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Environmental Acoustic Comfort in the Built Environment: Measurements and Simulations of the Speech Transmission Index (STI), Sound Definition (D50) and Reverberation Time (RT) in University Classrooms

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SUMMARY

The acoustic quality of classrooms has a strong influence on the teaching and learning process. This interference assessed using the impulsive technique to measure the rate of speech transmission (STI), reverberation time (RT) and sound definition (D_{50}). These are the most relevant acoustic descriptors in the assessment of classrooms, where verbal exposure is the means of communication between teachers and students. The evaluation took place in two buildings of the Federal University of Paraná (UFPR), built in the 1960s and another in 2016. The measured values of STI, provided in the classrooms' actual acoustic conditions, were used as an adjustment parameter for simulations made with the software ODEON. After carrying out the measurements and simulations, the dimensioning of improvements was possible. The acoustic simulations presented suggestions to qualify the quality of the classrooms' acoustic comfort, ensuring that teaching and learning to do not suffer losses due to the physical structure of the classrooms. The measured values of STI, RT and D_{50} show that, in the old building, except for a single classroom that preserves the original ceiling that had a high sound absorption coefficient, it has reasonable values, below the ideal for classrooms, according to the IEC 60268-16 (2011) standard. The investigation showed that the rooms with a roof replaced by a PVC covering had a sharp drop in acoustic quality. The newest building has classrooms with proper acoustic comfort conditions.

KEYWORDS: Speech transmission index (STI). Reverberation time (RT). Sound definition (D_{50}).

1 INTRODUCTION

The learning process depends on several elements such as teacher, student, teaching material, environment, climate, light, ambient colors, and acoustics. Educational institutions must offer physical spaces proper to the development of educational activities. The acoustic quality of the teaching space is one of the variables that strongly influence student learning. Unfavorable acoustic conditions make the learning environment exhausting (HAGEN; HUBER; KAHLERT, 2002). Speech perception depends on the sound level at which the "speech" is emitted. It depends on the location of the speaker and listener, the distance between the speaker and the receiver, and the physical conditions of the environment where communication takes place.

An example is the room format, absence, or presence of materials with higher or lower sound absorption coefficient, among others (SALA; RANTALA, 2016). Speech intelligibility still strongly depends on where classrooms are located. If the rooms are located near avenues and/or streets with a large flow of vehicles, the external noise will damage verbal communication no matter how good the "room acoustics" is. If located in an environment far from avenues and/or streets, they will provide good communication between the speaker and the listeners.

Speech intelligibility describes a method of measuring the comprehension of a fraction of words or sentences by a listener (LONG, 2006). The two main ways to calculate speech intelligibility are (HONGISTO; KERANEN; LARM, 2004, p. 481): 1) the audiological method, described in the standard of the American National Standards Institute ANSI/ASA S12.60-2010/PART 1, providing the speech intelligibility index (SII) or through 2) articulation index (AI). The modulation transfer function (MTF) method, described in IEC 60268-16 (2011), generates the speech transmission index (STI).

A comparison and evaluation between measured reverberation time (RT) values, through STI simulations in rooms of two buildings of the Federal University of Paraná, built at different periods. The examination of the influence of different finishing materials on the RT and STI was carried out by Zannin et al. (2009). The simulations even indicate for one of the rooms, with an average RT of 2.5 s., the need to replace finishing materials, especially on the floor and ceiling, by materials with a higher coefficient of sound absorption. The results of the simulations, using materials with higher sound absorption, point to a reduction of almost 2 seconds in the RT and an improvement in the original STI. The original values vary between 0.39 and 0.42, qualitatively considered as "poor", to values between 0.73 and 0.76, considered as "excellent", according to the IEC 60268-16 (2003).

2 OBJECTIVES

The present work studied speech intelligibility through the measurements of the Speech Transmission Index (STI), Definition (D50) and Reverberation Time (RR) of classrooms of the Polytechnic Center of the Federal University of Paraná built in 1960 and 2016. These three parameters are the adequate acoustic descriptors to characterize the acoustic quality of rooms, in this case, university classrooms (FASOLD; VERES, 2003; LAZARUS; SUST; STECKEL; KULKA; KURTZ, 2007, p. 274; ANSI/ASA s12.60, 2010). Simulations were also carried out with the "software" ODEON, seeking to improve the acoustic comfort of university classrooms.

3 METHODOLOGIES

The present work comprises two stages: the first consists of data collection through sound measurements and the second in mathematical modelling using the ODEON 11 combined software.

For the STI measurements, a computer, a sound card, a sound pressure level meter, an equalizer, an amplifier, and an artificial mouth (directional soundbox simulates the human mouth). For the measurement of RT and D50, which are measured together, the same equipment was used, with minor changes. The equalizer was removed, and the artificial mouth replaced a dodecahedral speaker (omnidirectional speaker).

It is essential to highlight that the STI measurements were made separately from the RT and D50 measurements, as the settings and equipment are different.

3.1 Data survey

In the data collection stage, the measurements of STI, RT and D50 were carried out in the classrooms of the two buildings of the Polytechnic Center of UFPR. In one building from the '60s, the dependencies PG03, PG 04, PG05, PG06, PG07 and PG15 were analyzed. Another, from the exact sciences, built-in 2016, rooms PA01, PA03 PA05 and PA06 were analyzed in the new building. This step was carried out in periods when the rooms were unoccupied, a condition placed by the technical standards and current literature that were followed to develop this work: 1) Standard IEC 60268-16 (2011); 2) the book Noise Control and Room Acoustics (Schallschutz + Raumakustik in der Praxis) by Fasold and Veres (2003); and 3) ANSI/ASA Standard s12.60 (2010).

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All measurements were carried out on Saturday afternoons, thus ensuring students' absence in the classrooms and in the buildings where these classrooms are located.

Measurements were taken in silence, without students, except operators. The rooms had the door and windows closed, except where the window closing mechanism was broken, which were the cases of PG03 and PG04. External noise, which forms the background noise of the rooms, was measured for use in simulations. Figure 1 shows some of the classrooms during the measurement period.

Figure 1: Classroom in the block built in 1960

Source: the authors, 2021.

3.2 Simulations ODEON 11 Combined software

Firstly, classrooms were built in a virtual environment, using Sketchup software in the free version. Classrooms with vectorized layers (lining, flooring, windows, desks, seats) were finally exported to ODEON 11.

New modellings were carried out with the rooms in a virtual environment after attending comparable values between measured and simulated values. This time, to verify the sound quality of the classrooms, with the acoustic ceiling. Table 1 shows the sound absorption values of the materials used in the ceiling linings, for the old classrooms (designation "PG") of the old building of the Polytechnic Center of UFPR, according to the frequency spectrum from 125 Hz to 8000Hz. Table 2 shows the new buildings' sound absorption values with acoustic ceilings (designation "PA").

Table 1: Sound absorption values of old (Celotex M1) and new (PVC) ceilings

Material	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
Celotex M1	0.12	0.48	0.50	0.79	0.93	0.82	0.48
PVC	0.03	0.03	0.04	0.05	0.05	0.06	0.06

Sources: KNUDSEN & HARRIS (1978, p.408); SILVA (2009).

Table 2: Sound absorption values of Thermatex® Star SK ceiling

Material	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
Thermatex®	0.05	0.05	0.04	0.55	0.65	0.45	0.45

Source: KNAUF AMG (2016).

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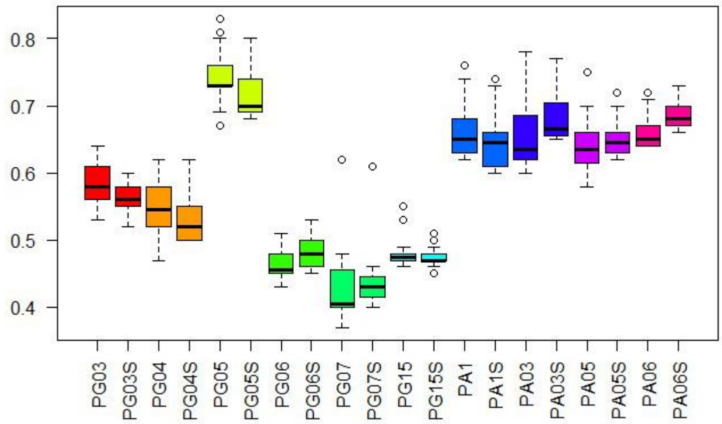
4 RESULTS

Below, the data of measurement and simulation obtained in the classrooms of the building built in the 60s (designation PG) and 2016 (designation PA) are presented.

Figure 2 shows the measured STI values in the classrooms and the STI values from the simulations – which are recognized, ending in 'S', i.e., Room PG06S.

Figure 2: Measured and simulated STI averages of classrooms



Source: the authors, 2021.

When analyzing the old building rooms in Figure 2, it is seen that rooms PG03 and PG04 have a slightly better STI performance than PG06, PG07 and PG15. This difference is attributed to a defect in the lever in the window closing system, as some windows could not be closed. Thus, according to the study by Tang and Yeung (2006), there is an increase in STI.

The upper "outliers" in Figure 2 represent the positions in the classrooms or the students who sit directly in front of the artificial mouth or teacher, indicating that students who are positioned right in front of the teacher receive privileged speech intelligibility. The inferior "outliers" show the students that they would have impaired speech intelligibility.

The dispersion or variability of the data, given by the size of the boxes, shows a certain homogeneity in the STI of the classrooms. PG15 was highlighted for having the lowest variability despite the STI below 0.5.

As rated by ISO 9921 (2003), the classrooms assessed in the old building are 'reasonable', except PG05. By the same parameter, the new building rooms and PG05 are classified as 'good'.

The standard adopted for measurement, IEC 60268-16 (2011), suggests in its Annex G that the STI value for classrooms should be above 0.62. This reference further highlights the PG03, PG04, PG06, PG07 and PG15 classrooms, all from the old construction. On the other hand, the rooms of the most recent building and PG05 areas suggested by the standard for the specific application mentioned for classrooms.

From the Finnish standard SFS 5907 (2006) point of view, none of the analyzed rooms is appropriate, given that the requirement is for STI greater than or equal to 0.80 for classrooms.

Table 3 compares the standards presented with the measured classrooms.

Table 3: Comparison of STI values - Quantitative and qualitative

Building	Classroom	Quantitative	ISO 9921 (2003)	Annex G - IEC 60268-16 (2011)	SFS 5907 (2006)
60'S 20th century	PG03	0.58	Reasonable	Not compliant	Not appropriate
	PG04	0.55	Reasonable	Not compliant	Not appropriate
	PG05	0.74	Good	Compliant	Not appropriate
	PG06	0.46	Reasonable	Not compliant	Not appropriate
	PG07	0.43	Poor	Not compliant	Not appropriate
	PG15	0.48	Reasonable	Not compliant	Not appropriate
EXACT SCIENCES Second decade of the 21st century	PA01	0.66	Good	Compliant	Not appropriate
	PA03	0.65	Good	Compliant	Not appropriate
	PA05	0.64	Good	Compliant	Not appropriate
	PA06	0.66	Good	Compliant	Not appropriate

Sources: ISO 9921 (2003); Annex G IEC 60268-16 (2011); SFS 5907 (2006).

Milulski and Radosz's (2011) survey of 110 classrooms in Poland found a great diversity of acoustic properties across classrooms. This diversity was related to differences in construction and materials used in the rooms.

In Finland, 16 of the 40 rooms studied by Sala and Rantala (2016), the STI was below 0.75, while in the present study, nine of the ten analyzed rooms obtained this value. Regarding RT values in the range of 250 Hz to 4000 Hz, in Finland, 30 of the 40 rooms had values below 0.6 seconds against one of the ten analyzed at UFPR; where only the PG05 has a lower RT, being 0.5 seconds. When comparing the values obtained in the measurements with the qualitative scales of D50 by Fasold and Veres, (2003) and Ansay and Zannin (2016), Table 4 was compiled. It is worth remembering that Ansay and Zannin (2016) scale was calculated from Marshall (1994). It is concluded that the qualitative values stipulated by Marshall demand a higher performance of the acoustic quality of the rooms.

Table 4: Comparison of D50 values - Quantitative and qualitative

Building	Classroom	Quantitative	Fasold e Veres (2003)	Ansay e Zannin (2016)
60'S 20th century	PG03	0.5	Not compliant	Reasonable
	PG04	0.41	Not compliant	Reasonable
	PG05	0.82	Compliant	Good
	PG06	0.48	Not compliant	Reasonable
	PG07	0.41	Not compliant	Reasonable
	PG15	0.44	Not compliant	Reasonable
EXACT SCIENCES Second decade of the 21st century	PA01	0.71	Compliant	Good
	PA03	0.66	Compliant	Reasonable
	PA05	0.66	Compliant	Reasonable
	PA06	0.65	Compliant	Reasonable

Sources: FASOLD & VERES (2003); ANSAY & ZANNIN (2016).

Table 5 shows a comparison between the STI, D50 and RT measures, with their corresponding values in their qualitative scales, considering that the reasonable STI value does not meet the acoustic standard for the classroom. It is observed that there is a substantial unity in what concerns the qualitative classifications of ISO 9921 (2003), with Fasold and Veres (2003) and with ANSI/ASA S12.60 (2010).

Only the RT values in rooms PA03 and PA05 had different qualitative results but very close to meeting ANSI s12.60 (2010).

Table 5: Measured values (quantitative) and relationship with qualitative values of STI, RT and D50

	STI		D_{50}		RT 500, 1000 e 2000 Hz	
Classroom	Quantitative	Qualitative ISO 9921 (2003)	Quantitative	Qualitative Fasold e Veres (2003)	Quantitative (s)	Qualitative ANSI/ASA s12.60 (2010)
PG03	0.58	Reasonable	0.5	Not compliant	1.15	Not compliant
PG04	0.55	Reasonable	0.41	Not compliant	1.49	Not compliant
PG05	0.74	Good	0.82	Compliant	0.51	Compliant
PG06	0.46	Reasonable	0.48	Not compliant	1.19	Not compliant
PG07	0.43	Poor	0.41	Not compliant	1.73	Not compliant
PG15	0.48	Reasonable	0.44	Not compliant	1.55	Not compliant
PA01	0.66	Good	0.71	Compliant	0.6	Compliant
PA03	0.65	Good	0.66	Compliant	0.7	Not compliant
PA05	0.64	Good	0.66	Compliant	0.7	Not compliant
PA06	0.66	Good	0.65	Compliant	0.65	Compliant

Sources: ISO 9921 (2003); FASOLD & VERES (2003); ANSI/ASA s12.60 (2010).

By verifying the change in the acoustics of the building rooms from the '60s where PVC replaced the Celotex M1 ceiling, new simulations were carried out for comparison. Recalling that PVC lining is widely used in Brazil, it is durable and economically accessible, despite its poor sound absorption. Table 6 shows the average values in the simulations with the acoustic ceiling and with the PVC ceiling.

Table 6: STI values with PVC and Celotex M1 lining

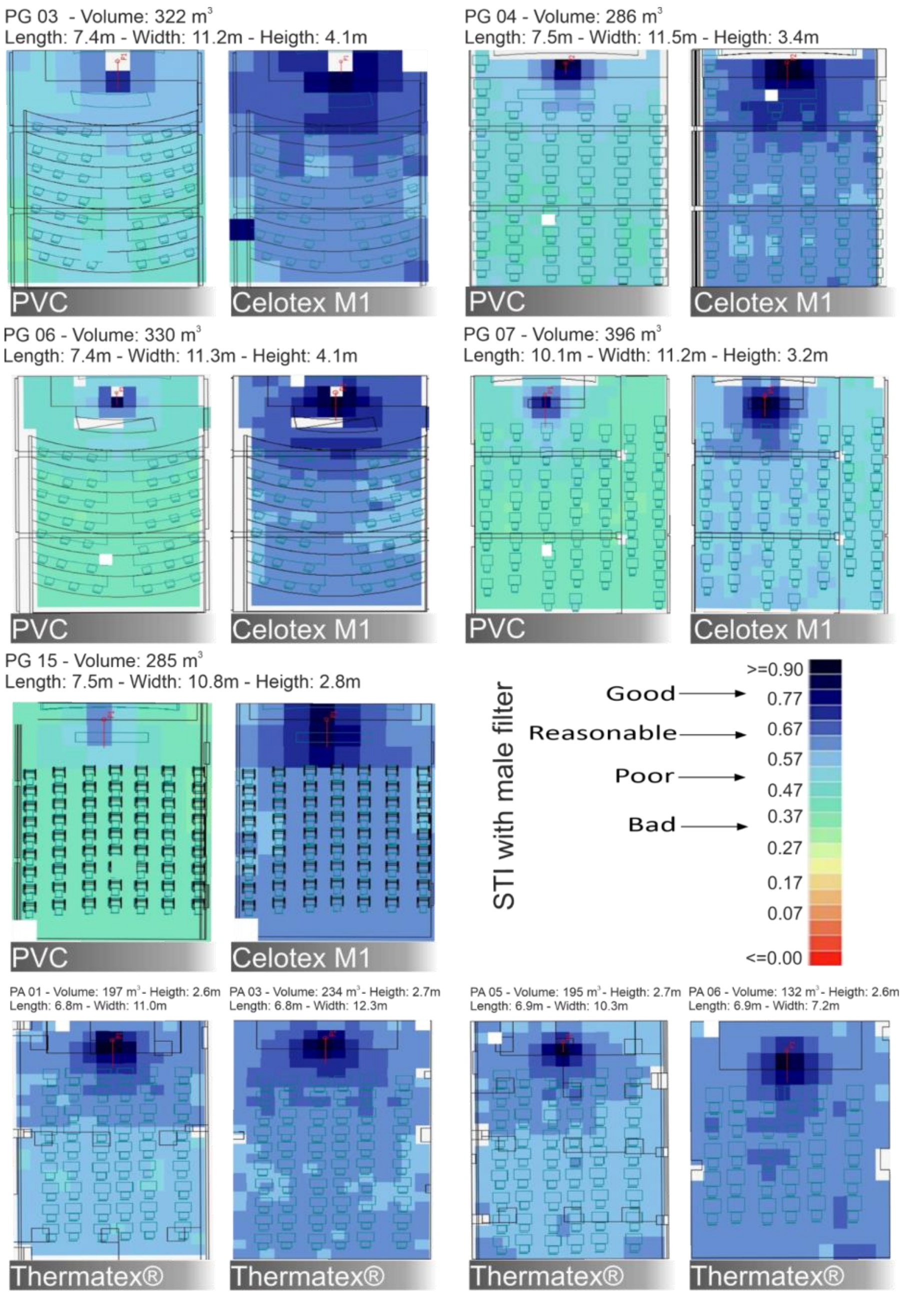
Classroom	Average STI measured with PVC lining	Average STI simulated with PVC lining	Average STI simulated with Celotex M1 lining
PG03	0.58	0.56	0.71
PG04	0.55	0.53	0.69
PG06	0.46	0.48	0.67
PG07	0.43	0.44	0.61
PG15	0.48	0.47	0.68

Source: the authors, 2021.

According to the simulated values, the change in the acoustic quality of the rooms observed after changing the ceiling material triggers a significant difference in the STI values.

The improvement can be seen in Table 6 and in Figure 3, which show the simulated STI, where darker shades of blue indicate higher STI values, representing an improvement in the acoustic quality of the classroom. This change in the quality of STI is remarkable and tends to improve communication between students and teachers. The simulations were performed using the ODEON 11 combined, using PVC ceiling and Celotex M1 for the rooms with the "PG" designation. In the rooms of the UFPR Exact Building, built-in 2016, with the name "PA", the precise quality of the acoustic rooms can be seen due to the ceiling covered with Thermatex® absorbent material, concerning the rooms from the 60s that have the PVC coated top. As a comparison of acoustic performance, see Tables 5 and 6.

Figure 3 - Simulations with PVC, Celotex M1 and Thermatex® ceiling lining



Source: the authors, 2021.

5 CONCLUSIONS

Although recent studies point to the need for acoustic quality in learning environments, the present work presents results that suggest that the acoustics of the analyzed classrooms are neglected and underestimated by the Maintenance Department at UFPR.

The replacement of the Celotex M1 ceiling by a PVC ceiling in the oldest rooms at the Polytechnic Center impaired the speech transmission in the classrooms, which was confirmed through the results obtained in the simulations carried out.

Finally, in much of the literature consulted, there is no clear description of the methodology, and the use of not recommended equipment was verified. It should be noted that STI measurements must be made with a directional loudspeaker (such as the mouth simulator). As well RT must be made with an omnidirectional loudspeaker (such as the dodecahedral speaker), following ISO 3328-1 (2009) and IEC standards 60268-16 (2011).

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