Revista Nacional de
Gerenciamento de Cidades
ISSN eletrônico 2318-8472, volume 09, número 72, 2021

Acoustic quality assessment in a classroom through simulations and measurements

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ABSTRACT

The acoustic quality in a classroom directly impacts the educational relationship between the student and the teacher, reducing speech intelligibility. In addition, inadequate acoustic comfort burdens the vocal health of teachers. This study evaluated a classroom at the Federal University of Paraná, Campus Centro Politécnico, to verify its acoustic quality. The measurements of the acoustics descriptors: Reverberation Time (RT), Definition (D50), Central Time (Ts), Early Decay Time (EDT) were performed according to the ISO 3382-2 standard, concerning Noise Curves (NC) and Background Noise (BGN) these were evaluated by the NBR 10152 and S12.2 standards. The Speech Transmission Index (STI) was measured according to IEC 60268-16 and evaluated according to ISO 9921. The useful-detrimental ratio (U50) and the other descriptors were simulated in the ODEON software version 11. Thus, the results showed that the evaluated room did not meet the minimum requirements in terms of acoustic quality, for the descriptors RT, STI, Ts, D50, RF, and NC. Simultaneously, the RT and STI were also outside the limits established by the German and Finnish standards. Therefore, it is concluded that the evaluated classroom did not reach the minimum acoustic quality requirements.

KEYWORDS: Speech Transmission Index. Room acoustics. Reverberation Time. Acoustic quality

1 INTRODUCTION

Over the decades, the fundamental importance of establishing good acoustic quality in classrooms has been consolidated. Thus, it was shown to depend on architectural characteristics and the school's location (ZHU et al., 2020). Consequently, the people responsible for the urban planning should consider planning the strategic location of educational establishments, prioritizing areas without high noise exposure (DO NASCIMENTO et al., 2021).

Accordingly, several acoustic descriptors were proposed to assess the perception of noise on classroom acoustics quantitatively. Many of them were based on energetic ratios of sound propagation using the theory of sound diffusion in well-defined acoustic fields (MA; MAK; WONG et al., 2020). For example, one may cite the descriptors such as Reverberation Time (RT), Definition (D50), Central Time (Ts), Early Decay Time (EDT), Useful-to-detrimental sound ratio - U50 (ISO, 2008). These descriptors were standardized internationally or were implemented in the form of specific legislation or technical recommendations.

On the other hand, there are acoustic descriptors correlated with strictly subjective aspects of speech and sound perception, e.g., Noise Curves (NC) and Background Noise (BGN) which are evaluated by the NBR 10152 standard (ABNT, 1987) and by S12.2-2008 standard (ANSI/ASA, 2008), respectively. For the evaluation of noise in indoor environments, it is essential to measure the background noise. The BGN is defined as the drop in the sound pressure level associated with residual noise. When all sources within the environment are ceased, the only noise measured comes from external contributions to the environment.

While the Speech Transmission Index (STI) is the most consolidated descriptor to measure speech intelligibility, because of the incredible variety of acoustic descriptors available in the literature, many studies aimed to quantify the relationships between the STI and the descriptors T30, D50, Ts, EDT, U50. As a result, multiple researchers discussed case studies that sought to clarify the relationship between the speech intelligibility descriptors and how these can vary in the most diverse conditions (YANG; MAK, 2021; RANTALA; SALA, 2015, AUGUSTYŃSKA et al., 2010).

This work aimed to evaluate the acoustic quality using the following acoustic parameters STI, T30, D50, Ts, EDT, and U50 through measurements and simulations. To this end, the measured value was benchmarked against the standards of each respective descriptor. Then, through acoustic simulations, using the ODEON software version 11, the effect of spatial attenuation was verified through acoustic maps. That is the distance between the position of the source and the receiver for each descriptor.

2 METHODOLOGY

2.1 RT, T30, D50, Ts, and EDT measurements

For the measurement of RT and other descriptors derived from the same Room Impulse Response (RIR), the procedures recommended by ISO 3382-2 (ISO, 2008) were applied. The instrumentation consisted of a) DIRAC 5.0 software (B&K 7841) installed on the Sony VAIO Notebook; b) RME Fireface 800 sound car; c) Lab. Gruppen LAB 300 amplifier and d) B&K 2260 sound pressure level meter analyzer.

2.2 Measurements of STI, BGN e NC

Regarding the STI measurements, the procedures of IEC 60268-16 (IEC, 2011) were followed. During the measurement, the classroom was occupied only by the operators. Doors and windows were kept closed, when possible, to reduce interference from outside noise. Background noise was measured by the Brüel and Kjaer 2260 sound pressure level meter in octave bands, and the sound level meter was positioned at a single position. The BGN measurement time was 5 minutes after the B&K 2260 Analyzer calculated the NC value.

The instrumentation presented in the B&K DIRAC software version 5 and the B&K 2260 analyzer was used for the STI measurements. The instrumentation consisted of a) DIRAC 5.0 software (B&K 7841) installed on the Sony VAIO Notebook; b) RME Fireface 800 audio acquisition board; c) Behringer Equalizer FBQ 800 model; d) Amplifier Lab. Gruppen LAB 300; e) Artificial Mouth Simulator B&K 4227; f) B&K 2260 sound pressure level meter and analyzer. In total, 25 internal points corresponding to the receivers were measured inside the classroom.

2.3 Acoustic simulations

The modeling of the classrooms was performed using ODEON software version 11 (Brüel & Kjaer). ODEON is notably one of the most consolidated software’s in acoustic simulations, and it applies the Ray Trace Method. The Ray Trace method models sound waves' propagation as straight rays or beams that can undergo reflection, absorption, and diffraction (CHRISTENSEN, 2013). The modeling process consisted of the following steps:

a) Classroom modeling in Sketchup software version 2017. Sketchup is a CAD (Computer Aided Drawing) type software;

b) Drawing layers/layers were created in SketchUp modeling to represent each material present in the classroom;

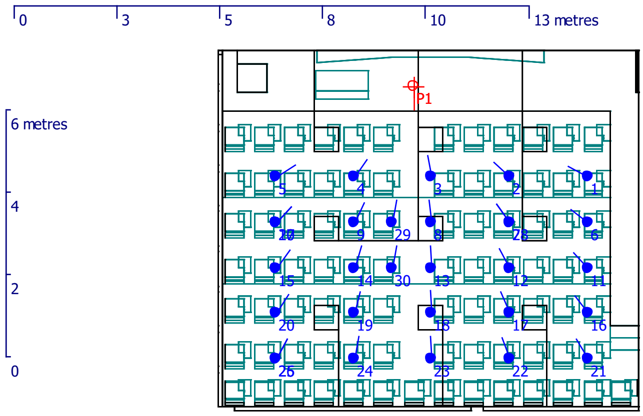
c) The classroom model was exported through the plug-in (SU2Odeon) with the file extension (<filename>.par);

d) Import of the Sketchup room model coming from the file name, (<file_name>.par), into ODEON;

e) With the classroom model already present in ODEON, a material was assigned to each layer previously created in Sketchup. Each material was assigned in the "material list", allocating the absorption coefficient in the octave bands from 63 Hz to 8 kHz (wood, concrete, flooring, coating in general).

The classroom's dimensions were; width of 10.00 m, length of 8.70 m and height of 2.95 m, the volume of 236.06 m^3. Figure 1 shows the virtual model of the classroom.

Figure 1: Virtual schematic model of the evaluated classroom



Source: The Authors, 2021

For each relevant surface in the classroom, a value for the sound absorption coefficient was adopted as a function of the respective material, as shown in Table 1.

Table 1: Sound absorption coefficient for the relevant surfaces in the modeled classroom

Area surface	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz
Floor	0.02	0.02	0.03	0.03	0.03	0.03	0.02	0.02
Aluminum rods	0.02	0.02	0.03	0.03	0.03	0.04	0.07	0.07
ventilation space	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Chair plywood	0.03	0.02	0.05	0.05	0.05	0.04	0.03	0.02
Painting	0.15	0.15	0.11	0.10	0.07	0.06	0.07	0.07
Wooden door	0.14	0.14	0.10	0.06	0.08	0.10	0.10	0.10
Wall	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02
Roof	0.15	0.19	0.21	0.32	0.41	0.49	0.53	0.53
Upholstered armchairs	0.15	0.15	0.19	0.22	0.39	0.38	0.30	0.30
common glass windows	0.35	0.35	0.25	0.18	0.12	0.07	0.04	0.04
Court hearing	0.07	0.07	0.31	0.49	0.81	0.66	0.54	0.54

Source: The Authors, 2021

The sound absorption coefficient values were taken from the internal library of the ODEON software. According to the documentation of the ODEON software (CHRISTENSEN, 2013), the acoustic descriptor simulation procedure must be done according to the standards for in situ measurements as per sections 2.1 and 2.2.

3 RESULTS

3.1 Acoustic Quality Assessment

Table 2 shows the measured background noise (BGN) values, the equivalent sound pressure level (LAeq), and the respective NC value.

Table 2: Background Noise Values [dB] and NC curve

Frequency	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8kHz	NC	LAeq
Background Noise	52.6	48.3	38.6	32.2	32.0	29.9	23.0	19.5	35	38.2

Source: The Authors, 2021

Based on the BGN, the value for the NC noise curve of 35 was obtained. Table 3 contains the normative comparison of the adequacy of the NC descriptor, in relation to NBR 10152 and ANSI/S12.2:2008 standards.

Table 3: Normative comparison of noise curves - NC [dB]

NBR 10152:1987			ANSI/ S12.2:2008		
Measured value	Requirement	Result	Measured value	Limit	Result
35	35 – 45	conformity	35	25 - 35	nonconformity

Source: The Authors, 2021

In Table 3, according to the Brazilian standard NBR 10152:1987 (ABNT, 1987) and the American standard ANSI/S12.2:2008 (ANSI/ASA, 2008), the classroom meets the requirements of the NC curve.

According to Table 4, the classroom was outside the recommended values for the reverberation time according to the NBR 12179 standard (ABNT, 1992). However, the ANSI/ASA S12.60:2010 (ANSI/ASA, 2010) considered the classroom to be adequate. It should be noted that the weighting criteria of the classroom volume were considered. Therefore, the volume of 350 m^3 was adopted for consultation in NBR 12179 (ABNT, 1992).

Table 4: Comparison of RT [s] against standards

NBR 12179:1992 RT – 500 Hz				ANSI/ASA S12.60-2010*: RT – 500 Hz, 1 kHz e 2 kHz			
Measured	Volume	Requirement	Result	Measured	Volume	Requirement	Result
0.60 s	350 m^3	< 0.50 s	nonconformity	0.50 s	236. m^3	< 0.60 s	conformity

Source: The Authors, 2021

Table 5 shows the results for the D50. According to ISO 3382-2 (ISO, 2008), the reference values for D50 are compressed in the range of 30% to 70%. These values are considered typical of rooms up to 25000 m^3. Furthermore, the German standard DIN 18041:2004 (DIN, 2004) recommends C50 ≥ 0 dB, which corresponds to the value of D50 ≥ 50%.

Table 5: Adequacy of the D50 according to different standards

Evaluated standard	Measured	Requirement	Result

ISO 3382-2:2008 D50: 500 Hz and 1 kHz	79%	30% up to 70%	nonconformity
DIN 18041:2004 D50: 125 Hz up to 8 kHz	76%	≥ 50 %	conformity
Ansay e Zannin (2016) Qualitative criterion	76%	> 50 %	Good

Source: The Authors, 2021

Therefore, it was found that the D50 generated ambiguous results since the ISO 3382-2 (ISO, 2008) standard requirements for the D50 were not fulfilled, while the DIN 18041:2004, and Ansay and Zannin (2016) showed the contrary. Table 6 shows the results for the descriptors Ts and EDT, which highlighted the non-compliance of the acoustic situation of the classroom, even though the reverberation time was short.

Table 6: Normative comparison of Ts and EDT

Evaluated standard	Measured	Requirement	Result
ISO 3382-1:2009 Ts: 500 Hz and 1 kHz	32.65 ms	60 ms up to 260 ms	nonconformity
ISO 3382-2:2008; EDT: 500 Hz and 1 kHz	0.50 s	1.0 s a 3.0 s	nonconformity

Source: The Authors, 2021

Qualitatively, the STI was evaluated according to ISO 9921 (ISO, 2003) and IEC 60268-16 (IEC, 2011) standards. The values of the signal-to-noise ratio (SNR) were consolidated in Table 7.

Table 7: Signal-to-Noise Ratio [dB] measured in the classroom for the STI

Frequency	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz
Signal-to-Noise ratio	21.28	20.48	19.48	17.44	10.96	6.04	-9.32

Source: The Authors, 2021

When considering the SNR values shown in Table 7, an average STI of 0.63 in the room was obtained for (n = 25 points). Consequently, Table 8 shows the quantitative values of the STI and its adequacy, according to various international standards.

Table 8: Comparison of the adequacy of STI measured values by various standards

Evaluated standard	Country	Measured	Requirement	Result
DIN 18041:2004	Germany	0.63	≥0.56	conformity
SFS 5907:2004	Finland*	0.63	≥0.70	nonconformity
BB93:2015	United Kingdom	0.63	≥0.60	conformity
ISO 9921:2003(E)	International**	0.63	≥0.60	conformity

*Class C. other classes are A and B ≥ 0.80.
**Corresponding to Person-to-Person Communication condition. Reasonable level (Fair). Table 1 of ISO 9921:2003(E). For the Fair rating, the STI is between 0.45 and 0.60. which IEC 60268-16:2011(E) corresponds to the STI of 0.60.
Source: The Authors, 2021

The Finnish standard SFS 5907:2004 (SFS, 2004) sets the most restrictive limits for STI, followed by England and later by Germany. Therefore, according to SFS 5907:2004 (SFS, 2004),

Revista Nacional de
Gerenciamento de Cidades
ISSN eletrônico 2318-8472, volume 09, número 72, 2021

the classroom would have been in non-compliant STI. On the other hand, according to DIN 18041:2004 (DIN, 2004) and the BB93 (DFE, 2015) and ISO 9921 (ISO, 2003), the evaluated classroom meets all requirements.

3.2 Effect of distance on acoustic descriptors

This section aims to demonstrate, using simulations, the effect that distance produces on the descriptors Leq, STI, D50, U50, EDT, and D50 using the color maps generated by ODEON. However, before entering the objective of this section, the validation of the simulations must be verified. The descriptors T30 and STI were used for validation. Regarding reverberation time, Table 9 shows the percentage error between the measured and simulated values, with an average value of -3%.

Table 9: Errors in the validation of simulated classroom for T30 for n = 4 points

	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8kHz
Measured [s]	0.97	0.82	0.62	0.49	0.47	0.46	0.39
Simulated [s]	0.89	0.81	0.66	0.50	0.45	0.43	0.36
Error [%]	-8.00	-1.00	6.00	2.00	-4.00	-7.00	-8.00

Source: The Authors, 2021

Regarding the STI, the validation results were consolidated in Table 10.

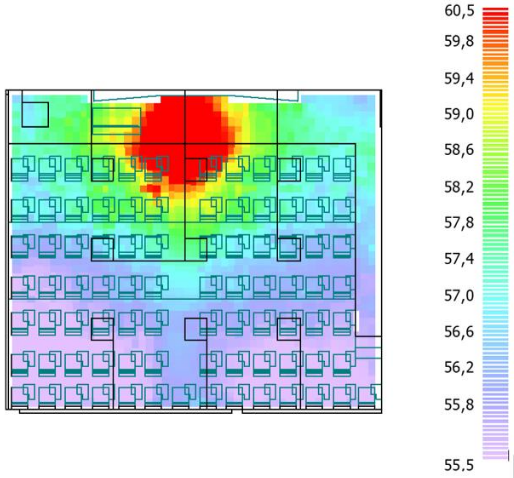
Table 10: Errors in the validation of the virtual model of the simulated classroom for the STI for n = 15 points

Point	X - Axis X [m]	Y – Axis [m]	Z – Axis [m]	STI measured	STI simulated	Error %
Noise source *	1.50	2.50	1.50	--	--	--
1	1.20	3.10	1.45	0.60	0.64	7
2	3.10	3.10	1.45	0.65	0.67	3
3	5.00	3.10	1.45	0.67	0.72	7
4	6.90	3.10	1.45	0.66	0.71	8
5	8.80	3.10	1.45	0.61	0.63	3
6	1.20	5.30	1.55	0.61	0.59	-3
7	3.10	5.30	1.55	0.63	0.63	0
8	5.00	5.30	1.55	0.65	0.67	3
9	6.90	5.30	1.55	0.64	0.61	-5
10	8.80	5.30	1.55	0.62	0.63	2
11	1.20	7.50	1.65	0.61	0.62	2
12	3.10	7.50	1.65	0.62	0.61	-2
13	5.00	7.50	1.65	0.62	0.64	3
14	6.90	7.50	1.65	0.63	0.63	0
15	8.80	7.50	1.65	0.62	062	0

* Sound source position of the Artificial Mouth Simulator B&K 4227
Source: The Authors, 2021

It was found that the room was validated for the STI, as the average error was 2%, which shows a higher linear relationship between simulated and measured values. With the classroom correctly simulated and validated, the maps of the acoustic descriptors were made to verify the spatial distribution of the descriptors as a function of distance. Thus, Figure 2 shows the change in the Equivalent Sound Pressure Level (Leq) in the virtual model validated as a function of the distance between the source and the receiver.

Figure 2: Spatial attenuation of Leq [dB]



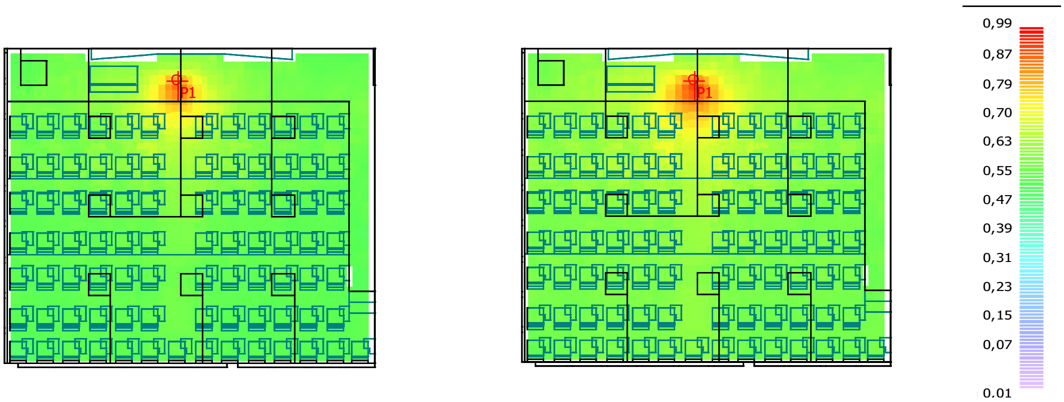
Source: The Authors, 2021

Figure 3 shows the comparison between the STI simulation methods by changing the envelope filter of the frequency spectrum of the voices, which can be: the neutral (STI), the male voice (STI male), the female voice (STI female), and the analytical method (analytical STI).

Figure 3: STI spatial attenuation and weighting by sex

a) STI

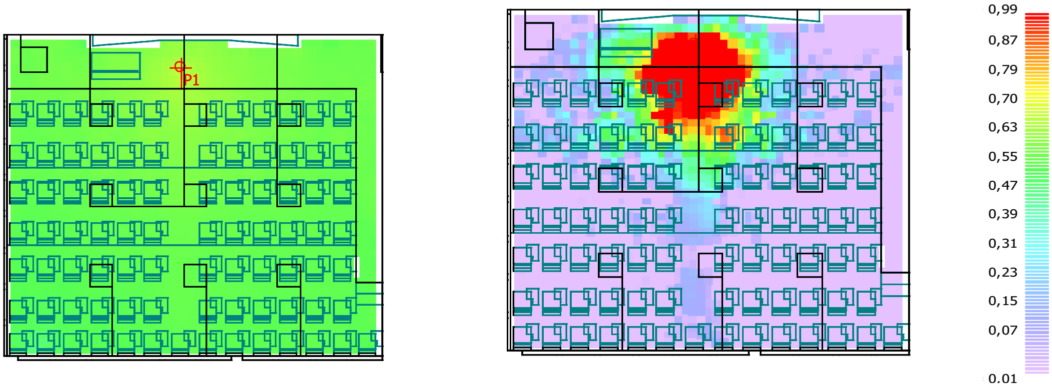
b) STI Male



c) STI analytical

d) STI Female

Revista Nacional de
Gerenciamento de Cidades
ISSN eletrônico 2318-8472, volume 09, número 72, 2021

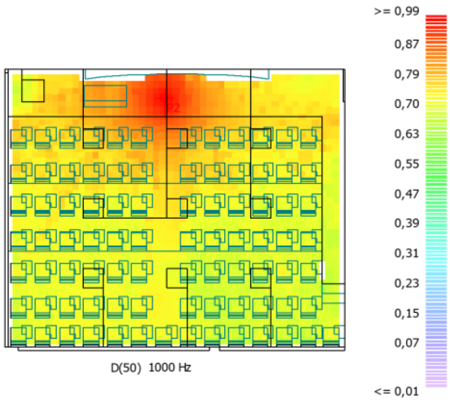


Source: The Authors, 2021

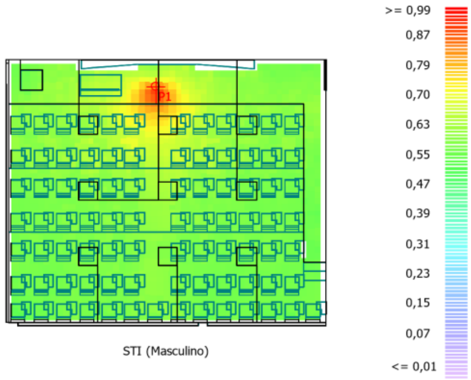
As shown in Figure 3, it was verified that the effects of the filters generated equivalent results, showing a zone with the highest STI values close to the source. The position of the source is shown in Figure 1. The attenuation of the STI is verified as the distance between the source and the position of the receiver increases, as shown in Figure 3. Similarly, Figure 4 shows that the U50 descriptor varied accordingly to the distance between the source and the receiver.

Figure 4: Spatial attenuation of the STI, D50, U50, and EDT as a function of distance

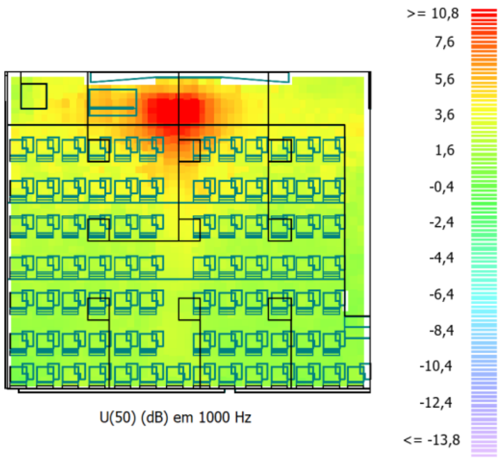
a) D50



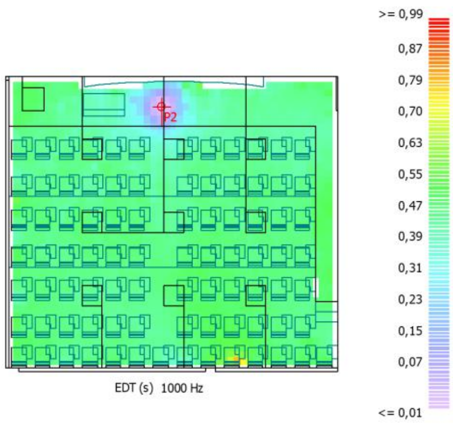
b) STI



c) U50



d) EDT



Source: The Authors, 2021

Thus, a common feature was identified between the U50 and STI responses. In turn, the variation associated with the EDT values was shown as a function of the distance between the source and the receiver. In this sense, the effect that the distance has on the EDT was verified, revealing the attenuation of the direct energy in the receiver for high distance positions, a similar fact also observed in the STI. In this same bias, the values of D50, simulated with the omnidirectional dodecahedral sound source, also show the effect of reducing the D50 according to the distance between the source and the receiver.

Zannin, Ferreira, and Sant'ana (2009) measured the RT and simulated the STI in simulated scenarios using the ODEON software version 9.0. The measurements were conducted in 8 classrooms at the Federal University of Paraná, built in different decades, 1963 and 2000. The results indicated a major influence of the constructive characteristics, which interfere directly in the simulated RT and STI.

Campbell, Nilsson and Svensson (2015) showed that two identical classrooms could present the same reverberation time, but the other acoustic descriptors can be different. Thus, the criteria used to assess the classroom acoustically for each descriptor can result in different diagnoses. In other studies, conducted in classrooms of the Federal University of Paraná (UFPR), on the Polytechnic Center campus, it was also verified that most classrooms are outside the optimal values stipulated by legislation (FERREIRA, 2006).

The acoustic inadequacy of university classrooms is not a phenomenon exclusively of the UFPR, and a plethora of researchers had demonstrated an international trend that the acoustic parameters are below the minimum levels of quality (RANTALA; SALA. 2016; SECCHI et al., 2017; DONGRE et al., 2017; DO NASCIMENTO, 2018). Regarding the STI, this situation is even more worrying due to the complexity of measurements and the cost of the instrumentation involved; there are not many references, especially at the Brazilian level.

4 CONCLUSIONS

This work had the following objectives: to evaluate a classroom at the Federal University of Paraná acoustically, Campus Centro Polytechnic, and to conduct a study to verify the acoustic quality of the classroom considering several descriptors to examine the effect of the distance between the source and the receiver through simulations.

Thus, in terms of acoustic quality, evaluating the descriptors RT - reverberation time; STI - Speech Transmission Index; D50 - Definition and NC - Noise Curves. The results showed that the evaluated classroom did not simultaneously reach the minimum requirements for both the RT and the STI. This demonstrates that the Federal University of Paraná should pay more attention to the acoustic design of its classrooms. With poor acoustic quality, teachers and students can be subject to elevated levels of stress and increased blood pressure, in addition to the teaching-learning relationship being impaired.

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