as differences that result from the architectural proprieties of the rooms that experience shows actually exist. The hypothesis that *Modern* libraries have an acoustically different behavior than the older *Classic* libraries was tested.

2. Method

2.1 The sample

The investigation is focused on public libraries of Portugal that can be considered a representative example of similar rooms in the world. This study reports on acoustical field measurements done in a major survey of 28 libraries[1] that were selected to represent the different styles and layouts found throughout Portugal and to represent this type of construction. The sample is listed in Table 1 and the statistical summary of their main architectural characteristics is shown in Table 2.

The sample was also divided in two groups of libraries (named *Classic* and *Modern*) regarding their interior layout and date of construction, to check for possible acoustic differences (Table 3). The *Modern* libraries have on average, a smaller volume (about half) than the *Classic* and they are usually longer and wider but with a smaller ceiling height. Figures 1 to 6 show some of the libraries tested (three of each group).

Table 1. List of the sample of 28 libraries tested.

Library	Code	Volume (m^3)	Library	Code	Volume (m^3)
A. Garret Porto	PG	3256	Matosinhos	MA	1866
Ajuda (Lisboa)	LA	1099	Monforte	MO	812
Alverca	AL	604	Oliv. Azeméis	OA	1954
P. Galveias (Lisboa)	LC	579	Oliv. Bairro	OB	292
U. Coimbra	CG	4261	Porto Munic.	PM	2100
B. Nacional (Lisboa)	LN	8094	Stg. Cacém	SC	804
Púb. Braga	BP	214	Sesimbra	SE	1047
Campo Maior	CM	675	Santo Tirso	ST	994
Castro Verde	CV	749	Viana do Castelo	VA	1077
Évora	EV	1197	V. Conde	VC	1098
FEUP (Porto)	FE	1765	S. M. Feira	SF	2100
Fig. Vinhos	FV	501	Viseu	VI	1452
Gondomar	GO	1014	V. N. de Gaia	VG	1283
Joanina (Coimbra)	CJ	4382	Vila Real	VR	1750

Figures 1 to 6. Six of the 28 libraries tested (above, *Classic* libraries: Lisboa-LN, Évora-EV, and Porto-PM; below, *Modern* libraries: FEUP-FE, A.Garret-PG, and V.Conde-VC).

Table 2 - Simple statistics of the main architectural characteristics of the entire sample of 28 libraries.

Parameter	Minimum value	Mean	Median	Maximum value	Standard deviation
L - Length (m)	10.8	27.2	27.7	43.8	9.4
W - Width (m)	4.5	12.5	11.5	24.1	4.7
H - Height (m)	2.7	4.5	3.5	10.2	2.3
S - Surface area (m^2)	46	356	335	996	212
V - Volume (m^3)	214	1679	1099	8094	1634
A - Sound absorption (m^2)	34	206	158	652	150

Table 3 - Main architectural characteristics of the two groups of libraries (*Classic* and *Modern*).

Group of libraries	number of libraries	Architectural parameters (avg. values)					
		L (m)	W (m)	H (m)	S (m^2)	V (m^3)	A (m^2)
Classic	8	25.9	11.1	7.4	322	2741	273
Modern	20	27.7	13.0	3.4	369	1255	179
Δ (= *Classic-Modern*)	-	-1.8	-1.9	4.0	47	1486	94

2.2 Methodology and equipment

In each library (main reading room), several measuring points were used for each parameter.

For the Reverberation Time analyses, nine measure points were used (with two measurements at each position) and one sound source position at each main reading room. All room average *RT* values are the mean of 18 measures. Octave band results from 125 to 4k Hz were used. The average of the 500, 1k and 2k octave bands results was also used because this is the parameter employed in the Portuguese legislation[2].

For the *RASTI* measurements, nine measure positions (with five measurements at each position) and one sound source location were used. All room average *RASTI* values are the mean of 45 measures.

For the characterization of the background noise (with and without the HVAC equipment on), three measure positions were used. The parameters measured were SPL (31 to 8k Hz) and L_{Aeq}.

The equipment used was a sound level meter B&K 2260, a microphone B&K 1/2", a sound source B&K 4224, and a *RASTI* set B&K 3361.

3. Results and Analysis

3.1 Reverberation time

Table 4 and Figure 7 show the main results for the Reverberation Time measurements. Figure 8 shows the average RT spectra for the overall sample and controlling for the two types of libraries (*Classic* and *Modern*). On average the *Modern* libraries have slightly lower RTs than the *Classic*.

Table 4 - Simple statistics of the Reverberation Time results for the entire sample of 28 libraries (regarding 28 averaged values).

Parameter	Reverberation Time (s)						
	125	250	500	1k	2k	4k	(500+1k+2k)/3
Minimum value	0.69	0.54	0.49	0.48	0.53	0.52	0.5
Mean	1.41	1.24	1.28	1.30	1.26	1.15	1.3
Median	1.29	1.10	1.21	1.24	1.24	1.14	1.2
Maximum value	3.27	3.14	3.38	3.47	3.15	2.57	3.3
Standard error	0.59	0.52	0.55	0.55	0.50	0.41	0.5

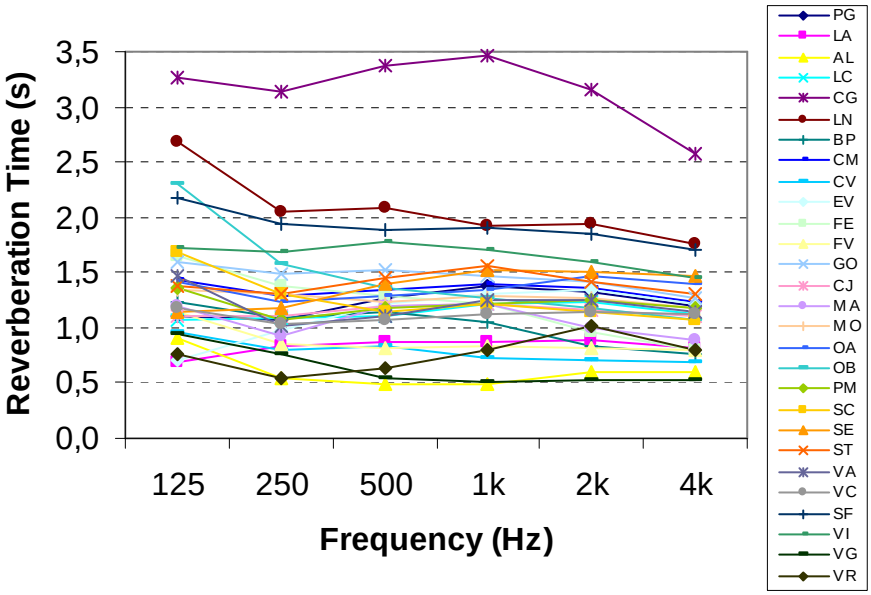

Figure 7. Reverberation Time spectra for the entire set of 28 libraries.

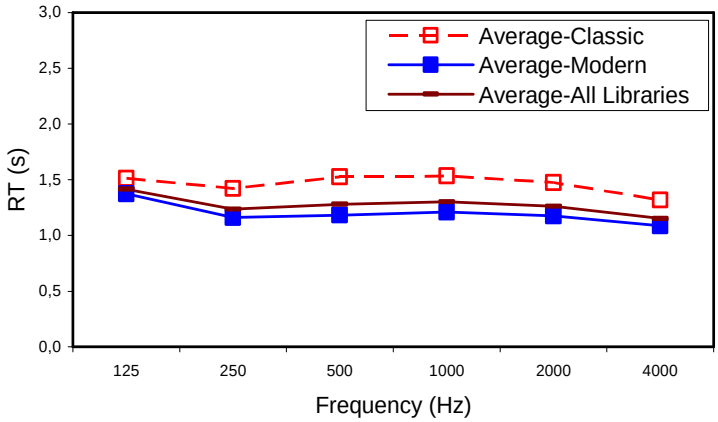

Figure 8. Mean RT spectra, overall results and controlling for the type of libraries (*Classic* and *Modern*).

3.2 RASTI

Table 6 shows the general results for the RASTI measurements and Table 5 the conversion for the related speech intelligibility. Table 6 and Figure 9 show the RASTI main data controlling for the two groups of libraries. On average the *Modern* libraries have a higher (and better) RASTI value (a 0.04 average difference).

Table 5 - RASTI conversion table.

RASTI score	[0-0.30[	[0.30-0.45[	[0.45-0.60[	[0.60-0.75[	[0.75-1.00]
Speech intelligibility	Bad	Poor	Fair	Good	Excellent

Table 6 - RASTI general results for the entire sample (regarding 28 averaged values) and controlling for the two groups of libraries (*Modern* and *Classic*).

Parameter	RASTI			
	Entire sample	*Classic* libraries	*Modern* libraries	Δ (= *Classic*-*Modern*)
Minimum value	0.40	0.40	0.52	-0.12
Mean value	0.62	0.59	0.63	-0.04
Median	0.62	0.61	0.64	-0.03
Maximum value	0.77	0.74	0.77	-0.03
Standard error	0.08	0.10	0.07	0.03

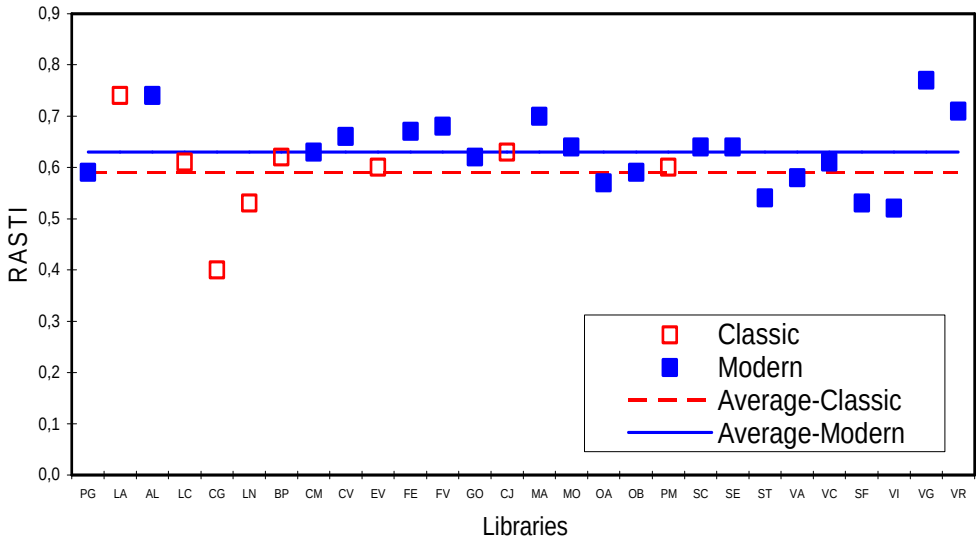

Figure 9. RASTI mean value for each library controlling for the group of libraries (*Modern* and *Classic*).

3.3 Background noise

Table 7 shows the main data for the sound level measurements regarding the background noise (bn). Figure 10 shows the LAeq general results for the entire sample with the average mean values for both groups (*Classic* and *Modern*). *Modern* libraries have, on average, a higher background noise of about 3 dB(A). This can be the result of a higher glass area and lower airborne sound insulation of the facades. Nevertheless differences up to 18 dB(A) were found in the LAeq(bn) among the 28 libraries due to their location.

Table 7 - LAeq(bn) general results for the entire sample (28 libraries) and controlling for the Classic/Modern groups.

LAeq(bn) dB	Minimum value	Mean	Median	Maximum value	Standard error
Entire sample (28 libr.)	22.0	32.0	32.3	39.7	3.3
Classic libraries (8 libr.)	22.0	29.8	31.3	34.6	4.4
Modern libraries (20 libr.)	28.6	32.9	32.6	39.7	2.4
Δ (= *Classic-Modern*)	-6.6	-3.1	-1.3	-5.1	2.0

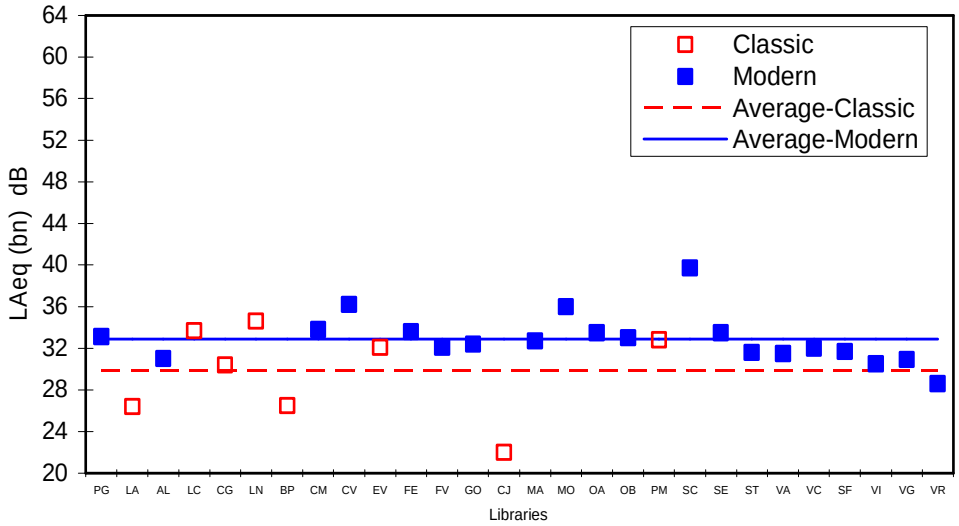

Figure 10. LAeq(bn) general results for the entire sample (28 libraries) with the average mean values for both groups (*Classic* and *Modern*).

3.4 HVAC noise

Table 8 and Figure 11 show the main data for the sound level measurements regarding the ambient noise with the HVAC equipment working (LAeqHVAC). Only 20 libraries had HVAC systems.

LAeq values from 35 to 57 dB were measured that demonstrate very different acoustic environments.

Modern libraries have generally a sound level with the HVAC system on, about 4 dB(A) lower than the *Classic*.

The HVAC system noise increases, on average, about 11 dB(A) the background sound level (bn) within the libraries. However the increase is higher in the *Classic* libraries (on average about 15 dBA) than on the *Modern* libraries (about 10 dBA) mainly due to lower background noise.

Table 8 - LAeq(HVAC) and ΔLAeq general results for the entire sample and controlling for *Classic*/*Modern* groups.

Parameter	LAeq(HVAC) (dB)			ΔLAeq (dB) (=L_{HVAC}*on* - L_{HVAC}*off*)		
	Entire sample	*Classic*	*Modern*	Entire sample	*Classic*	*Modern*
Minimum value	34.7	45.3	34.7	3.9	12.5	3.9
Mean	43.0	46.4	42.4	10.5	15.1	9.6
Median	41.8	46.3	40.8	9.4	13.1	8.2
Maximum value	57.2	47.7	57.2	22.6	19.8	22.6
Standard error	6.0	1.2	6.3	5.6	4.1	5.6

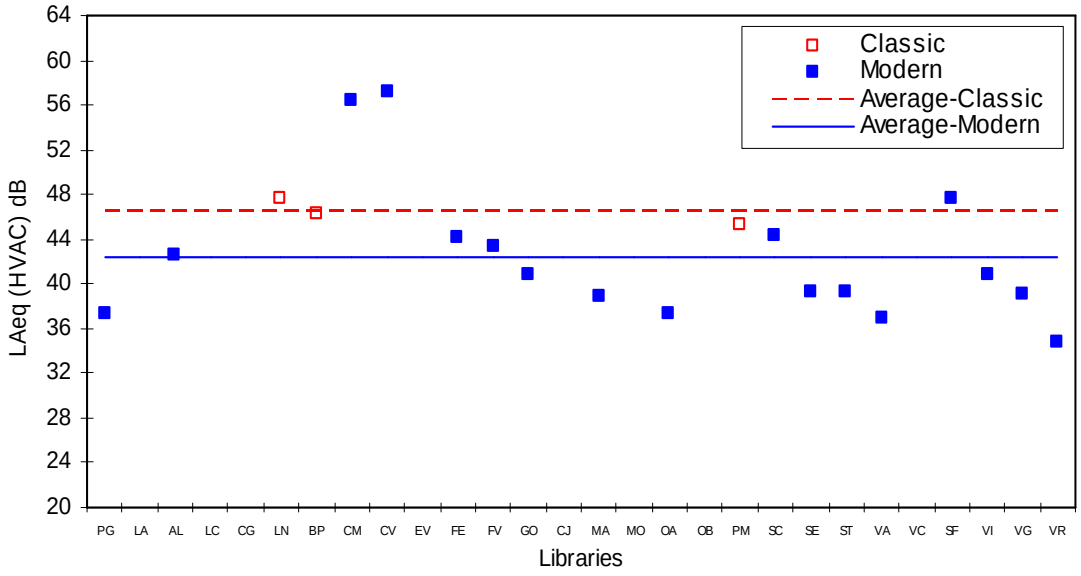

Figure 11. LAeq(HVAC) general results for the entire sample (20 libraries) with the average mean values for both groups (*Classic* and *Modern*).

Figure 12 shows all the HVAC noise spectra where differences up to 25-30 dB are found among the libraries. If using the A filter the higher SPL values are found in the 500 and 1000 Hz frequency bands. Figure 13 shows the average spectra controlling for the group of library, where higher SPLs for the *Classic* libraries (about 3 to 5 dB on average) can be seen.

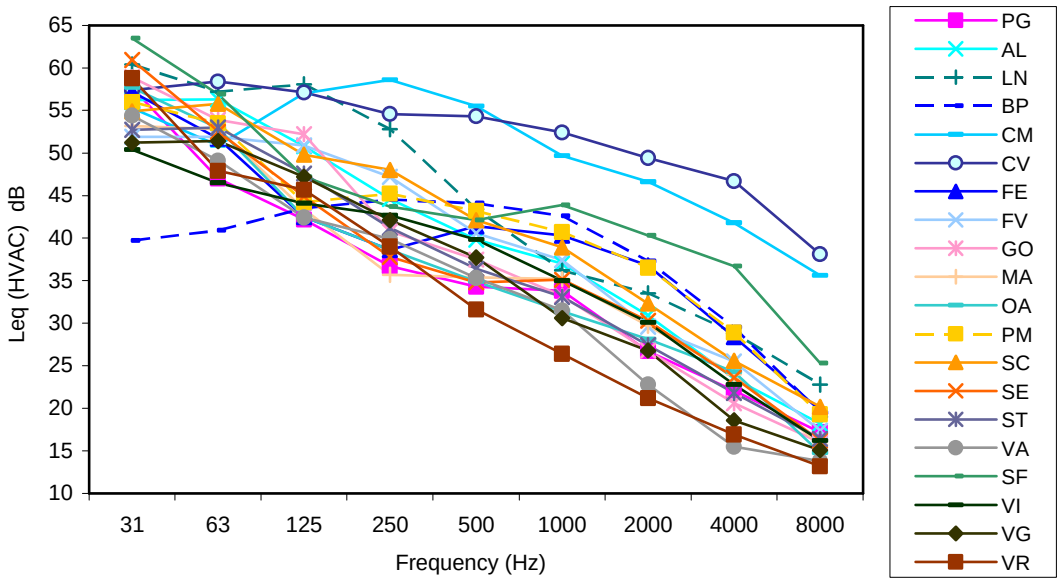

Figure 12. SPL spectra for the HVAC equipment noise for the entire sample (20 libraries).

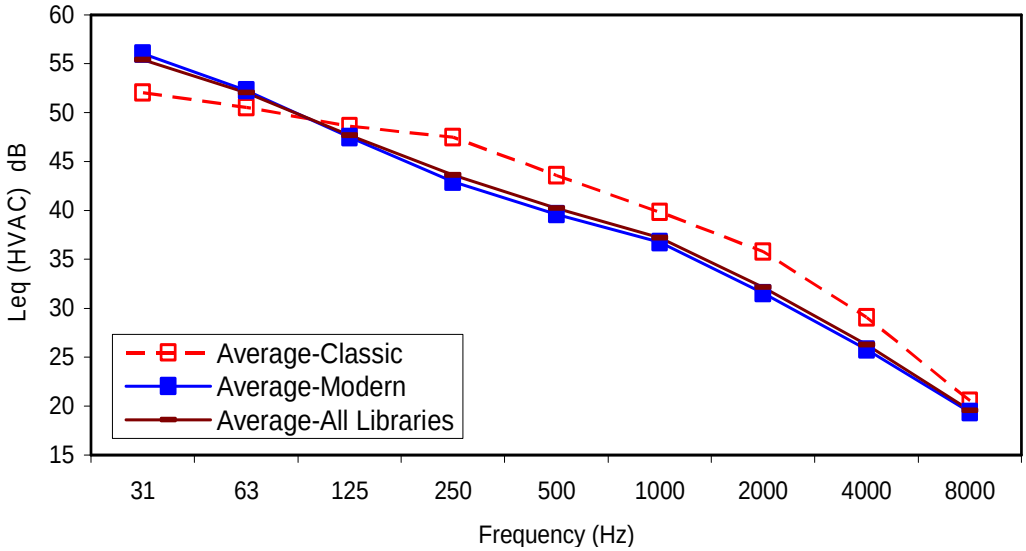

Figure 13. Average SPL spectra for the HVAC equipment noise for the entire sample and controlling for the type of libraries (*Classic* and *Modern*).

3.5 Noise curves (NC/NR)

Table 9 shows the Noise Criteria / Noise Rating (NC/NR) main data (HVAC noise) for the entire sample and controlling for the two groups of libraries. In general the *Classic* libraries have a higher NC/NR rating (6 dB on average). However, the maximum NC/NR values (51 / 52) were found in *Modern* libraries.

Table 9 - NC and NR main results.

Parameter	Entire sample	*Classic* libraries	*Modern* libraries	Δ (= *Classic-Modern*)
NC / NR average	37 / 38	42 / 43	36 / 37	6 / 6
NC / NR minimum	27 / 29	40 / 41	27 / 29	13 / 12
NC / NR maximum	51 / 52	43 / 44	51 / 52	8 / 8
NC / NR st. error	6.8 / 6.6	1.5 / 1.5	7.0 / 6.7	5.5 / 5.2

3.6 Relationships among parameters

Regression models between the architectural parameters and among the architectural and acoustical parameters were established (Table 10).

Table 10 - Best regression models among parameters.

Best regression models among the acoustical parameters	R^2
RASTI = 0,8288 e $^{-0,2347[RT500,2k]}$	0.84
RASTI = 0.81756 - 0,00096 LAeq(bn) – 0,13011 [RT avg 500,1k,2k]	0.77
Best regression models between the acoustical and the architectural parameters	
RT(avg 500,2k) = -2.08E-08V^2 + 3.27E-04V + 0.8355	0.33
RASTI = 0.6532 e $^{-3,59E-05V}$	0.20

4. Law and design rules

The Portuguese legislation[2] states that the average RT (500, 1k and 2k Hz) should not be higher than $0.15V^{1/3}$. Applying this rule to the 28 libraries tested it was found that 96% fulfilled that requirement even if, in many cases, the average RT is very high (up to 3.0 s if the Volume reaches 8000 m^3 as one of the libraries does). This rule is very permissive because it is based in the room volume. For this reason a short set of enhanced design goals are presented (Table 11) to help acoustical consultants to achieve a good environment in this type of building.

Table 11 - Proposed design rules.

Parameter	Libraries main reading rooms
Average Reverberation Time - *RT(500,1k,2k)*	≤ 1.0 s
Sound level (HVAC) – L_{Aeq}	≤ 30 dB
Noise Curves NR "*noise rating*" and NC "*noise criteria*"	≤ 35

5. Conclusion

This work was centered in a selected 28-room sample and confirmed that the libraries have distinct characteristics. The results show that, on average, the tested libraries have a RT (1 kHz) of 1.3 ± 0.6 s, a RASTI of 0.62 ± 0.08, a LAeq (background noise, without HVAC) of 32.0 ± 3.3 dB and a LAeq (HVAC noise) of 43 ± 6 dB.

It was verified that 80% of the HVAC systems did not fulfill the ideal acoustical requirements and 50% of the libraries with HVAC, had NR or NC values higher than the recommended.

Classic libraries seem to have slightly higher RT values, lower RASTI (≈0.04), lower LAeq(background noise) (≈3 dB), higher LAeq(HVAC) (≈4 dB), higher NC/NR (≈6 dB). However, no strong statistical evidence was found to support the hypothesis that *Classic* libraries behave acoustically better than the *Modern*.

A set of ideal goal values for objective acoustic parameters was proposed that can be useful in the design of new libraries.

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REFERENCES

[1] A.E.B. Costa, *Caracterização Acústica de Bibliotecas em Portugal e Análise de Influência na Reabilitação Acústica*, (in Portuguese), M.Sc. thesis, Faculty of Engineering, U. Porto, 2009.

[2] Law, *Regulamento dos Requisitos Acústicos dos Edifícios RRAE* (in Portuguese) (Noise Code: Acoustical Requirements for Buildings), Decreto-lei nº 96/2008.