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Effect of outdoor noise and façade sound insulation on indoor acoustic environment of Italian schools

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ABSTRACT

The paper deals with the effect of outdoor noise mainly due to traffic and façade sound insulation on indoor noise level and speech intelligibility in classrooms. Results refer to the complete building stock of the Italian school buildings based on a census of the Italian Ministry of Education.

The selected school sample consists of more than one hundred Italian schools of all levels (from nursery to upper secondary school) located in three Italian regions, built in different time periods and with different building techniques. The selected sample is representative of typical Italian schools.

The façade sound insulation and the reverberation time of each school have been measured. The average outdoor noise level of about half the investigated schools has been measured and, for each school, the age of the building and the main characteristics of the façade have been listed (kind of glass, kind of ventilation, windows size, etc.). Based on these data, the correlations between both the main characteristics of the façades and the year of construction and the façade sound insulation have been investigated. Moreover, the influence of the noise coming from outdoor on the indoor noise level, speech intelligibility and speech to noise ratio have been analysed with reference to the situations both before and after the works carried out to improve the acoustic performances of façades.

Results show that the indoor sound pressure level due to traffic noise is considerably reduced after the improvement of the façade acoustic insulation, while further treatments to indoor surfaces should be necessary to reduce internal reverberation time and to improve speech intelligibility.

Keywords: Façade sound insulation, School building, Indoor noise level, Speech intelligibility, Outdoor noise level.

1. Introduction

Many issues related to excessive noise in schools arise from their inclusion in noisy environments, or from their original surrounding environment which has grown from silent to very noisy over the years. The main strategy to limit the noise inside the school buildings is the façade insulation improvement. Regulatory requirements and classification schemes in Europe present a high degree of diversity; in particular, the regulatory requirements for façade sound insulation are different concerning not only the limit values but also the different descriptors used in the different Countries.

The different façade descriptors were analysed in previous studies [1, 2, 3]. The regulatory requirements are divided into two main categories, related to:

- the performance of the building - global facade or single element of facade (weighted standardized level difference, $D_{2m,nT,w}$, weighted standardized level difference plus the spectrum adaptation term for A-weighted urban traffic noise, $D_{2m,nT,w}+C_{tr}$, or weighted apparent sound reduction index, R'_w);
- the indoor sound pressure level (A-weighted equivalent sound pressure level, L_{Aeq}, A-weighted day-evening-night sound pressure level, L_{den} or A-weighted sound pressure level, L_{pA}).

In the same way, the maximum unoccupied indoor noise level and the optimal reverberation time permitted in classrooms present a high degree of diversity in European Countries [4, 5]. For example, the UK Building Bulletin 93 [6], for unoccupied existing classrooms, requires a maximum ambient noise level of 40 dB, $L_{Aeq,30min}$, plus a maximum reverberation time of 0.8 s, quoted in terms of the average in the 500 Hz, 1 kHz and 2 kHz octave bands.

The World Health Organization (WHO) [7] sets the maximum indoor L_{Aeq} to 35 dB and the optimal reverberation time to 0.6 s. According to Picard and Bradley [8], the optimal value of the mid-frequency reverberation time in occupied classrooms, is estimated to be 0.5 s. As far as the noise level is concerned, an upper noise level of 40 dB(A) is considered acceptable for general purposes in the case of +12 years old children, but it should be less than 30 dB(A) in the case of 6-7 years old pupils.

In Italy, the first provisions on acoustic performance of schools were set by Italian Ministerial Decree 21 March 1970 [9] on technical standards relating to school buildings, replaced in 1975 by the Italian Ministerial Decree on updated technical standards relating to school buildings [10], that specifies both dimensional and physical properties and the relative limit values for new schools. The physical properties (habitability conditions) concern thermal, acoustic and lighting requirements of school buildings and building components. Some specifications concerning reverberation time, sound insulation properties and noise from equipment have been replaced by those set by D.P.C.M. (Decree of the President of the Council of Ministers) of 5 December 1997 [11], on the determination of building passive acoustic requirements. The D.P.C.M. refers to the Ministerial Circular 22/05/1967 n. 3150 [12] for reverberation time limit values. The recent Decrees 28 December 2015, n. 221 [13] and 11 January 2017 [14] recall the Italian standard UNI 11367 [15, 16] as reference to be applied in cases of treatments aimed at increasing the energy efficiency [17, 18] of schools and anyway for their renewal or new construction, awaiting the approval of new Regional standards for schools. According to the D.P.C.M. of December 1997 [11], the new school buildings must guarantee a façade sound insulation $D_{2m,nT,w} \geq 48$ dB, that is very restrictive and difficult to obtain. On the other hand, the UNI 11367 [15, 16] distinguishes the sound insulation requirements for schools in two levels of performance: basic performance, with $D_{2m,nT,w} \geq 38$ dB, and high performance, with $D_{2m,nT,w} \geq 43$ dB; this last value is also the minimum requirement for new schools and hospitals according to the decree [14]. The UNI 11367 also requires a Speech Transmission Index in classrooms higher than 0.6 and sets the optimum value of reverberation time (T_{opt}), as average value between 500 and 1000 Hz, for unoccupied classrooms (s), as:

$$T_{opt.} = 0.32 \cdot log\ (V) + 0.03 \text{ [s]} \qquad (1)$$

where V is the volume of the classroom (m^3).

An optimal degree of reverberation was found in literature for maximizing speech intelligibility and reducing the vocal effort of the teacher, in occupied primary school classrooms, which corresponds to a reverberation time at the average frequencies of about 0.7 s [5, 19, 20]. The recommended values of reverberation time in fully occupied classrooms for flexible teaching methods, considering flat across frequency from the octave bands of 2 kHz to 4 kHz, are instead between 0.45 s and 0.6 s (between 0.6 and 0.7 s in an unoccupied but furnished condition) for classrooms with less than 40 students and volumes below 210 m^3 according to Pelegrín-García *et al.* [4].

Italian legislation, as stated by Italian Decree of March 2004 [21], also establishes the maximum indoor sound pressure level, L_{Aeq}, due to road traffic noise in schools, to 45 dB, with closed windows; nevertheless, this value is allowed only when it is impossible to reduce otherwise the outdoor noise (with mitigation at the source or along the transmission path).

The improvement of façade sound insulation of school buildings, in general, leads to a sensible decrease of indoor exposure to outdoor noise and to an improvement of speech intelligibility as well.

This study, whose preliminary results were published in [22], has investigated the correlations between both the main characteristics of the façades and the year of construction and the façade sound insulation. In addition to what already analysed in [22], also the influence of the noise coming from outdoor on the indoor noise level and speech intelligibility is investigated. These correlations are evaluated on the basis of more than 100 façade sound insulation measurements, representative of the Italian façade building stock of schools, linked to the typical outdoor noise levels referred to Italian schools as evaluated in a previous study [23]. In some of these schools, where façades were refurbished to improve the acoustic insulation from outdoor noise, data referred to the situation both before and after the acoustic treatments of façades are reported and the effect of the façade insulation improvement is analysed.

2. Material and methods

2.1 Analysis of the Italian school building stock

The Italian government has recently carried out a census of all Italian schools of different levels (pre-schools, primary schools, lower and upper secondary schools) in order to determine whether or not they needed to be improved. Only nurseries and universities were left out of the investigation.

Globally, more than 42,000 buildings, (of which 33,800 are active), distributed across all Italian Regions, have been examined [24]. Results are mainly referred to general aspects of the school buildings such as year of construction, property, dimensions and kind of building structure and windows typology. The acoustic requirements were investigated only in a qualitative way and, in particular, concerning the presence of the following aspects:

1. general measures for acoustic protection;
2. acoustic protection from outdoor noise;
3. acoustic insulation between classrooms, corridors and other spaces;
4. acoustic insulation of floors.

Figures 1, 2 and 4 show some general results of this census, while figure 3 shows the detail of the analysis of “qualitative” acoustic requirements with reference to three regions of Central and Northern Italy (out of 21 Italian Regions).

In Figure 3 it can be noted that less than 10% of schools have some kind of acoustic protection against outdoor noise (such as improved acoustic insulation windows, noise barriers or other).

The sample of schools studied here belongs to three Italian regions, namely Tuscany, Lombardy and Piedmont which have around 33% of active schools.

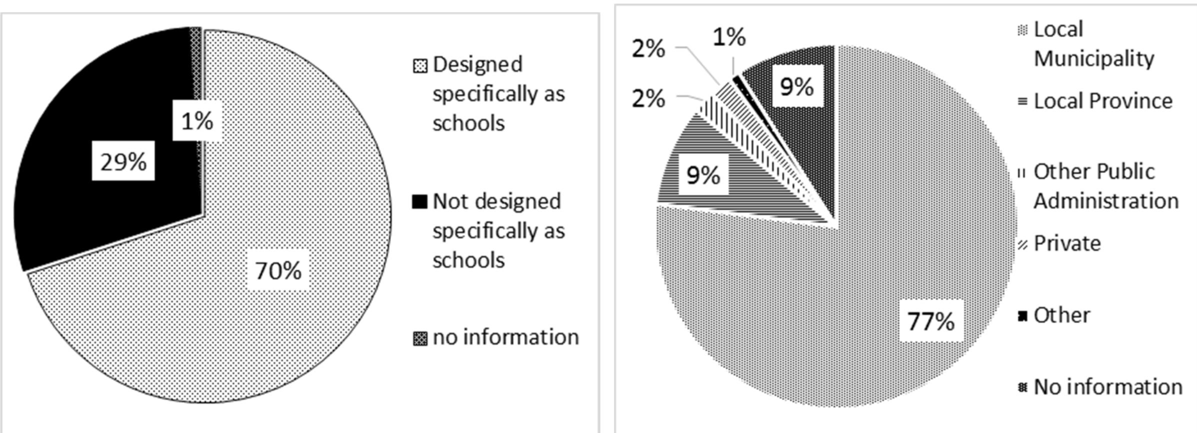

Figure 1 – Left: percentage of Italian building specifically designed as schools; right: property of Italian school buildings [24].

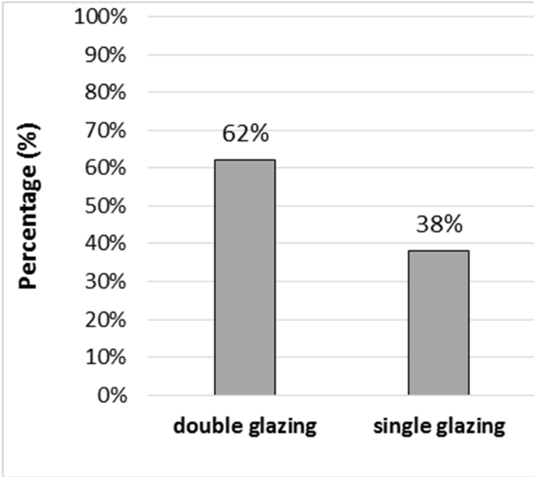

Figure 2 – Percentage of schools with single and double glazing windows [24].

Figure 4 highlights that 55% of buildings were built before 1976. Figure 2 shows that more than 60% of Italian school buildings have double glazing windows; most of which are composed of two single glass panes separated by an air gap that have exclusively thermal purposes. Indeed, buildings constructed before 1976 had almost exclusively single glazing windows (with glass thickness typically around 4 mm) and very poor sound insulation in general. Many of these buildings were renovated after the adoption of the 1975 national regulation on schools [10], that led to the substitution of whole windows, or just the glass panes, to achieve better energy performances of the facades. Furthermore, the enactment of Law n. 373 on the reduction of energy consumption in 1976 has spread the use of double glazing in new and existing renovated buildings, including schools [25], with a better air tightness of the new windows.

It is well known that the acoustic insulation of a double glazing window with two identical glass panes is only slightly better than that of a single glazing window with a glass pane of the same thickness, because of the effect of the resonance mass–spring–mass of double glass panes. The typical double glazing window used in Italy until the '90s is composed of two glass panes each 4 mm in thickness separated by an air gap in the range 6 to 12 mm; the mass-spring-mass resonance frequency of a 4/12/4 double glazing windows is around 220 Hz, where the acoustic insulation strongly decreases.

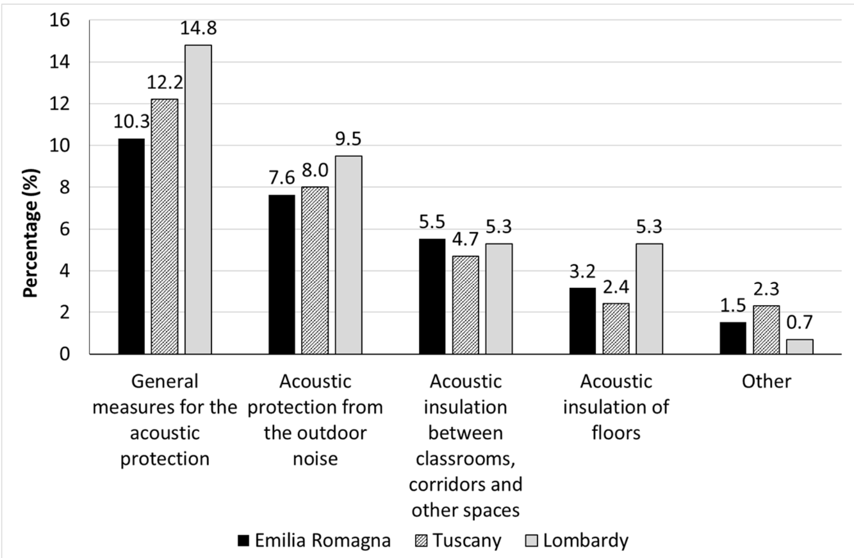

Figure 3 – Typology of measures against noise in the schools of Tuscany, Lombardy and Emilia Romagna Regions (information supplied by local authorities).

2.2 Description of the sample of school building stock

The results of many in-field measurements carried out by the authors roughly over the last 10 years have been collected and analysed in order to better analyse the acoustic performances of Italian schools. In particular, the database collected concerns the acoustic measurements carried out on 64 school buildings in 17 Municipalities and 3 Italian Regions (Tuscany, Lombardy and Piedmont). 103 façades, belonging to 64 schools, have been analysed and in 45 of these cases the standardized level difference of façade ($D_{2m,nT}$) has been measured both before and after the treatment to improve acoustic insulation. Globally, 148 results of façade sound insulation and reverberation time have been collected.

It is important to underline that in almost all the cases these measurements have been carried out as a consequence of a municipal strategy or airport strategy [26] for noise abatement in the school buildings. The need for an acoustic refurbishment is established by the Italian Municipalities as a function of the exposure of the building to outdoor noise and not of the acoustic performances of the building envelope itself. Moreover, the selected sample includes schools of any level (from nursery to upper secondary school) and built in different time periods and with different building techniques. For these reasons, it can be considered as representative of typical Italian schools. At this purpose, as it can be noted in figure 4, the distribution of the selected schools by year of construction is similar to that of the entire national building stock.

For each school analysed the following information has been collected:

- school level (nursery, pre-school, primary school, lower secondary school, upper secondary school);
- year of construction (not the year of renovation);
- window frame material (wood, aluminium, iron);
- kind of window glass (single, double or laminated). Note: a laminated glass is made of two glass panes, each separated by a PVB (PolyVinyl Butyral) film;
- presence of air vent in the façade;
- shading system of the façade (in particular, presence of roller shutter boxes);
- dimensions of classrooms, façades and windows.

Furthermore, the following quantities have been measured:

- standardized façade level difference ($D_{2m,nT}$) from 100 Hz to 5000 Hz one-third octave bands, weighted standardized façade level difference ($D_{2m,nT,w}$) and spectrum adaptation terms (C, C_{tr});
- reverberation time (T) from 100 Hz to 5000 Hz one-third octave bands;
- average outdoor A-weighted equivalent sound pressure level (L_{Aeq}). This last quantity was measured in about half of the sample of schools in a single position in front of the façade during a short period and cannot be considered as representative of the long-time outdoor acoustic environment of the school.

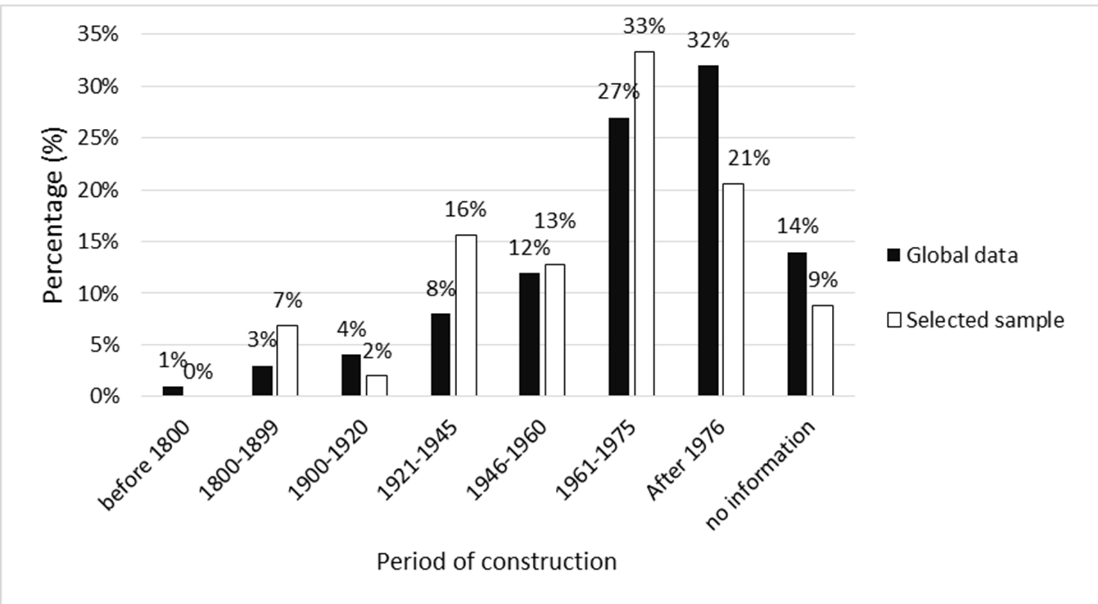

Figure 4 – Year of construction of the examined schools (selected sample) compared to values of the Italian school building stock (global data).

Figure 5 shows the distribution by level of school. In Italy, schools from nurseries to lower secondary schools are generally owned by the local Municipalities while upper secondary schools are owned by the local Provinces.

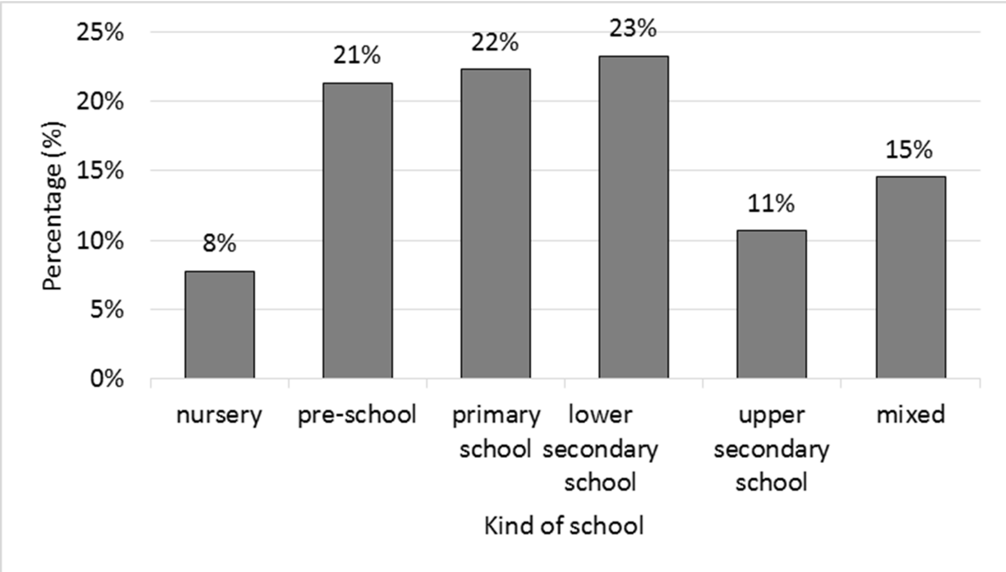

Figure 5 – Typology of examined schools (selected sample).

Figure 6 shows some detailed information about the window frame material and type of glass, while Table 1 illustrates the acoustic performances of the type of glass typically used in Italian schools and similar to those under EN 12354 [27]. These data refer only to the glass performances; to determine the sound reduction index for a glazed window with these data, the sound transmission through the window frame and through the sealing should be taken into account. The information given by Figure 6 is referred to the situation of the analysed schools before the acoustic improvement (refurbishment), i.e. the treatment to improve acoustic insulation, called "ante operam" situation. Indeed, in almost all the cases, the acoustic improvement required the substitution of the existing windows with windows with aluminium frame and double laminated glass.

Figure 7 shows the percentage of school façades with roller shutter box. The use of external roller shutters is very frequent in Italian residential buildings but not so much in schools. This kind of shading system usually decreases the façades sound insulation because it represents an important path of airborne sound transmission.

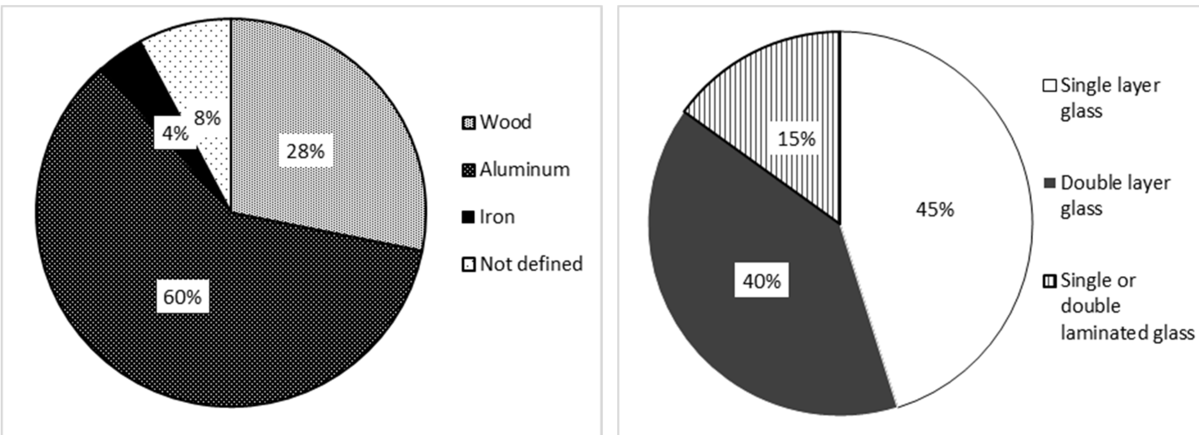

Figure 6 – Window frame material (left) and typology of glass (right) of the windows of the selected sample (ante operam).

Table 1 – Sound reduction index of the type of glass installed in the windows (ante operam) similar to those contained in EN 12354-3 [27]

	Glazing type	R_w (C,C_{tr}) (dB)
Single panes (mm)	4	29 (-2;-3)
Double pane units with single panes (mm); air filled cavity from (6-16) mm	4-(6-16)-4	29 (-1;-4)
Laminated panes (mm) + plastic laminate (0,5-1) mm	6+	32 (-1;-3)
Double pane units with single or laminated panes (mm); air filled cavity from (6-16) mm	6-(6-16)-6+	33 (-2;-5)

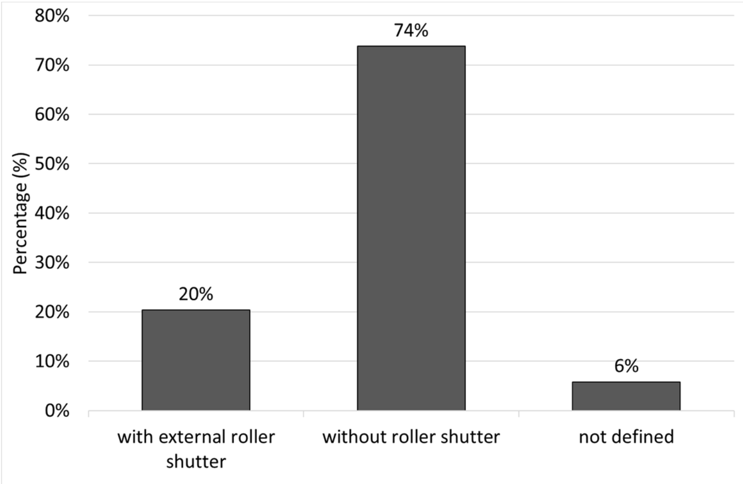

Figure 7 – Percentages of examined façades with and without roller shutter box.

2.3 Typical exposure to noise of Italian school façades

It is well known that the sound environment of classrooms is mainly due to the sound coming from other interior spaces of the school [28, 29]. However, in some cases, the outdoor noise can be problematic, especially for schools built in very noisy environments.

The analysed schools were all built near busy roads or other noise sources (airports). In particular, the average outdoor L_{Aeq} value measured in front of the façades of the school sample, during the schools opening times, is 64.2 dB, with a standard deviation of 6.0 dB. Measurements were carried out for a duration variable between 15 min and 1 hour, usually at a distance between 1 and 2 meters from the façade, in a point representative of classrooms, using class 1 sound level meters. Anyway, this measured value of L_{Aeq} cannot be representative of the sound exposure of all the Italian schools, as the sample is referred to schools located in very noisy environments, as already underlined in paragraph 2.2.

To better characterize the typical outdoor noise in Italian schools, it is necessary to refer to a previous study [23] carried out on a random sample of schools (i.e., not selected on the basis of poor acoustic insulation or inclusion in a very noisy outdoor environment and need for refurbishment). This study refers to 43 schools (from nurseries to upper secondary schools) located in Florence and in other small towns in the surroundings, and is based on short-time measurements (10 – 15 mins) of road traffic noise, at a distance of 1 meter from the façade, in points corresponding to classrooms windows, using class 1 sound level meters. Figure 8 shows the distribution of L_{Aeq} levels for the sample of the 43 school buildings. 53.5 % of the L_{Aeq} levels are lower than 60 dB and the average value is 60.9 dB with a standard deviation of 8.1 dB.

In general, it is not possible to give a unique value for the exposure of schools to road traffic noise: it depends on many factors and mainly on the volume of road traffic and its composition and on the distance of the school building from the road as well. Nevertheless, the average value of 61 dB for L_{Aeq} will be considered as indicative for a typical sample of school buildings and assumed for the following estimations. This level is greater than the one given by Dockrell and Shield [30] that found the average value of 57.4 dB L_{Aeq} measured on a sample of 53 schools in one area of London. In this case, the measurement duration was 5 min and the standard deviation of measurements 8.8 dB. Anyway, these measurements were carried out at a distance of 4 meters from the façade and therefore are not affected by the sound reflection from the façade itself. Taking into account the reflection effect of the façade, the value obtained by Dockrell and Shield is similar to the one considered in this study.

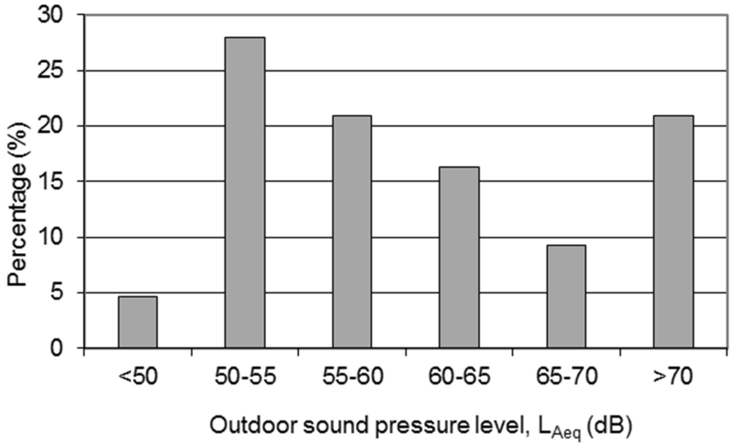

Figure 8 - Distributions of outdoor sound level due to road traffic noise reported in [23].

3. Acoustic conditions in classrooms

The acoustic conditions in typical Italian classrooms were investigated in terms of indoor sound pressure level transmitted through the school façade and Speech Transmission Index (STI). STI is one of the main indicators of speech intelligibility in the case of non-negligible effect of reverberation time, according to ISO standard 9921 [31].

3.1 Indoor sound pressure level transmitted through the façade

The estimation of the indoor sound pressure level, L_2, due to the sound coming from outdoor is obtained by eq. (2), based on ISO 12354-3 [27].

$$L_2 = L_{1,2m} - D_{2m,nT} + 10 \cdot log(T/T_0) \text{ [dB]} \quad (2)$$

where:

$L_{1,2m}$ is the outdoor sound pressure level 2 m in front of the façade (dB), in frequency bands, here assumed equal, as A-weighted global vaues, to the previously given value of 61 dB;

$D_{2m,nT}$ is the standarized level difference, measured for each façade according to ISO 16283-3 [32] or to ISO 140-5 [33] for measurements carried out before 2014;

T is the reverberation time measured in each receiving room (s);

T_0 is the reference reverberation time (0.5 s).

Eq. (2) is valid under the hypothesis of diffuse field in the indoor environment (L_2); this condition has been assumed as valid in the case of the analyzed classrooms.

The calculated value of the indoor sound pressure level (L_2) may be considered as unoccupied ambient noise level due to traffic noise and will be used for the further evaluation of the speech intelligibility.

Scrosati *et al*. [34] found that a comparison between the outdoor noise level and the indoor noise level is inadequate as far as real measurements and single number quantities are concerned. In fact, the differences between the measured $D_{2m,nT,50}$ (i.e. the single number in the enlarged range from 50 to 5000 Hz) and the calculated value found were about 8-9 dB. There is an ongoing study aimed to find a better relation between the outdoor noise level and the indoor sound pressure level. Nevertheless, at present level of knowledge and considering that eq. (2) refers to one-third octave bands, said equation could be used as a general reference value for the considerations included in the present study.

3.2 Speech Transmission Index

The Speech Transmission Index (STI) [35] is an objective method for the prediction and measurement of speech intelligibility from talker to listener by a transmission channel. The speech transmission quality of the channel is derived and expressed in a value between 0 and 1, as STI. The potential speech intelligibility can be determined using the obtained STI value.

In the case of person-to-person communications, as in a classroom, speech intelligibility may be reduced by noise and temporal distortion such as echoes and reverberation. Originally, the STI-method was developed for measurements, but it is possible to predict the STI value within the framework of statistical room acoustics [36]. Calculation is based on a predicted direct field, combined with an exponential reverberant decay. This excludes prediction for acoustically coupled enclosures and very complex environments, so the STI can be derived mathematically from the room's volume, the room's reverberation time, the ambient noise level, the talker's vocal output, the directivity of the talker's sound field, the directional-hearing capacity of the listener and the talker-to-listener distance.

In the examined sample of schools, STI was calculated for each room and for each octave frequency band on the basis of measured values of reverberation time and dimensions (room's volume and talker-to-listener distance), while the ambient noise level was calculated on the basis of the procedure described above (section 3.1).

4. Results

The results are shown below with reference both to measured values of façade sound insulation and reverberation time and to calculated values of unoccupied indoor sound pressure level and STI. Results of façade sound insulation are divided in measurements carried out before and after the acoustic treatments of the façades. The number of classrooms whose façade had been acoustically treated is smaller than the complete sample of classrooms examined, as described in section 2.2. Results of reverberation time measurements are only referred to measurements carried out before the treatments of the façades since these treatments (usually the replacement of the window with a better acoustically performing window) did not influence the reverberation time. Calculations of indoor Sound Pressure Level (SPL) and STI were performed for each classroom with the procedure described in the previous sections on the basis of measured values of façade sound insulation and reverberation time. In addition, to better analyse the effect of short duration noise events due to traffic noise, the speech to noise ratio was calculated for each classroom with reference to a single noise event characterized by a well define maximum SPL.

4.1 Façade sound insulation

Figures 9 and 10 show the results of $D_{2m,nT,w}$ and $D_{2m,nT}$ measurements, respectively, for the analysed classrooms. Results referred to corridors or gyms have been excluded from this analysis.

In figure 9 it can be noted that there is no clear correlation between the age of the school (year of construction) and the façade sound insulation ($D_{2m,nT,w}$). On the other hand, previous studies pointed out a clear evolution of acoustic performances of Italian façades from the postwar period to the present time [37], although these studies were only referred to residential buildings. The lack of correlation in the present study is due to the fact that these school buildings were probably refurbished in the past and the information about the year of refurbishment is not known. The graph shows, with crosses, the results of measurements carried out before the recent acoustic improvements (ante operam) and, with black dots, after these refurbishments (post operam). It can be noted that results of $D_{2m,nT,w}$ obtained from schools built after the adoption of the Italian decrees on acoustic requirements [11], i.e. after 1997, are above the average but still do not satisfy the current limit value for Italian schools ($D_{2m,nT,w} \geq 48$ dB). This last value is particularly high and under revision considering that the current reference for the construction of new school buildings is assumed to be equal to 43 dB [14], consistent with the post-operam average value of Table 2.

Figure 10 shows the average value of $D_{2m,nT}$ in one-third octave frequency bands from 100 to 5000 Hz, before (ante operam) and after (post operam) the treatments, with error bars equal to 1 standard deviation of the measured data. The graph excludes results below 100 Hz because of the measurement uncertainty at these frequencies, as pointed out in previous studies of the authors [38, 39, 40]. The same results are reported also in Table 2 as weighted value $D_{2m,nTw}$. Schools with single glazed windows have typically lower insulation performances. The improvement of acoustic performances is evident especially at higher frequencies probably because of the better air tightness of the new windows.

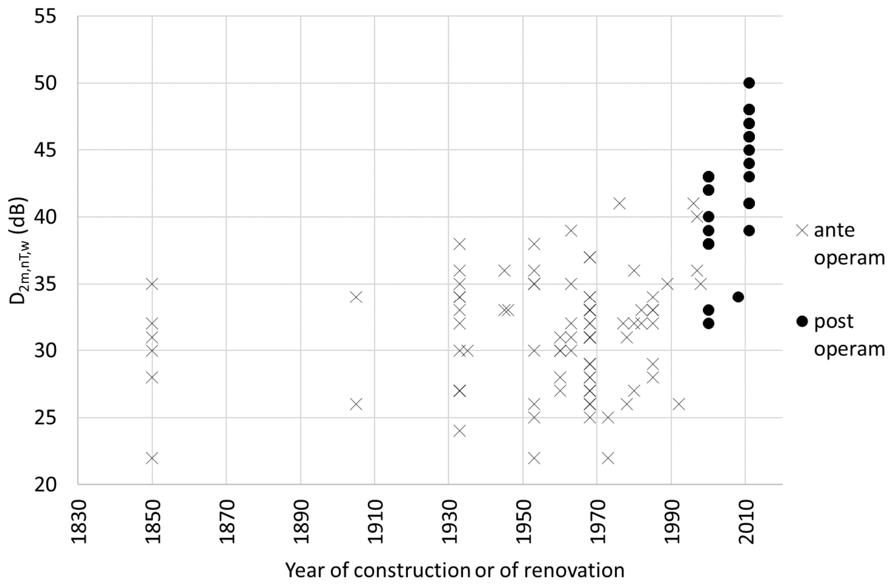

Figure 9 – Distribution of $D_{2m,nT,w}$ results as a function of the year of construction (or of renovation, for post operam measurements) of the building.

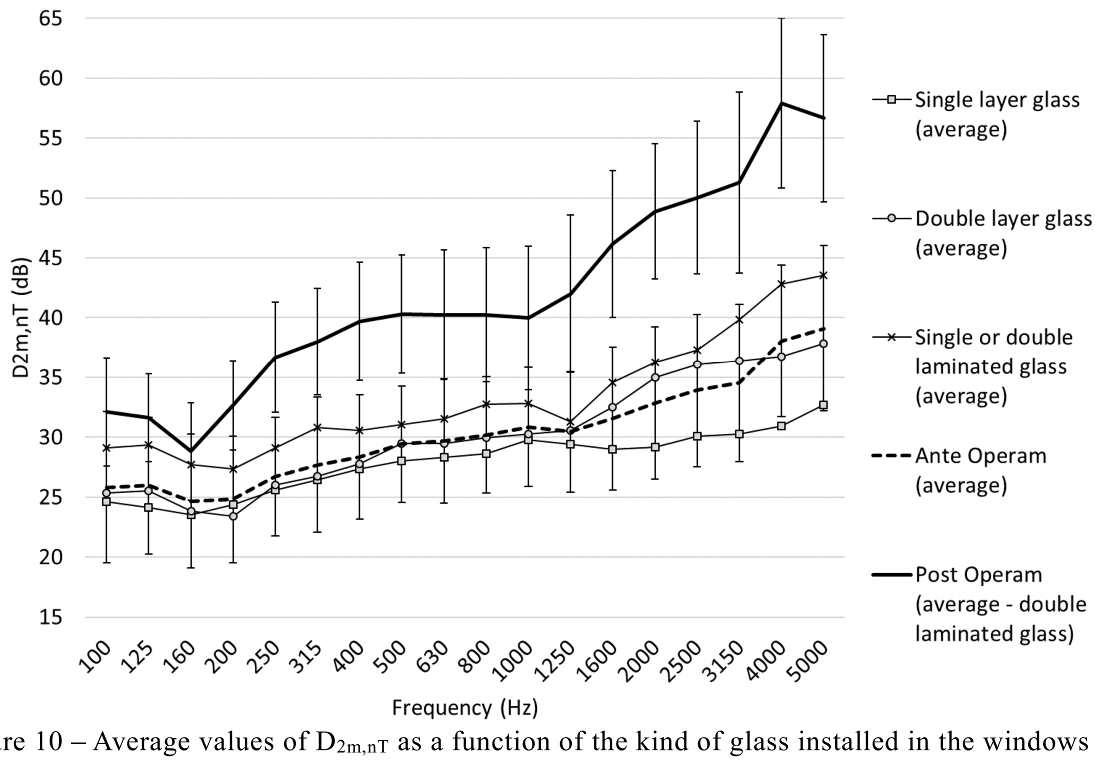

Figure 10 – Average values of $D_{2m,nT}$ as a function of the kind of glass installed in the windows (ante operam) and as ante and post operam global values (error bars = ± 1 standard deviation).

Table 2 - Average values of $D_{2m,nTw}$ and standard deviation as a function of the type of glass installed in the windows (ante operam) and as ante and post operam global values

	$D_{2m,nT,w}$ (dB)	**Standard dev. (dB)**
Single layer glass (Average - ante Operam)	28.7	3.8
Double layer glass (Average - ante Operam)	31.4	3.8
Single or double laminated glass (Average - ante Operam)	33.3	4.2

Ante Operam Average	31.0	4.3
Post Operam Average (double laminated glass)	**42.3**	**4.6**

4.2 Reverberation time

Figure 11 shows the average reverberation time measured in one-third octave bands in all the classrooms considered in this study. Error bars are equal to 1 standard deviation of the measured data.

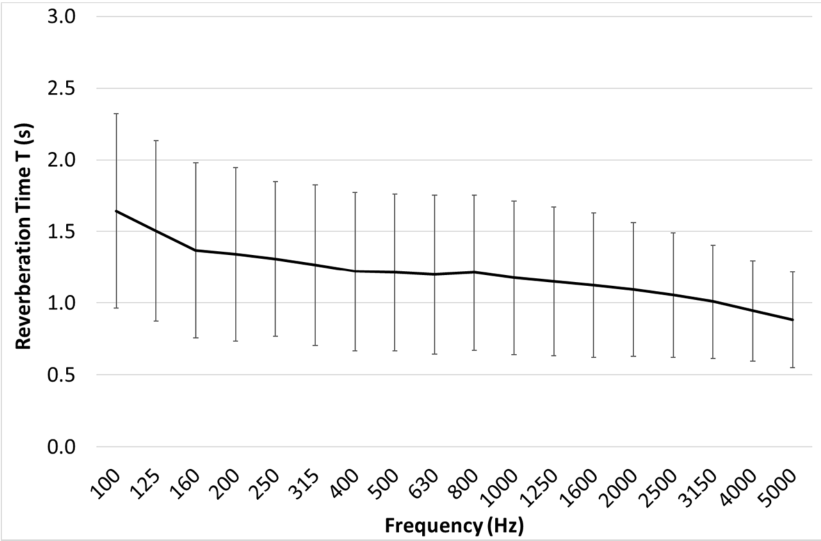

Figure 11 – Average values of reverberation time between 100 and 5000 Hz one-third octave bands (error bars = ± 1 standard deviation).

Measured reverberation time values were averaged between the 500 Hz and 1 kHz octave bands, and the average is equal to 1.3 s (stand. dev. 0.7 s).

The optimal value set by Italian legislation [10] is a function of the classroom volume. Considering the average value of the volume of the examined classrooms (160 m^3), the optimal value according to the UNI 11367 [15] is 0.7 s. This value is consistent with the maximum reverberation time, 0.6 s, considered by WHO [7].

The average reverberation time measured is quite high compared to the optimal values laid down by the Italian legislation and therefore, in order to enhance the listening experience in the classroom, joint actions of protection from outdoor noise and room acoustic treatment should be planned.

4.3 Indoor sound pressure level

Overall A-weighted indoor SPL for each classroom of the involved schools has been obtained from the one-third octave band values of the quantities reported in eq. (2). Note that the quantities used in eq. (2), from which the overall A-weighted indoor SPL has been obtained, are the quantities actually measured ($D_{2m,nT}$, T) for each façade, while one-third octave band outdoor noise levels ($L_{1,2m}$) have been calculated from the overall A-weighted outdoor level, which was assumed equal to 61 dB, as explained in section 2.3. Frequency values of the outdoor noise level were normalized to the road traffic noise spectrum given by EN 1793-3 [41].

Figure 12 shows the distribution, as percentage values, of the A-weighted indoor noise levels in the examined classrooms both before and after treatments of the façade to improve the acoustic performances.

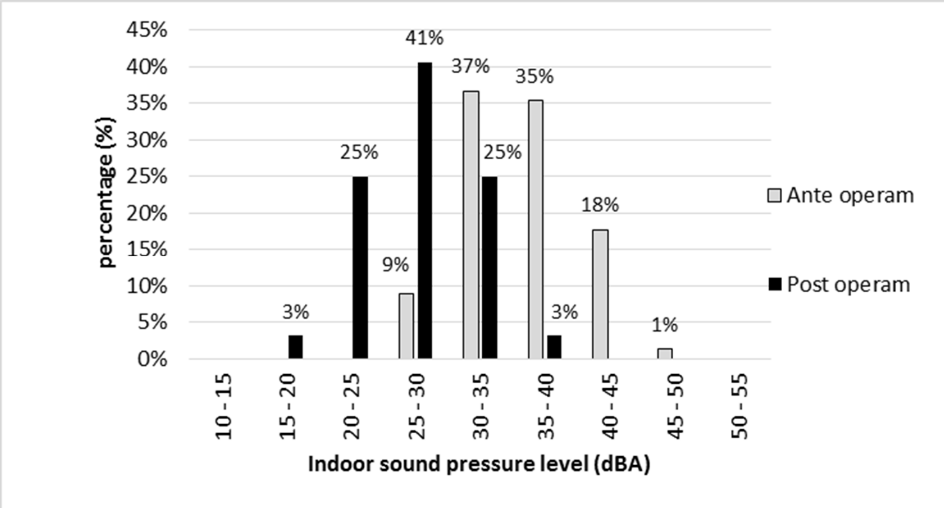

Figure 12 – Percentage distribution of the values of L_{Aeq} in the sample of schools ante and post operam calculated with reference to the average outdoor sound pressure level of 61 dBA (traffic noise).

The average value of indoor SPL due to traffic noise in the examined classrooms before the treatments is 35.7 dB, with a standard deviation of 4.5 dB; after the treatments, the average value is 27.4 dB with a standard deviation of 4.3 dB. Values obtained with reference to the situation before the treatments (ante operam) are similar to the ones measured by B. Shield *et al.* [42] in a sample of 86 classrooms of 13 schools located close to London. In this case, the unoccupied average indoor noise level was 33.6 dB with a standard deviation of 5.8 dB. They also found that both background and ambient SPLs during lessons mainly due to the teacher voice were related to the unoccupied indoor ambient noise levels and mid-frequency reverberation times.

Results shown in figure 12 can be compared to the limit values set by Italian legislation or by other relevant national or international references.

According to the results shown in figure 12, in only 1% of the classrooms, before the acoustic improvement treatments, the limit value of 45 dB is exceeded for the indoor sound pressure level due to traffic noise.

With reference to the limit value of 40 dB established by the Building Bulletin 93 of the United Kingdom Department for Education [6] and of 35 dB stated by WHO [7], 19% and 54% of the examined schools, pre-treatment, and 0% and 3%, post-treatment, respectively, would exceed the given limit values.

In short, it can be noted that the acoustic treatments of façades have greatly reduced (from 54% to 3%) the number of schools having indoor sound levels (due to traffic noise) above 35 dB.

4.4 Speech Transmission Index

The variation of the indoor SPL in the range of values described in Figure 12 (15 – 45 dBA) has a slight influence on the STI. Therefore, also the improvement of façade sound insulation has a little influence. For this reason, calculation of STI is referred only to the situation before the treatments of the façades (ante operam) since this sample of schools is broader.

The STI has been calculated in octave frequency bands for each classroom assuming the following conditions:

- unoccupied indoor noise levels calculated by means of eq. (2);
- negligible activity noise inside the classroom;
- frequency values of reverberation time measured in unoccupied classrooms;
- Female teacher with a “normal” or “high” vocal effort [31];
- teacher placed in front of the listener, with directivity equal to 2 dB below 2 kHz and to 3 dB from 2 kHz to 8 kHz [43];
- directional-hearing capacity of the listener equal to 2 dB for each octave band from 125 Hz to 8 kHz [43].

Vocal effort of teachers is usually high in typical schools, as highlighted in previous studies of Puglisi et al. [5, 44, 45, 46]. The present study has considered both “high” and “normal” vocal effort, to take into account all possible situations.

STI was calculated for a student at the back of the room, at the greatest distance from the teacher. This distance was calculated, for each classroom, as the square root of the floor area, since the exact shape of each classroom was not known.

Figure 13 shows the results of the distribution of STI in the cases of unoccupied or occupied classrooms, with “normal” vocal effort. In order to obtain occupied values, measured unoccupied reverberation times have been corrected for extra absorption due to the presence of the students and one teacher in the classrooms. The number of students in each classroom has been calculated as a function of the surface of the classroom. Values of sound absorption of students of different ages have been taken from DIN 18041 [47] for pre-school children, from Building Bulletin 93 [6] for primary school children and from Astolfi *et al.* [48] for secondary school students.

To this end, focus was set on the absorption effect of the pupils and of the teacher but not on their effect on the increase of ambient noise (negligible activity noise inside the classroom).

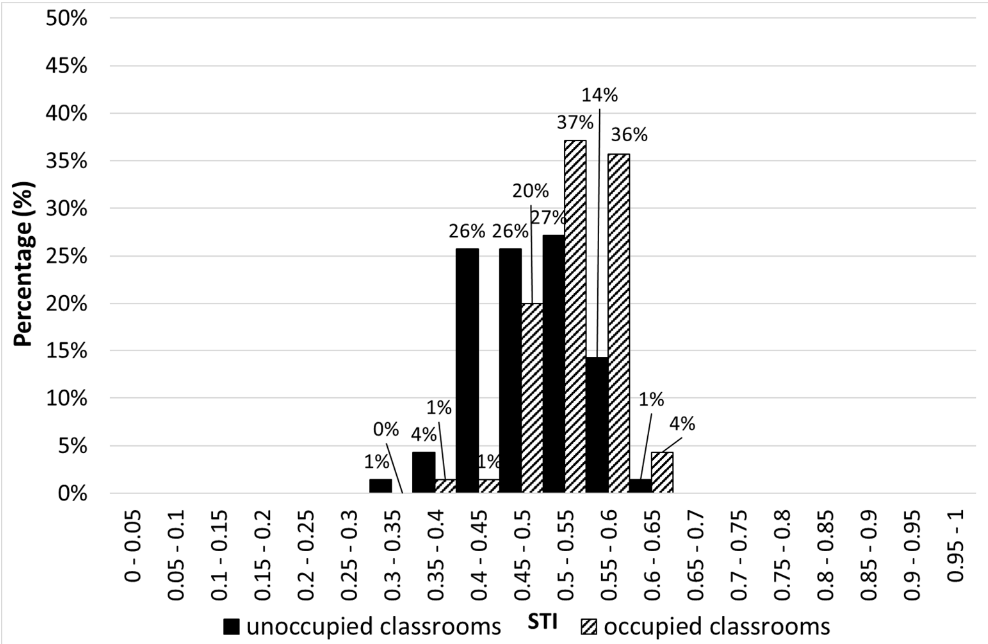

Figure 13 - STI distribution for unoccupied and occupied classrooms with a “normal” vocal effort

According to standard IEC 60268-16 [35] STI is considered “fair” above 0.45, “good” above 0.6 and “excellent” above 0.75. In the case of unoccupied classrooms, values of STI are “good” only in 1% of the cases and “poor” (below 0.45) in 31% of the cases. In the case of occupied classrooms, values of STI show a significant improvement: they are “good” in 4% of cases and “poor” (below 0.45) only in 2% of cases; moreover, the percentage of classrooms that have a STI between 0.55 and 0.6, that is very close to 0.6 (“good”), passes from a value of 14% (unoccupied) to a value of 36% (occupied).

With “high” vocal effort (not shown in figure 13), results of STI are not very different from figure 13; in this case, with unoccupied classrooms, values of STI are “good” in 6% of the cases and “poor” in 27 % of the cases; while, with occupied classrooms, values of STI are “good” in 9% of cases and “poor” in 1% of cases, showing a better behaviour.

The distribution of STI shown in figure 13 is almost entirely due to the different values of reverberation time and volume of the sample of classrooms, and not to their characteristics of sound insulation from external noise. Therefore, it can be concluded that, considering the high values of reverberation time in unoccupied classrooms, the speech intelligibility in classrooms is not affected by the values of façade sound insulation. Anyway, this consideration is the consequence of envisioning the indoor ambient noise in terms of equivalent SPL, as required for the evaluation of STI. This way, the effect of single outdoor noise events of great amplitude (such as the passage of trucks near the façade of the school or airplanes) is underestimated. In the next paragraph, the effect of these short duration noise events is analysed with reference to the examined case study.

4.5 Effect of short duration noise events

According to previous studies, the reaction of the students to environmental noise varies as a function of their age. In particular, Dockrell and Shield [30] found that younger children of primary schools are more affected by ambient and background levels of external noise, while the performance of older children of the same schools is more closely related to maximum noise levels. This suggests that the performance of older children (11 years old, in the studied case [30]) is affected by the noise of individual events such as sirens, lorries or motorbikes passing by the schools. For this reason, it does not seem fair to refer the limit values to the indoor equivalent SPL as in the case of the Italian regulation or other national or WHO regulations.

Instead, attention should be paid to the maximum SPL due to specific noise events that could significantly exceed the equivalent SPL. The problem is that it is very difficult to give specific indications about the amplitude of these events, since the maximum SPL due to a vehicle transit depends not only on its distance from the façade but also on its speed, the way of driving, the type of road surface and other parameters.

Some studies and guidelines [49, 50, 51] propose to assess the noise impact of new roads, evaluating the percentage of measuring intervals, each lasting 15 min or 1 h, for which it is L_{AFmax}(interval) - L_{Aeq}(interval) > 15 dB, in the night period.

Another work [52] shows that maximum levels due to vehicles passing by (L_{AFmax}) have a wider frequency distribution, for each vehicle class (passenger cars, non-articulated trucks, articulated trucks, motorcycles). In particular, the minimum value of standard deviation for cars passing at a speed of 80 km/h is 3.5 dB while the maximum value for articulated trucks travelling at 100 km/h is 9.0 dB with a significant overlapping of the distributions of each vehicle class.

The authors have started to study the typical distribution of noisy events in a preliminary work [53]. In particular, the hourly SPLs, measured in some roads of Italian cities, have been analysed by studying the correlation between maximum SPL and equivalent SPL; the sample includes different road types, from local to main roads.

These first results confirm that the distribution of the maximum SPLs is very dispersed and show that the difference L_{AFmax}(1h) - L_{Aeq}(1h), in the day period, has values that range from more than 20 dB to about 10 dB. Further studies and confirmations are certainly needed and the intention of the authors is to investigate these issues in future works.

However, from the cited literature and the preliminary study of the authors, it seems reasonable to assume that the excursion of a noisy event is at least 10 dB with respect to the equivalent SPL.

As a consequence, such an increase is assumed to evaluate the expected maximum SPL on the classroom façade. In particular, the effect of an outdoor maximum SPL of 71 dB, due to a road noisy event is analysed. This value is obtained by adding 10 dB to 61 dB, the latter having already been used as representative value of the equivalent SPL on the facade; the road traffic noise spectrum is applied to the event level, for frequency calculation. However, maximum SPL values greater than 71 dB may be expected on the facade as the difference of 10 dB with respect to the equivalent SPL is quite a low estimate for road noisy events.

Anyway, it is not possible to use short-duration noise events to calculate the STI, as in the previous section. On the other hand, the speech to noise ratio calculated with reference to these noise events could provide interesting information.

Shield *et al.* [42] calculated the speech-to-noise ratio as the difference between occupied L_{Aeq} and L_{A90} levels measured during lessons, when only one person is speaking.

The speech-to-noise ratio between the SPL generated at the listener's position by a teacher speaking at normal voice level and the maximum SPL at the listener's position transmitted from the façade is calculated in the present study.

The speech-to-noise ratio for each classroom in the frequency range from 125 Hz to 4000 Hz, considering the measured values of the façade sound insulation, $D_{2m,nT}$, and of the reverberation time, T, is calculated. Measured values of reverberation time were corrected to take into account the presence of pupils and teachers in classrooms as described in the previous section.

The maximum SPL of 71 dB for the outdoor sound pressure level 2 m in front of each façade was assumed for all classrooms. All the assumptions considered for the calculation of STI were used also for the analysis of speech-to-noise ratio.

Figure 14 shows the speech-to-noise ratio for all the classrooms before the treatment to improve the façade acoustic insulation, with "normal" vocal effort of teachers. At lower frequencies (125 Hz and 250 Hz) the ratio is near 0 for many classrooms and this could create problems of interference between speech and background noise.

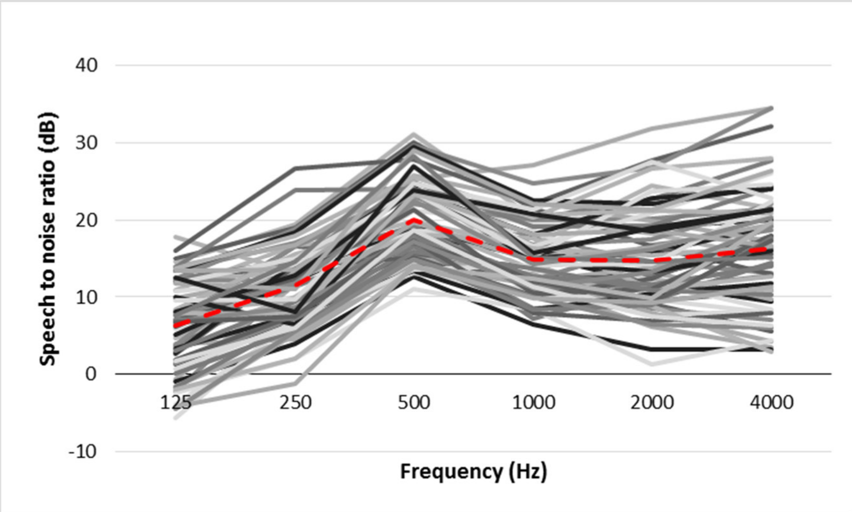

Figure 14 – Speech to noise ratio of all the classrooms before the treatment to improve the façade acoustic insulation and with outdoor maximum SPL of 71 dB, with normal vocal effort of teacher; red dashed line refers to average values

Figure 15 shows the results of the calculation of the speech-to-noise ratio for those classrooms that were treated to improve the façade acoustic insulation. In this case, the speech-to-noise ratio is almost always greater than 10 dB at all frequency bands from 125 Hz to 4000 Hz.

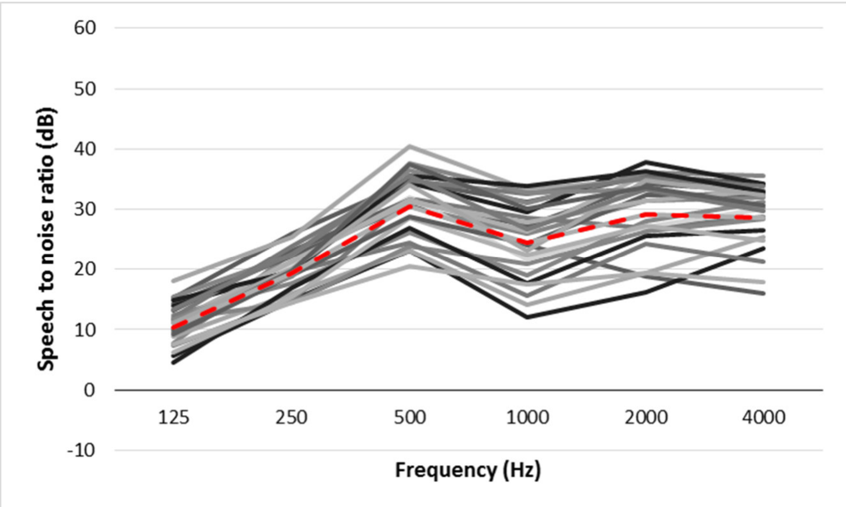

Figure 15 – Speech to noise ratio for the classrooms treated to improve the façade acoustic insulation and with maximum outdoor SPL of 71 dB, with normal vocal effort of teacher; red dashed line refers to average values

5. Discussion

The most frequently recommended solution for reducing the negative impact of outdoor noise in buildings near busy roads or airports is to increase sound insulation [54].

A sample of 103 façades was analysed in this study, as representative of typical façades of Italian schools, including schools of any level and building technologies as well as different time periods of construction.

In some of these schools (45 classrooms) acoustic improvement treatments were carried out on the façades. Results of measurements, carried out both before and after these treatments, show an average improvement in façade acoustic insulation of about 11 dB. On the other hand, the indoor reverberation times did not change after the treatments of the façades. Therefore, a great number of classrooms of the selected sample still had reverberation issues also after the acoustic treatments of the facades. Average values of the reverberation time, in the sample of schools, was more than double (1.3 s) than the values recommended by WHO [7] (0.6 s) and by literature [5, 19, 20].

The sample of schools is exposed to an average traffic noise, in day-time period, equal to about 64 dB. This value of the outdoor SPL is not representative of all the Italian schools since the schools selected were all located near very busy roads. To better characterize the typical outdoor noise in Italian schools, the analysis of outdoor noise is referred to a previous study [23] carried out on a random sample of 43 schools of all levels, where average outdoor noise level was 61 dB. Considering the effect of the sound reflection given by the façade, this level is similar to the one assumed by Dockrell and Shield [29] that analysed a sample of 53 schools in one area of London.

The analysis of indoor SPL and of STI with reference to this typical outdoor SPL, shows that, after the treatments of the façades, the main acoustic problem of the selected classrooms is the indoor reverberation time and not the intrusion of noise from outdoor sources.

Anyway, this analysis is referred to the outdoor noise, examined as equivalent SPL. This way, the effect of short-duration single noise events is not considered. Many studies [e.g. 28, 55] show that annoyance caused by occasional noise events such as overflying aircraft, trains or sirens may affect children and teachers disproportionately to their contribution to the overall noise environment of a school. For this reason, it was necessary to refer to a typical value of the maximum SPL associated to the transit of a single noisy vehicle.

This study analysed the typical difference between L_{AFmax} and L_{Aeq}, measured in the day period in some roads of an urban area. Preliminary results confirm that the distribution of the maximum sound levels is very dispersed and shows typical values of this difference ranging from 20 dB to 10 dB. In this study it was assumed that the noisiest events have an excursion of 10 dB with respect to the averaged SPL.

The analysis of the speech-to-noise ratio, calculated as the difference between the SPL, generated at the listener's position by a teacher speaking at normal voice level, and the maximum SPL at the listener's position transmitted from the façade, shows that the improvement of the façade sound insulation reduces indoor SPLs below the speech level at all frequencies also when short-duration noise events of typical amplitude occur. Although this consideration requires further studies, maximum SPL values larger than 71 dB may be expected on the façade, since the 10 dB difference with respect to the equivalent SPL is quite a low estimate for road noisy events.

6. Conclusions

In this study, a sample of 103 façades belonging to 64 schools located in three Italian Regions was examined. Information about the school level, the year of construction, the window frame material, the typology of façade components and the dimensions of the classrooms was collected for each classroom. The data collected were compared to the ones referred to the national school building stock, as reported in the census of all Italian schools (including more than 42,000 buildings distributed across the Italian Regions) carried out by the Italian government.

Both the standardized façade level difference and the reverberation time from 100 Hz to 5000 Hz one-third octave bands of the examined sample of schools were measured.

The average improvement of the façade sound insulation was 11.3 dB, which, in general, allows to create a comfortable sound environment inside the classrooms where the maximum statistical distribution of all the indoor levels shift to the left, from 30-40 dB to 25-30 dB, referring to an average outdoor noise level of 61 dB.

As expected, the refurbishment of façades aimed at improving sound insulation led to no significant difference in the measured reverberation times before and after the treatments and therefore in the internal absorption coefficient. The average value of reverberation time between the 500 Hz and 1 kHz octave-bands, measured in the sample of 103 classrooms, is equal to 1.3 s with a standard deviation of 0.7 s.

The Speech Transmission Index, calculated with negligible activity noise inside the classroom (the only noise coming from the façade), in unoccupied classrooms is poor in 31% of cases while in occupied classrooms is poor only in 2% of cases, with "normal" vocal effort of the teacher, according to the classification given by the standard IEC 60268-16 [35].

The effect of short-duration noise events due to road traffic was analysed and a minimal difference of 10 dB between L_{Aeq} and L_{Amax} was considered, according to previous studies. It was found that the improvement of façade sound insulation carried out on the sample of classrooms reduces the indoor noise level below the speech level at all the frequencies between 125 Hz and 4000 Hz octave bands in all the classrooms analysed. Anyway, the intention of the authors is to deeply investigate the relationship between maximum noise levels due to traffic noise and average sound levels, with reference to typical roads.

Therefore, it can be concluded that the acoustic treatment of facades, that usually consists in the replacement of windows, produces good results in the abatement of indoor noise level also with respect to the analysed short-duration noise events. On the other hand, as high reverberation times affect the intelligibility and, in general, the acoustics comfort in a classroom, it is necessary to plan the façade refurbishment and the acoustic treatment of classrooms together.

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