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Acoustic characterization of courtrooms by a multi-criteria method

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ABSTRACT

This paper proposes a new multi-criteria analysis model to acoustically characterize a specific type of building: the courtrooms. A Courtroom is acoustically studied regarding several criteria: their speech intelligibility, speech privacy (to/from contiguous rooms) and intruding noise. These characteristics are evaluated by numerical parameters that describe the sound field within and the sound insulation. In this paper several significant acoustic parameters are used and logically weighted to find a representative unique index of evaluation of the room, the GIAE (*Global Index of Acoustic Evaluation*) rated on a scale for 0 (worst) to 20 (best). The acoustic parameters used are: Reverberation Time (RT) (average of 500 and 1000 Hz frequency bands), weighted normalized airborne sound level difference of walls and partitions (Dn,w according to ISO 140-4 and 717-1) and facades (D2m,n,w according to ISO 140-5 and 717-1), Rapid Speech Transmission Index (RASTI) (with sound source in the judge position and in the defendant position). The multi-criteria mathematical model is presented and numerically tested with a large selected sample of 28 courtrooms in Portugal (Height from 2.75 to 6.85 m and Volume from 150 to 880 m^3).

1. INTRODUCTION

A Courtroom is acoustically studied regarding several criteria: their speech intelligibility (within), speech privacy (to/from contiguous rooms) and intruding noise. These characteristics are evaluated by numerical parameters that describe the sound field within and the sound insulation given by their separating walls with bordering rooms or entrance hall, and the facade.

Several significant acoustic parameters are used and logically weighted to find a representative unique index of evaluation of a courtroom, the GIAE (*Global Index of Acoustic Evaluation*) rated on a scale for 0 (worst) to 20 (best).

The acoustic parameters used are: Reverberation Time (RT) (average of 500 and 1000 Hz frequency bands), weighted normalized airborne sound level difference of walls and partitions to surrounding rooms (Dn,w according to ISO 140-4 and 717-1, similar to FSTC) and facades (D2m,n,w according to ISO 140-5 and 717-1), Rapid Speech Transmission Index (RASTI) (with sound source in the judge position - J - and in the defendant position - D).

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2. GLOBAL INDEX OF ACOUSTIC EVALUATION (GIAE)

The GIAE *Global Index of Acoustic Evaluation* is found from a mathematical function that depends on several decision criteria $C_{ap\ i}$ (*ap* are the several acoustical parameters named above). Each Criterion $C_{ap\ i}$ normalizes the value of the acoustical parameter (for instance *RT* in s) to a normalized scale from 0 (the worst value) to 20 (the best value). Each acoustical parameter is weighted (W_{ap} from 0 to 1) regarding its importance on the overall acoustical behavior of the room.

Each Courtoom (that is, each alternative a_i) is rated by the GIAE as follows:

$$GIAE(a_i)=W_{RT} \,.\, C_{RT}(a_i)+W_{Dn,w(interior)}.C_{Dn,w(interior)}(a_i)+W_{D2m,n,w}.C_{D2m,n,w}(a_i)+W_{RASTI}.C_{RASTI}(a_i) \quad (1)$$

Or using the values for the weights *W*,

$$GIAE(a_i) = 0.50\ C_{RT}(a_i) + 0.20\ C_{Dn,w(interior)}(a_i) + 0.10\ C_{D2m,n,w}(a_i) + 0.20\ C_{RASTI}(a_i) \quad (2)$$

Where:

$C_{RT}\ (a_i)$	- normalized performance (from 0 worst to 20 best) regarding acoustical parameter RT for alternative a_i (courtroom *i*);
$C_{Dn,w\ (interior)}\ (a_i)$	- normalized performance (from 0 worst to 20 best) regarding acoustical parameter Dn,w(interior walls) for alternative a_i (courtroom *i*);
$C_{D2m,n,w}\ (a_i)$	- normalized performance (from 0 worst to 20 best) regarding acoustical parameter $D_{2m,n,w}$ (facade) for alternative a_i (courtroom *i*);
$C_{RASTI}\ (a_i)$	- normalized performance (from 0 worst to 20 best) regarding acoustical parameter RASTI for alternative a_i (courtroom *i*);
W_{RT}	- weight factor for criteria RT (=0.5);
$W_{\mathrm{Dn,w(interior)}}$	- weight factor for criteria $D_{n,w(interior)}$ (= 0.2);
$W_{\mathrm{D2m,n,w}}$	- weight factor for criteria $D_{2m,n,w}$. (= 0.1);
W_{RASTI}	- weight factor for criteria *RASTI* (= 0.2).

The $C_{Dn,w\ (interior)}$ and C_{RASTI} are also the accumulation of two sub-criteria:

- The criterion for Interior Sound Insulation $C_{Dn,w\ (interior)}$ adds the effect of the sound insulation with contiguous rooms with the sound insulation to the entrance lobby (this is usually worst because of the door that connect both spaces), as follows:

$$C_{Dn,w\ (interior)}\ (a_i) = 0.20\ C_{Dn,w\ (contiguous\ rooms)}(a_i) + 0.80\ C_{Dn,w\ (entrance\ lobby)}(a_i) \quad (3)$$

- The criterion for RASTI C_{RASTI} adds the effect of the RASTI with the sound source at the judge position (J) with the RASTI with the sound source at the defendant position (D) as follows:

$$C_{RASTI}\ (a_i) = 0.60\ C_{RASTI\ J}\ (a_i) + 0.40\ C_{RASTI\ D)}(a_i) \quad (4)$$

Tables 1 to 5 present the conversion functions for all the Criteria used regarding all acoustical parameters: *RT*, *RASTI*, *Dn,w with contiguous rooms*, *Dn,w with entrance lobby* and *D2m,n,w (facade).*

Table 1: Conversion function for Reverberation Time (*RT*) (average 500-1k Hz)

RT (s)	C_{RT} (points)	RT (s)	C_{RT} (points)
[0.0 ; 0.1[	6	[1.0 ; 1.2[	19
[0.1 ; 0.2[	8	[1.2 ; 1.4[	18
[0.2 ; 0.3[	10	[1.4 ; 1.6[	16
[0.3 ; 0.4[	13	[1.6 ; 1.8[	14
[0.4 ; 0.5[	14	[1.8 ; 2.0[	12
[0.5 ; 0.6[	17	[2.0 ; 2.5[	8
[0.6 ; 0.7[	18	[2.5 ; 3.0[	6
[0.7 ; 0.8[	19	[3.0 ; 3.5[	3
[0.8 ; 1.0[	20	≥ 3.5	0

Table 2: Conversion function for *RASTI*

RASTI	C_{RASTI} (points)	*RASTI*	C_{RASTI} (points)
[0.90 ; 1.00]	20	[0.50 ; 0.55[	11
[0.85 ; 0.90[	19	[0.45 ; 0.50[	10
[0.80 ; 0.85[	18	[0.40 ; 0.45[	8
[0.75 ; 0.80[	16	[0.30 ; 0.40[	7
[0.70; 0.75[	15	[0.20 ; 0.30[	4
[0.65 ; 0.70[	14	[0.10 ; 0.20[	2
[0.60 ; 0.65[	13	[0.00 ; 0.10[	0
[0.55 ; 0.60[	12		

Table 3: Conversion function for $D_{n,w}$ (with contiguous rooms)

$D_{n,w\ (contiguous\ room)}$ (dB)	$C_{Dn,w(c.r.)}$ (points)	$D_{n,w\ (contiguous\ room)}$ (dB)	$C_{Dn,w(c.r.)}$ (points)
≥ 50	2.0	39	9
49	19	38	8
48	18	37	7
47	17	36	6
46	16	35	5
45	15	34	4
44	14	33	3
43	13	32	2
42	12	31	1
41	11	≤ 30	0
40	10		

Table 4: Conversion function for $D_{n,w}$ (with entrance lobby)

$D_{n,w\ (entrance\ lobby)}$ (dB)	$C_{Dn,w(e.l.)}$ (points)	$D_{n,w\ (entrance\ lobby)}$ (dB)	$C_{Dn,w(e.l.)}$ (points)
≥ 36	20	27	7
35	19	26	6
34	18	25	5
33	16	24	4
32	14	23	3
31	12	22	2
30	10	21	1
29	9	≤ 20	0
28	8		

Table 5: Conversion function for $D_{2m,n,w}$ (facade)

$D_{2m,n,w}$ (dB)	$C_{D2m,n,w}$ (points)	$D_{2m,n,w}$ (dB)	$C_{D2m,n,w}$ (points)
≥ 34	20	25	7
33	19	24	6
32	18	23	5
31	16	22	4
30	14	21	3
29	12	20	2
28	10	19	1
27	9	≤ 18	0
26	8		

2. APPLICATION

A. The Sample

The above described multi-criteria method was used with a sample of 28 courtrooms[1] in Portugal that are described in Table 6 (with four examples shown in Figures 1 to 4).

Figures 1 and 2: Examples of Courtrooms (Vouzela and Celorico da Beira)[1]

 

Figures 3 and 4: Examples of Courtrooms (Covilhã and Seia)[1]

Table 6: Main characteristics of the 28 courtrooms in Portugal used as sample[1,2]

Alt.	Courtroom	Volume (m^3)	Area (m^2)	Height (m)	Length (m)	Width (m)	Absorption (m^2)	N. seats
a_1	Almeida	208	67	3.10	9.6	7.00	29.9	40
a_2	C. Branco	878	172	5.10	15.1	11.40	31.0	170
a_3	Cel. Beira	516	101	5.10	13.5	7.50	38.7	85
a_4	Covilhã 1	880	173	5.10	15.0	11.50	121.4	120
a_5	Covilhã 2	169	59	2.85	8.3	7.15	78.2	50
a_6	FCRodrigo	484	103	4.70	14.3	7.20	31.4	60
a_7	F.Algodres	441	100	4.40	11.4	8.80	35.8	55
a_8	Fundão 1	478	107	4.45	11.3	9.50	47.3	85
a_9	Fundão 2	397	107	3.70	11.3	9.50	46.5	85
a_{10}	Gouveia	424	115	3.70	15.5	7.40	67.2	90
a_{11}	Id.-a-Nova	719	153	4.70	15.0	10.20	30.2	90
a_{12}	Mangualde	707	120	5.90	14.1	8.50	38.5	35
a_{13}	Meda	331	95	3.50	13.7	6.90	68.8	90
a_{14}	Oleiros	195	71	2.75	9.7	7.30	25.9	35
a_{15}	O. Frades	374	98	3.80	11.3	8.70	96.8	30
a_{16}	O.Hospital	416	109	3.80	12.3	8.90	94.2	45
a_{17}	Pinhel	468	104	4.50	13.0	8.00	40.8	55
a_{18}	Sabugal	469	92	5.10	11.5	8.00	28.7	55
a_{19}	Sátão	256	83	3.10	13.1	6.30	39.9	65
a_{20}	Seia 1	508	107	4.75	11.5	9.30	30.6	55
a_{21}	Seia 2	574	121	4.75	13.0	9.30	32.9	65
a_{22}	Sertã	662	97	6.85	10.5	9.20	80.5	60
a_{23}	S. Vouga	150	50	3.00	10.0	5.00	52.1	24
a_{24}	Trancoso	416	113	3.70	12.5	9.00	25.8	70
a_{25}	VNFCôa	276	89	3.10	13.1	6.80	23.1	70
a_{26}	Viseu 1	560	111	5.05	15.2	7.30	31.1	90
a_{27}	Viseu 2	156	46	3.40	8.8	5.20	25.1	27
a_{28}	Vouzela	343	116	2.95	11.3	10.30	121.5	80
	Minimum	150	46	2.8	8.3	5.0	23	24
	Mean	445	103	4.2	12.3	8.3	50	67
	Maximum	880	173	6.9	15.5	11.5	122	170
	St. Deviat.	199	30	1.0	2.0	1.6	29	31

Table 7 presents the results found especially for GIAE and Table 8 shows a statistics summary of the values found.

GIAE values were found from 3 (minimum) to 15 (maximum) with a mean and a median of about 11.2 (that is 56% of a maximum of 20).

The Figure 5 shows the statistics histogram of the 28 GIAE values calculated.

Table 7: Results of the application of the multi-criteria method to the 28 courtrooms sample

Alt. i – Courtroom's town	C_{RT}	$C_{RASTI\ J}$	$C_{RASTI\ D}$	C_{RASTI}	$C_{Dn,w}$ *(entrance lobby)*	$C_{Dn,w}$ *(interior)*	*GIAE*
a_1 - Almeida	18	13	12	13	0	2	13
a_2 - Castelo Branco	12	10	10	10	0	2	9
a_3 - Celorico da Beira	16	10	10	10	2	3.6	12
a_4 - Covilhã 1	0	7	7	7	3	4.4	3
a_5 - Covilhã 2	18	12	11	12	2	3.6	13
a_6 - F. Castelo Rodrigo	18	12	11	12	3	4.4	13
a_7 - Fornos de Algodres	8	8	8	8	3	4.4	7
a_8 - Fundão (1)	18	11	11	11	3	4.4	13
a_9 - Fundão (2)	18	11	11	11	3	4.4	13
a_{10} - Gouveia	19	12	11	12	10	10	15
a_{11} - Idanha-a-Nova	6	7	7	7	0	2	6
a_{12} - Mangualde	12	10	10	10	3	4.4	10
a_{13} - Meda	16	11	10	11	1	2.8	12
a_{14} - Oleiros	20	13	13	13	0	2	14
a_{15} - Oliv. Frades	20	14	13	14	4	5.2	15
a_{16} - Oliv. Hospital	20	13	13	13	0	2	14
a_{17} - Pinhel	16	11	11	11	2	3.6	12
a_{18} - Sabugal	8	10	8	9	4	5.2	8
a_{19} - Sátão	20	13	12	13	0	2	14
a_{20} - Seia (1)	12	10	10	10	0	2	9
a_{21} - Seia (2)	12	10	10	10	0	2	9
a_{22} - Sertã	6	8	7	8	2	3.6	6
a_{23} - Sever do Vouga	19	13	12	13	0	2	13
a_{24} - Trancoso	16	11	11	11	1	2.8	12
a_{25} - VNFoz Côa	14	10	10	10	0	2	10
a_{26} - Viseu (Sala 1)	12	10	8	9	5	6	10
a_{27} - Viseu (Sala 2)	19	12	12	12	7	7.6	14
a_{28} - Vouzela	15	15	15	15	3	4.4	12

C from 0 (worst) to 20 (best)

Table 8: Statistics summary of values found

Parameter	Minimum	Mean	Median	Maximum
GIAE	3	11.2	11.2	15
C_{RT}	0	14.6	16	20
$C_{RASTI\ J}$	7	11	11	15
$C_{RASTI\ D}$	7	10.5	10.5	15
C_{RASTI}	7	11	11	15
$C_{Dn,w(interior)}$	2	3.7	3.6	10

C from 0 (worst) to 20 (best)

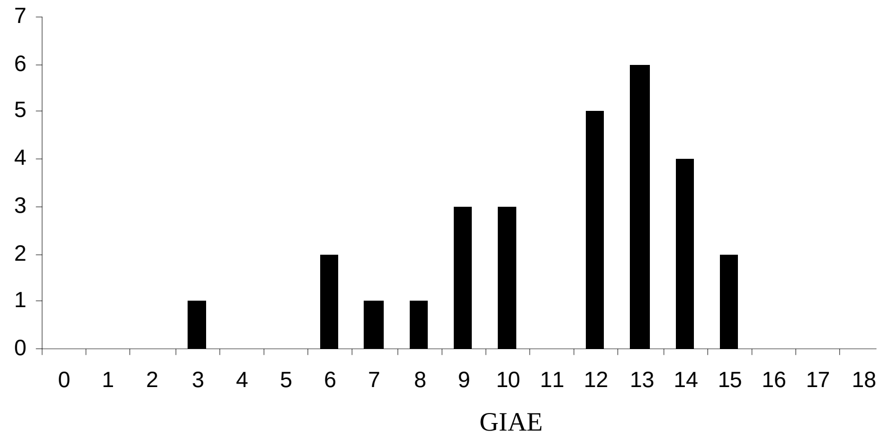

Figure 5: The histogram of all 28 GIAE found with the sample used.

C. Relationships Between GIAE and Architectural Features

Simple models

The Table 9 displays simple models to expeditely predict the *GIAE* for a courtroom using an architectural feature of the room (Figure 6 shows a graphical example with the best value found).

It was found that about 55% of the variance in the *GIAE* is explained by the Volume of the room, being this and the Height two most important architectural features.

Table 9: Best simple regression models between *GIAE* and architectural features.

Model	R^2
$GIAE = -8{,}00 \times 10^{-6} \times V^2 - 0{,}003 \times V + 14{,}5$	0.55
$GIAE = -0{,}015 \times H^2 - 1{,}82 \times H + 19{,}1$	0.45

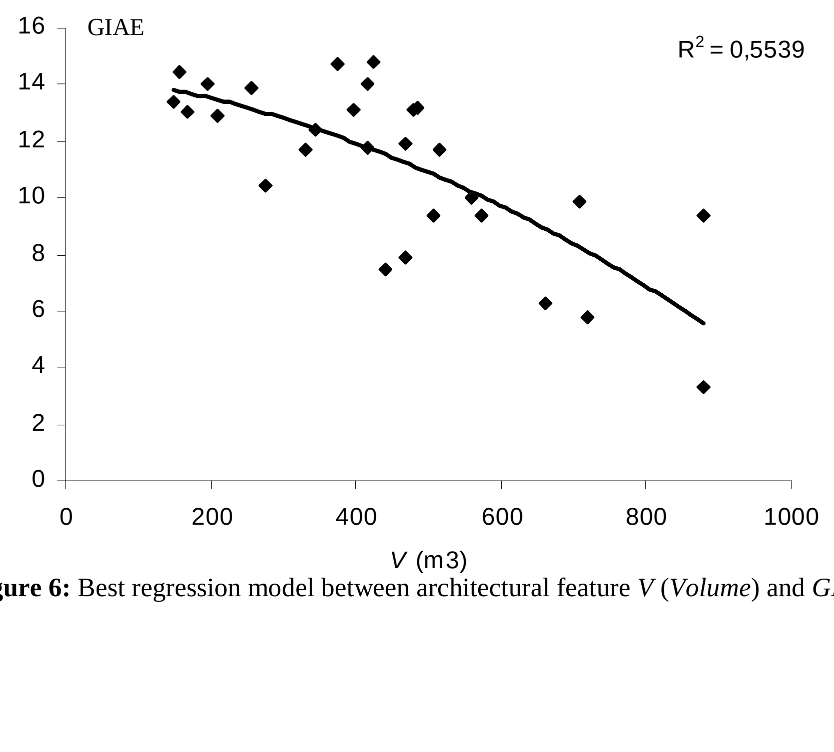

Figure 6: Best regression model between architectural feature *V* (*Volume*) and *GIAE*.

General linear models

To improve the simple models of Table 9, general linear models were tested and the results are shown in Table 10. Using two architectural features the variance explained by the model for *GIAE* increases now to 58%. The Table 10 also shows the general linear models for the prediction of C_{RT} and C_{RASTI}.

Table 10: General linear models

$GIAE = 11.46 - 0.01446\ V + 0.4934\ L$	$R^2 = 0.58$
$C_{RT} = 16.299 - 0.02432\ V + 0.7380\ L$	$R^2 = 0.59$
$C_{RASTI} = 16.577 - 1.2723\ H + 0.01459\ A - 0.01657\ N$	$R^2 = 0.60$

GIAE - Global Index of Acoustic Evaluation, *V* - Volume (m^3), *L* - Length (m), *H* - Height (m), *A* - Sound Absorption (m^2), *N* (number of seats)

D. Design rules

In order to synthesize the goals of this study, Table 11 presents the ideal values for the acoustical parameters used in this multi-criteria method to achieve two types of objectives:

- An ideal GIAE *Global Index of Acoustic Evaluation* (about 20, or 100%);
- A good GIAE *Global Index of Acoustic Evaluation* value (about 15, or 75%).

Table 11: Values for the main acoustical parameters to achieve ideal or good GIAE results

Parameter	Courtroom with an ideal acoustical behavior (*GIAE* ≈ 20)	Courtroom with a good acoustical behavior (*GIAE* ≈ 15)
RT (s)*	[0.8; 1.0[	[1.4; 1.8[
RASTI	[0.90; 1.00]	[0.70; 0.80]
$D_{n,w\ (contiguous\ rooms)}$ (dB)	> 49	[44; 46]
$D_{n,w\ (entrance\ lobby)}$ (dB)	> 35	[32; 33]
$D_{2m,n,w\ \text{(facade)}}$ (dB)	> 33	[30; 31]

GIAE - Global Index of Acoustic Evaluation, * Average of 500 and 1k Hz

4. CONCLUSIONS

This paper proposes a new multi-criteria analysis model to acoustically characterize the courtroom. A Courtroom should be acoustically studied regarding several criteria: their speech intelligibility (within), speech privacy (to and from contiguous rooms) and intruding noise. These characteristics must be evaluated by numerical parameters that describe the sound field within and the sound insulation given by their separating walls with bordering rooms and with the entrance lobby, and the facade.

In this paper several significant acoustic parameters were used and logically weighted to find a representative unique index of evaluation of the room, the GIAE (*Global Index of Acoustic Evaluation*) rated on a scale for 0 (worst) to 20 (best).

The objective acoustic parameters used were:

- Reverberation Time (*RT*) (average of 500 and 1000 Hz frequency bands);
- Weighted normalized airborne sound level difference of walls and partitions (*Dn,w* according to ISO 140-4 and 717-1, similar to the FSTC);

- Weighted normalized airborne sound level difference of facades (*D2m,n,w* according to ISO 140-5 and 717-1);
- Rapid Speech Transmission Index (*RASTI*) (with the sound source in the judge position, facing the audience and in the defendant position, facing the judge).

The multi-criteria mathematical model was presented and numerically tested with a large selected sample of 28 courtrooms in Portugal (with *Heights* from 2.75 to 6.85 m and *Volumes* from 150 to 880 m^3).

Simple formulas and general linear models were found for expedite relationships between GIAE and the main architectural features. In this case, expedite relationships were found that could explain about 60% of the variance in the calculated GIAE values.

A short set of ideal values for the objective acoustic parameters are proposed in order to achieve a high value of the GIAE that can be useful in the design of new courtrooms or on rehabilitation projects.

A very good acoustically courtroom will be achieved if there is a *RT* of about 1 s, an average RASTI of about 0.7, a Dn,w (or FSTC) with contiguous rooms above 44 dB, a Dn,w with the entrance lobby above 32 dB and a D2m,n,w (facade) above 30 dB.

This new method is a reasonable and easy way to rate and/or evaluate an overall acoustic quality of a courtroom.

REFERENCES

[1] Carlos A. Monteiro, *Caracterização acústica de salas de audiências de tribunais* [in Portuguese] (M.Sc. thesis, University of Porto, 2003).

[2] Antonio P. Carvalho and Carlos A. Monteiro, "Acoustics of Courtrooms in Portugal", *Noise-Con 2003 Proceedings*.