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On the relationship between acoustic quality of concert halls and the architectural style

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Abstract. *This study analyzes several concert halls in order to find a relationship between architectural style and some acoustic quality parameters of buildings. Initially they were considered two important properties which are the distribution of sound in the rooms from a source located on stage and its reverberation time. In addition, depending on the results obtained in analyzes made in Raynoise software, compounds roofs of several reflectors plans are designed to correct the lack of sound field homogeneity in the room. It was found that there is an important correlation between the sizes of rooms and architectural styles.*

Keywords: Reverberation Time, NBR 12179, Raynoise, UFRJ, Architectural acoustics.

1. INTRODUCTION

In this work, several concert halls with different architectural styles were analyzed. It was found that a relationship exists between the architectural style of the building, their specific size and their acoustic properties. For each of the 16 rooms chosen, we determine the reverberation time and the distribution of the sound field in the audience from two point sources situated on stage.

The materials used in the environment directly influence the analyzes to be made, thus, the adequacy of the reverberation time with use of the room and the uniformity of the sound field according to the type of roof was verified by considering the material used and the purpose of the environment.

2. PRESENTATION OF ROOMS

The rooms will be presented in the order chronological of its architectural style. Tab. 1 below shows all the rooms along with their geometric dimensions and other useful information in analyzing.

Tab 1 – Rooms Presentations

Environment	Dimensios (height, length and width) [m]	Volume [m³]	Classification	Architectural style
Teatro Municipal de Ouro Preto	9.15 x 24.58 x 11.37	2557.19	Conference Room	Colonial
Teatro Sabará	6.5 x 31.05 x 13.16	2788.6	Conference Room	Colonial
Mosteiro de São Bento	14.19 x 49.8 x 12.5	9585.95	Catholic Church	Barroque
Igreja do Carmo	17.4 x 70.27 x 18	12598.77	Catholic Church	Racoco
Cinema íris	16.7 x 33.1 x 15.48	4972.22	Cinema	Art Nouveau
Teatro Gláucio Gil	5.75 x 20 x 15.7	2177.63	Conference Room	Art Deco
Escola de Música da UFRJ	18.5 x 30 x 17.38	11291.66	Concert Hall	Eclectics
Theatro Municipal do Rio de Janeiro	27.18 x 55.12 x 29.58	31372	Conference Room	Eclectics
Auditório do MEC	5.5 x 20 x 17.14	2639.07	Conference Room	Modern
Sala Cecília Meireles	16.96 x 44.28 x 18.5	6816.28	Concert Hall	Modern
Teatro Armando Gonzaga	6.91 x 20 x 12.97	1295.4	Conference Room	Modern
Auditório BNH	10 x 20.5 x 13.86	1951.88	Conference Room	Contemporary
Teatro dos Quatro	7.75 x 25.12 x 22.17	2301	Conference Room	Contemporary
Teatro Villa Lobos	19.2 x 40 x 17.25	13231.44	Conference Room	Contemporary
Fundição Progresso	13.41 x 89 x 24.08	14309.4	Concert Hall	Various
Teatro João Caetano	14.94 x 49.8 x 12.5	9585.95	Conference Room	Various

3. REVERBERATION TIME STUDY

By concept, "Reverberation time is the time required for a sound check to be heard after the extinction of the sound source and measured in seconds.[…]"(NBR 12179/1992 - Standard for acoustic treatment in doors-Procedure). The calculation of Rt (Reveberation time –*Tr: Tempo de Reverberação*) was using a program to implement the formula of Sabine and Norris-Eyring, presented below in Eq(1) -. Sabine equation-and Eq(2) -. Norris-Eyring equation. Eq. (3) presented the Middle Absorption Coefficient.

$$Tr= (0.161 \times V)/(\sum S_i \times \alpha_i)$$

$$Tr= (0.161 \times V)/(-2.3 \times \log(1 -\alpha_m))$$

$$\alpha_m =(\sum\alpha_i \times S_i)/\sum S_i$$

The program gives us the Rt according to Sabine's and Eyring's formula in the center frequencies of octave bands. In NBR 12179/1992 is set that α_m<0.3 at a frequency of 500 Hz must use the result by Sabine.

In standard is also shown a graphic which defines the ideal Rt at 500 Hertz considering its use and its volume (its dimensions). The Reverberation Time Ideal 500 Hz chart was used in determination of the each room's ideal Rt.

According to item 6 of NBR12179/1992, regarding the acceptance of the insulation efficiency and acoustic conditioning, there is a tolerance (tol.) of 10% of the obtained Ideal Rt value, otherwise the room must undergo acoustic treatment. Following the results of the analyzed environment.

Then, inTab.2, they will be shown the results of Rt.

Tab. 2 – Rt's Results, where tol = tolerance; Ob = Obtained

Environment	Ideal Rt [s]	Obtaine d Rt [s]	Rt Efficiency	Analysis
Teatro de Ouro Preto	0,92	0,97	Good	Ideal Rt is very close Ob. Rt
Teatro Sabará	0,9	2,11	Reflector	Ideal Rt is much smaller than Ob. Rt
Mosteiro de São Bento	1,99	2,3	Reflector	Ideal Rt is smaller than Ob. Rt
Igreja do Carmo	2	1,97	Good	Ideal Rt is close to Ob. Rt
Cinema Íris	1	3,91	Reflector	Ideal Rt is much smaller than Ob. Rt
Teatro Gláucio Gil	1,3	2,3	Reflector	Ideal Rt is much smaller than Ob. Rt
Escola de Música UFRJ	3,65	7,09	Reflector	Ideal Rt is much smaller than Ob. Rt
Theatro Municipal do Rio de Janeiro	1,3	10,36	Reflector	Ideal Rt is much smaller than Ob. Rt
Auditório MEC	0,9	2,09	Reflector	Ideal Rt is much smaller than Ob. Rt
Sala Cecília Meireles	1,55	1,49	Good	Difference between Rts is inside of tol.
Teatro Armando Gonzaga	0,6	1,8	Reflector	Ideal Rt is much smaller than Ob. Rt

Auditório BNH	0,75	0,5485	Absorbent	Ideal Rt is bigger than Ob. Rt
Teatro dos Quatro	0,9	1,09	Good	Difference between Rts is inside of tol.
Teatro Villa Lobos	1,7	2,5	Reflector	Ideal Rt is much smaller than Obtained Rt
Fundição Progresso	1,6	1,9	Reflector	Ideal Rt is much smaller than Ob. Rt
Teatro João Caetano	1,45	2	Reflector	Ideal Rt is much smaller than Ob. Rt

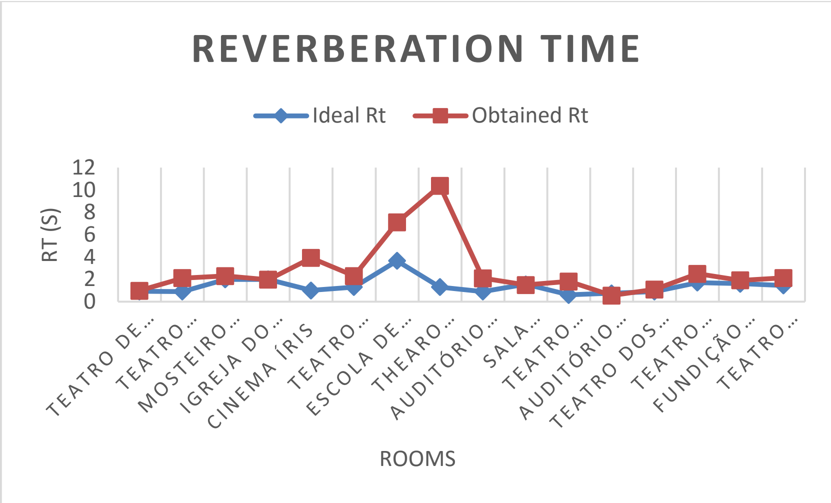


Figure 1 - Reverberation Time of all presented environments [Source: Produced in LAVI/UFRJ]

4. STUDY OF PRESSURE LEVEL OF SOUND HOMOGENEITY IN ROOMS

The analysis determines the sound attenuation with respect to distance the audience to the sound source. It was considered that if the environment has a difference Sound Pressure Level below 5 dB(A), the sound field can be considered homogeneous and well distributed; between 5 and 10 dB(A), the field is unevenly distributed because SPL has a difference that does not quite very disrupt the hearing; and the sound field present a discrepancy of more than 10 dB(A), we can consider the field very unevenly distributed and very heterogeneous. Next, there are the results of the simulations.

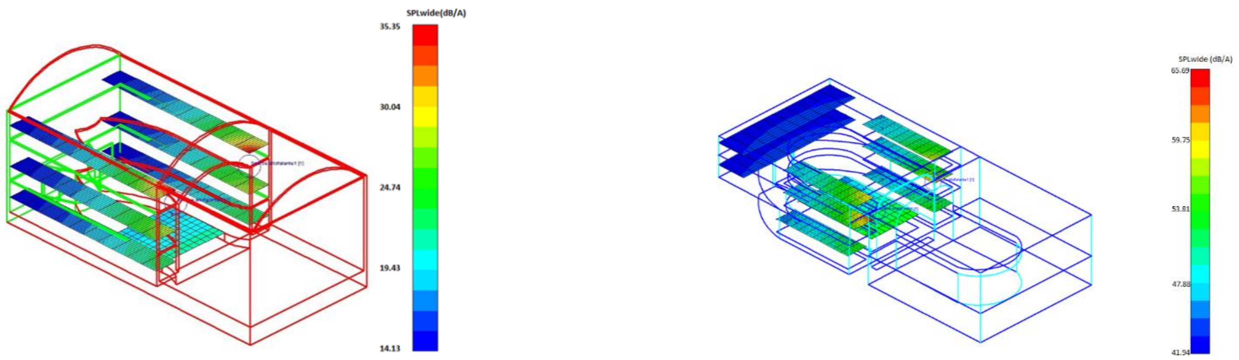
Teatro Municipal de Ouro Preto/ Teatro Sabará/ Mosteiro de São Bento/ Igreja do Carmo/

As the red region is very small, we can begin our analysis of the *Teatro Municipal de Ouro Preto* from the yellow region, so we have a discrepancy between the sound pressure level is15.91 dB(A). Therefore, it is very uneven.

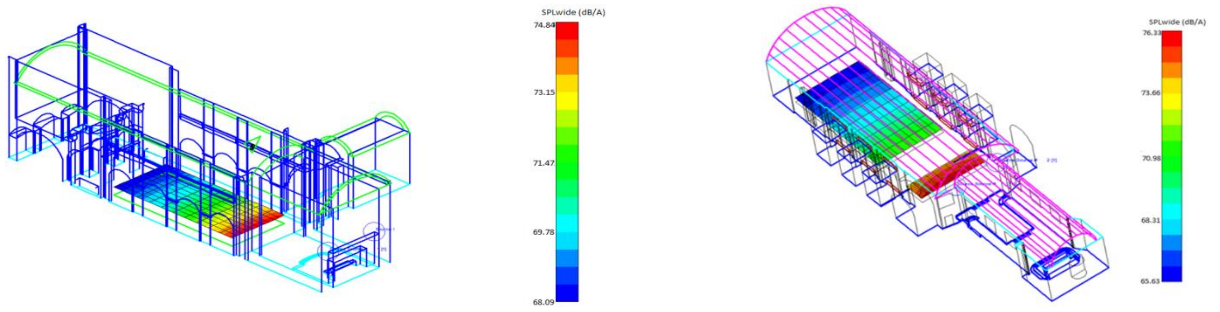
Analysis of the *Teatro Sabará* get the yellow area for the same reasons above, and we have a discrepancy between the sound pressure level is17.81 dB(A). Therefore, it is very uneven.

The *Mosteiro de São Bento* has a bad sound field distributed as well. Closest to the source is gotten a sound pressure level of 74.84 dB(A) and on the far region is 68.09 dB(A), so we have a difference of 6.75 dB(A).

The *Igreja do Carmo* has a sound field very unevenly distributed, with difference in sound pressure level of 10.7 dB(A), since the area in red, closer to the stage where they are placed sound sources, has 76.33 dB(A) and the darker blue- in the back of the church-has 65.63 dB(A).



(a) *(b)*



(c) *(d)*

Figure 2 - Simulation of the sound distribution on *(a)Teatro Municipal de Ouro Preto; (b) Teatro Sabará; (c) Mosteiro de São Bento; (d) Igreja do Carmo* [Source: Produced in LAVI/UFRJ]

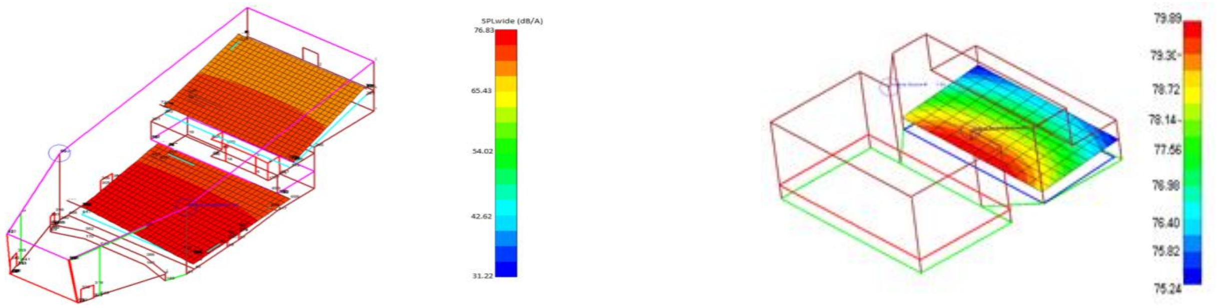
<u>*Cinema Íris/ Teatro Gláucio Gil/ Escola de Música da UFRJ/Theatro Municipal do Rio de Janeiro*</u>

The sound field in *Cinema Íris* is not very regular. Although there is little color variation in the audience sound field when analyzing its values we see that the measures in the red area and orange area are quite distinct. The region with the highest sound intensity reaches 76.83 dB(A) and does not reach the lowest 65.43 dB(A), one can estimate that is 58 dB(A) - the difference of 8.83 dB(A).

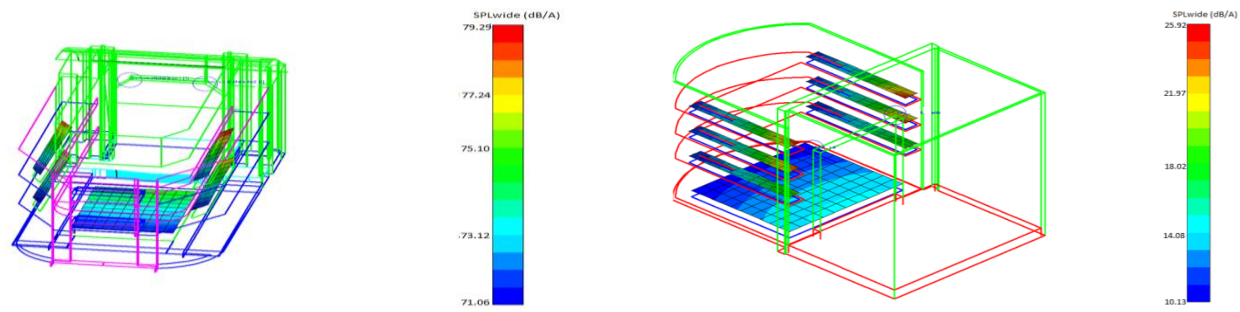
We can consider that the sound in the *Teatro Gláucio Gil* environment is well distributed. The difference in sound pressure level between the red regions-closer the source dark blue-and, more to the audience background, is 4.5 dB(A).

In *Escola de Música da UFRJ* there is a difference of 23.8 dB(A) between the area closer to the source -79.29 dB(A) – and the farthest-71.06 dB(A) -, so we see that the environment also does not present a homogeneous sound field.

As the red region is very small, we can begin our analysis of the *Theatro Municipal do Rio de Janeiro* from the yellow region, which has a level of 21.9 dB(A). When we take this value and compare with the region of background of the audience, we have a difference of 11.9 dB(A). Soon we see that the sound field is very unevenly distributed, requiring treatment.



(e) *(f)*



(g) *(h)*

Figure 3 - Simulation of the sound distribution on *(e)Cinema Íris; (f)Teatro Gláucio Gil; (g) Escola de Música da UFRJ; (h) Theatro Municipal do Rio de Janeiro* [Source: Produced in LAVI/UFRJ]

<u>*Auditório do MEC/ Sala Cecília Meireles/ Teatro Armando Gonzaga/ Auditório BNH*</u>

The area closest to the source has an average level of 21.97 dB(A) and the far has 12.50 dB(A) - a difference of 9.47 dB(A) – Sound pressure level. Soon we see that the sound field is heterogeneous.

Sala Cecília Meireles is an environment in which the sound is very unevenly distributed, the difference between the red region (23.67 dB(A)) and dark blue (7.84 dB(A)) reaches 15.83 dB(A).

The sound on the inside of the *Teatro Armando Gonzaga* is not so unevenly distributed, since the gap between regions closer to the source and the furthest is 6.9 dB(A).

We can see that the red area of the *Auditório BNH*, closer to the source, is in the range of 79.03 dB(A) and the part of the audience in the background is equivalent to a pressure level of 73.86 dB(A) - a difference of only 5.17 dB(A) -. Therefore, we conclude that the sound field is not homogeneous but also has a not very uneven distribution.

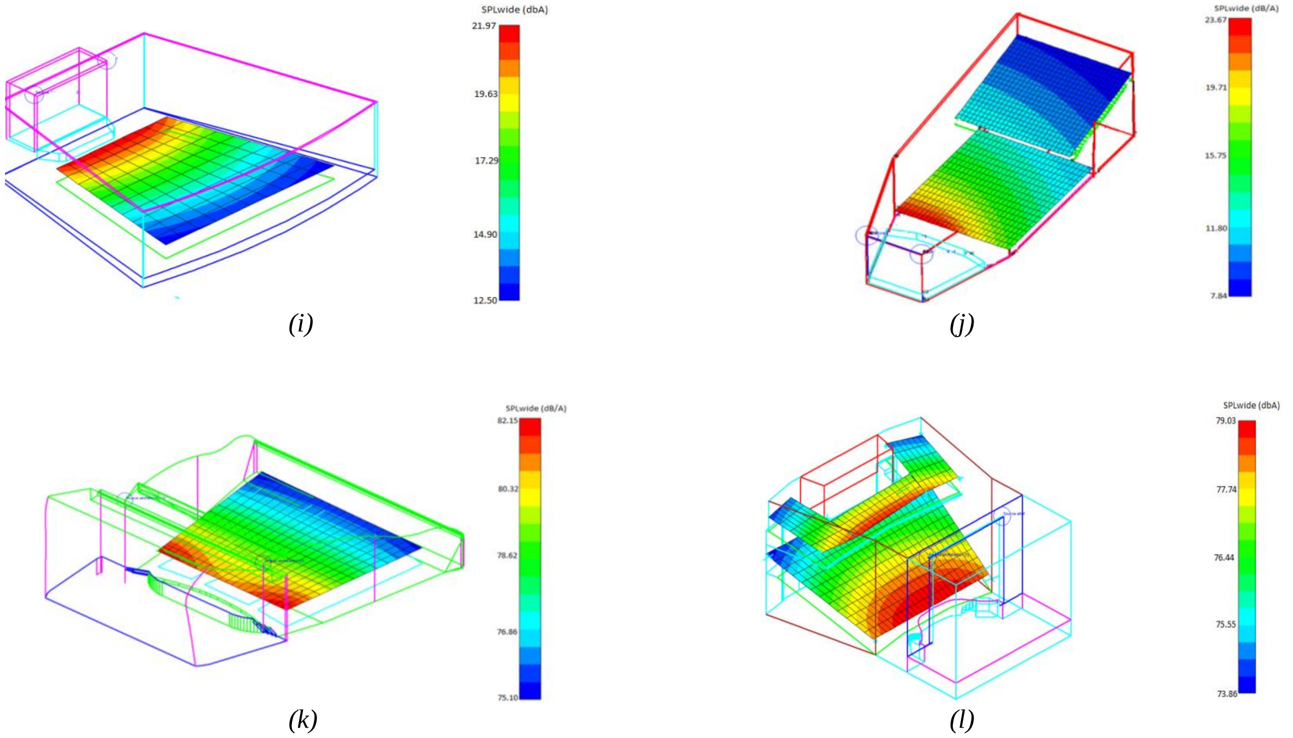


Figure 4 - Simulation of the sound distribution on *(i) Auditório do MEC; (j) Sala Cecília Meireles; (k) Teatro Armando Gonzaga; (l) Auditório BNH* [Source: Produced in LAVI/UFRJ]

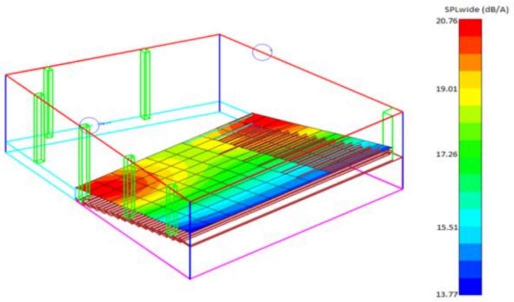
<u>*Teatro dos Quatro/ Teatro Villa Lobos/ Fundição Progresso/ Teatro João Caetano*</u>

The environment of the *Teatro dos Quatro,* according to the analysis also needs to acoustic treatment in order to let the sound field a bit more regular. The difference between the regions, which enabled this analysis, is 7.76 dB(A).

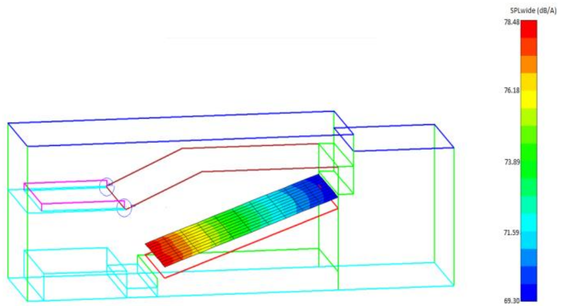
For the results found, note that the *Teatro Villa Lobos* has a sound pressure field poorly distributed, since the SPL difference between the area near to the source and away the most is approximately 9.18 dB(A).

In this analysis of Fig.5, item *(o)*, we can consider even a little more behind the green area, since the blue part is behind a wall and no makes effective part of the audience in the *Fundição Progresso*. Thus we see that there is a level difference of sound pressure equivalent to 3.86 dB(A), taking into account this result we can deduce that the environment has a sound field evenly distributed and smooth.

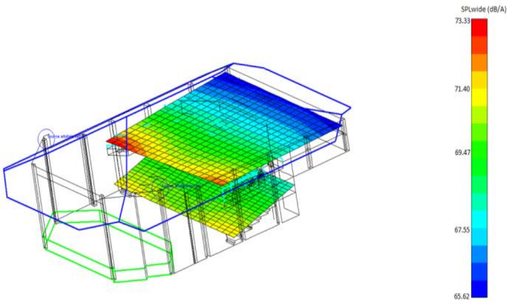
For the scale of the simulation in Fig.5, item *(p)*, it is easy to see that the *Teatro João Caetano* presents a poorly distributed sound field, since the SPL difference between the area close to the source and away the most is approximately 10.7 dB (A).



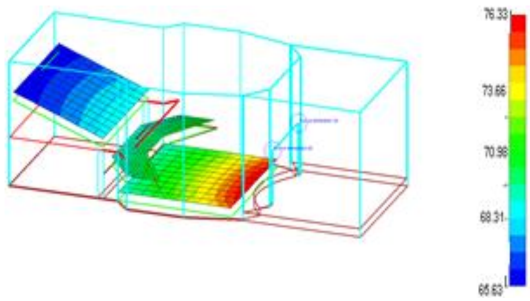
(m)



(n)



(o)



(p)

Figure 5 - Simulation of the sound distribution on *(m) Teatro dos Quatro; (n) Teatro Villa Lobos; (o) Fundição Progresso; (p) TeatroJoão Caetano* [Source: Produced in LAVI/UFRJ]

In Fig.6 presented below, you can see the different distributions of sound pressure level for the environment.

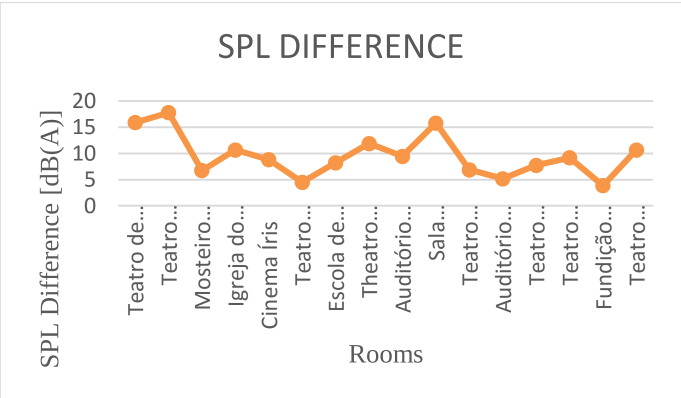


Figure 6 - SPL difference of all analyzed environments. If SPL<5 dB(A): homogeneous field; if 5< SPL<10 dB(A): misallocated field; and SPL <10 dB(A): very unevenly distributed field.[Source: Produced in LAVI/UFRJ]

5. CONCLUSION

It was necessary to disregard the ambient noise described by the standard NBR10152/1987--Noise levels for acoustic comfort-Procedure-- as these increase noise levels, not allowing a full analysis. We consider all flat walls (unadorned), and analysis of sound pressure level, the chairs were considered only as a listening plane composed of the material in this.

When we separate the rooms according to their architectural styles have very similar results both of its geometrical shapes as their acoustic quality and can set, thus, standards. The Tab. 3 demonstrates the conclusion of the dimensions of the rooms saw followed the conclusions of each architectural style. A measure of a=5 meters with fixed dimensions (height, length and width) from the environment were made from "a" to facilitate the visualization of proportions.

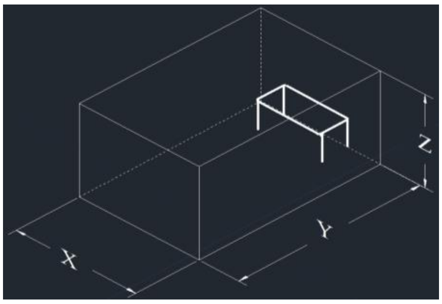


Figure 7 – Determination of the axes X, Y, Z and stage design. [Source: Produced in LAVI/UFRJ]

Tab.3 – Dimensions proportions of the rooms. a=5 m

Styles	Rooms	X–axis (m)	Y –axis (m)	Z-axis (m)
Colonial	*Teatro de Ouro Preto*	3 a	5 a	2 a
	Teatro Sabará	3 a	6 a	1 a
Barroque	*Mosteiro de São Bento*	2,5 a	10 a	3 a
Rococo	*Igreja do Carmo*	4 a	14 a	3,5 a
Art Nouveau	*Cinema Íris*	3,1 a	6,62 a	3,34 a
Art Deco	*Teatro Gláucio Gil*	3 a	4 a	1 a
Eclectic	*Escola de Música*	3,5 a	6 a	4 a
	Theatro do Rio de Janeiro	6 a	11 a	5 a
Modern	*Auditório do MEC*	3,4 a	4 a	1,1 a
	Sala Cecília Meireles	4 a	9 a	4 a
	Teatro Armando Gonzaga	3 a	4 a	1 a
Contemporary	*Auditório BNH*	2,7 a	4,1 a	2 a
	Tetro dos Quatro	4 a	5 a	2 a
	Teatro Villa Lobos	3,5 a	8 a	4 a
Various	*Fundição Progresso*	7,8 a	5,55 a	1,22 a
	Teatro João Caetano	6 a	12 a	3,5 a

Colonial style, which includes the *Teatro de Ouro Preto* and the *Teatro Sabará*, you can see that the geometric shape of the two refers to a shoe box, both are flat and well long. This contributes to the sound pressure levels of both are bad. The *Ouro Preto*'s reverberation time is within the tolerance provided for in the standard NBR 15179/1992 therefore can be considered good. But the environmental of *Teatro Sabará* reflector is due to the different materials chosen and also to two dimensions.

For the Baroque style we have the example of the *Mosteiro de São Bento*. The room is long, which guarantees a poorly distributed sound field. Its dimensions combined with the numerous materials used in elaborate Baroque architecture make the building has a high reverberation time.

The *Igreja do Carmo*, of Rococo style, is long without being flattened, giving the sound field a heterogeneous profile. However, its architectural style uses materials inside which makes its Rt be obtained close to ideal.

The Art Nouveau style have the *Cinema Íris*, which is also just long. With reflector environment-given the scale and the coating materials-and SPL poorly distributed field.

The representative of the Art Deco style we have the *Teatro Gláucio Gil*. Its width is proportional to the length, however it is very flat as a result the simulation showed a high Rt and the environment presented an SPL well distributed.

To do the Eclectic style pattern we have the *Escola de Música da UFRJ* and the *Theatro Municipal do Rio de Janeiro*. Both are long. The *Escola* has a very reflector and SPL poorly distributed environment. But the *Theatro* has very large dimensions that are not on the chart of the standard NBR15179/1992 and had to be adapted to reach the conclusion that the environment is reflector and SPL very poorly distributed.

As examples of Modern style have the *Auditório do MEC*, the *Sala Cecília Meireles* and *Teatro Armando Gonzaga*. The *Auditório do MEC* presents flat and gently expanded as shown below. This setting, along with the materials used earned him a higher reverberation time than ideal, being a reflective room, and poorly distributed sound field. *Sala Cecília Meireles* is long, making it easy for its SPL very poorly distributed. Its Rt close to the ideal, is a consequence of the choice of material together with the dimensions of the room. The *Teatro Armando Gonzaga* is also flat and long, resembling the *Auditório do MEC*. Therefore, as you might expect its results are very similar. The reverberation time is high and the sound field is poorly distributed.

The Contemporary style is represented by *Auditório BNH*, *Teatro dos Quatro*, and *Teatro Villa Lobos*. The *Auditório BNH* is cubic, with all dimensions proportional. This feature combined with the material and the gross volume of the room environment provided an absorbent as a SPL well distributed. The *Teatro dos Quatro* already has a different way. It is flat and slightly long, having a bad sound field distributed. The reverberation time is close to ideal because of the chosen materials. The *Teatro Villa Lobos* already have a third geometry: it is long. We know that this geometry comes with a bad SPL-poorly distributed sound field- which is what happens in *Villa Lobos*. The environment is reflector.

Exemplifying the latest architectural style, "Various", we have *Fundição Progresso* and the *Teatro João Caetano*. Both have the same geometric shape: flat and long. The *Fundição Progresso* not as flat, having the sound field evenly distributed and a reflector environment due to the materials. The *Teatro João Caetano* is flat and very long, which creates a sound field very poorly distributed. The materials and the dimensions of defined a reflector environment.

In Tab. 3, we have an overview of relations between the acoustic efficiency, the architectural style, its dimensions and geometric shapes.

Table 3 - Acoustic efficiency ratio x architectural style

	Examples environment	**Volume (m³)**	**Geometric Shape**	**SPL Distribution**	**Rt Efficiency**
Colonial	*Teatro de Ouro Preto*	2557.19	Flat and long	Very bad	Good
	Teatro Sabará	2788.6	Flat and long	Very bad	Reflector
Barroque	*Mosteiro de São Bento*	9585.95	Long	Bad	Reflector
Rococo	*Igreja do Carmo*	12598.77	Long	Bad	Good
Art Nouveau	*Cinema Íris*	4972.22	Long	Bad	Reflector
Art Deco	*Teatro Gláucio Gil*	2177.63	Flat and ± long	Good	Reflector
Eclectic	*Escola de Música*	11291.66	Long	Bad	Reflector
	Theatro M. do Rio de Janeiro	31372	Long	Very bad	Reflector
Modern	*Auditório do MEC*	2639.07	Flat and Wide	Bad	Reflector
	Sala Cecília Meireles	6816.28	Long	Very bad	Good
	Teatro Armando Gonzaga	1295.4	Flat and ± long	Bad	Reflector
Contemporary	*Auditório BNH*	1951.88	Cubic	Good	Absorbent
	Teatro dos Quatro	2301	Flat and ± long	Bad	Good
	Teatro Villa Lobos	13231.44	Long	Bad	Reflector
Various	*Fundição Progresso*	14309.48	± Flattened and very long	Good	Reflector
	Teatro João Caetano	9585.95	Flat and very long	Bad	Reflector

If the sound level in the far seat is much lower than the level of the front rows with respect to the stage – the direct sound tends to lose its intensity for more distant places of the source - is defined the need to design a ceiling composed of reflectors panels, made with a low absorption material to reduce this difference by increasing the noise level, based on the sound decay criteria. The reflector plates leave the best sound distributed in the environment, also improving Rt in some cases.

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