

# Multi-Objective Optimization Of Thermo-Acoustic Comfort Of School Buildings

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## Abstract

The reduction of the environmental impact of the building sector is one of the top priorities in the “climate change challenge”. As the primary energy consumption of the building decreases, a high level of indoor comfort must be maintained. Both thermal parameters, lighting, acoustic level, and indoor air quality affect indoor comfort. These aspects are fundamental, especially in school buildings, where a good level of indoor comfort can help student to stay focused. This paper proposes a methodology for a combined optimization of the energetic and the acoustic performance of a school building. A case study, located in the center of Italy, was analyzed. Firstly, the thermal and acoustic performance was determined. Then a list of interventions was hypothesized and simulated, involving both the building envelope, the lighting and thermal plants. Normalized acoustic insulation of partitions between adjacent rooms, acoustic insulation of the façade and reverberation time were evaluated. The outdoor and ambient noise levels were based on the main characteristics of the façade (type and stratifications of opaque and transparent components, ventilation system, etc.). Results show that the optimal combination of interventions reduces the CO<sub>2</sub> emissions of 88.55 % and the global energy performance index of 85.2 %. The indoor sound pressure level due to traffic noise is reduced by 19 dB after acoustic insulation of the façade, while further treatments to indoor surfaces should be implemented to reduce internal reverberation time and to improve speech intelligibility. The combined optimization shows that the highest reduction of the global impact (89.2 %) is obtained by weighting 80 %/20 % the acoustic/thermal performance.

## 1. Introduction

Nowadays, the building sector accounts for around 40 % of total global energy consumption and more than 30 % of CO<sub>2</sub> emissions. To achieve net-zero carbon emissions by 2050, the International Energy Agency (IEA) estimates that the sector has to halve its emissions by 2030. In the EU, the situation is similar, with 36 % of CO<sub>2</sub> emissions from the building stock, of which the final energy consumption for heating and cooling is 50 %. Accordingly, improving the energy efficiency and fostering total decarbonization is an essential step towards renewal of the building stock. The current rate of renovation of public buildings ranges from 0.4 % and 1.2 % per year, while it should be around 3 %, as reported by the 2018/844/EU Directive.

In addition, a high level of indoor comfort is required. Indoor comfort is affected by several factors, such as thermal level (air temperature and humidity, air velocity and quality), lighting and acoustic quality. In school buildings, students spend many hours a day in the classroom. The correct environment can help students to be focused and energetic. Different strategies have been proposed to evaluate and optimize the performance of school buildings (MacNaughton et al., 2018), or energy audits (Wang et al., 2015). Díaz-López et al. (2022) identified the 24 best passive intervention strategies, analyzing research trends in 42 countries. Li et al. (2021) proposed a multi-objective optimization method based on the response surface method, where optimal design trade-offs between thermal comfort and energy demand are obtained. Omar et al. (2022) based their optimization on lighting and cooling plant

Part of

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retrofitting, and on the integration of a photovoltaic plant to increase the share of renewable energy exploited. Results show a gain of renewable fraction of around 82 %. Gamarra et al. (2018) considered water consumption and carbon footprint, resulting in a life-cycle assessment.

Noise in schools derives from its original surrounding environment, which has turned from silent into very noisy over the years (Secchi et al., 2017). The specification regarding sound insulation properties and noise from equipment properties in Italy were defined in the D.P.C.M. 5/12/97. The recent Italian law D.M. 11/01/2017, recalls the Italian standard UNI 11367. According to these standards, new school buildings must guarantee a façade sound insulation of  $D_{2m,nT,w} \geq 48$  dB, which is very restrictive. In UNI 11367, the limit value for the normalized acoustic insulation of partitions between adjacent rooms of the same unit was presented: basic performance, with  $D_{nT,w} \geq 45$ , and high performance, with  $D_{nT,w} \geq 50$  dB. UNI 11367 also requires a Speech Transmission Index in classrooms higher than 0.60 and sets the optimum value of reverberation time (Tott) as average value between 500 and 1000 Hz for unoccupied classrooms (s). The limit values for the acoustic indoor room quality are also defined in the UNI 11532-1. In part 2 of the standard, the limit value for reverberation time, STI e/o C50, and sound pressure level for technologic systems installed inside the classroom are defined.

This paper presents a methodology for the thermo-acoustic optimization of an existing school building, based on combinations of interventions (Moazzen et al., 2020). A primary school building located in central Italy was taken as a case study. Firstly, the

current state of the building was analyzed using software to estimate the heating energy demand and acoustic performance. The analysis concerns both the design conditions and the dynamic consumption over a period of one year. Then, a list of interventions was hypothesized, involving both building envelope, the lighting system, the thermal plants and the acoustic parameters, to find out the optimal configuration. The novelty proposed is combined analysis, setting and optimizing weighting coefficients between thermal and acoustic performances.

## 2. Materials and Method

The methodology proposed consists of different steps:

- Identification of the case study building and determination of its properties and climatic conditions.
- Evaluation of energy and acoustic performance by software simulations.
- Proposal of interventions and combination of them.
- Simulation and index calculation.

The building chosen as reference case should be representative of the category of buildings under study, as regards the building geometry, energy performance for both envelope and plants, and climatic conditions. This way, the proposed model, once validated, can be easily applied to other buildings. In this paper, a primary school building has been chosen as reference case. Fig. 1 shows a real image of the building, while Fig. 2 shows the plan view.



Fig. 1 – Real image of the school building under study

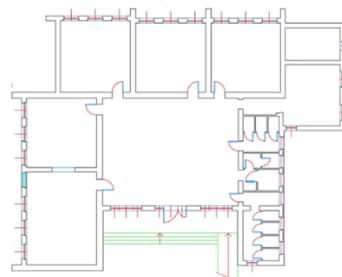


Fig. 2 – Plan view of the school building under study

The reference building presents a floor area of 350 m<sup>2</sup> and consists of 6 classrooms, with a net height of 3.25 m. The entrance hall has a sloped ceiling, average height 4.8 m. The occupancy has been hypothesized as typical of school buildings, namely on weekdays between 08.00 and 1700. According to the national standards, Italy is divided into six climatic zones, depending on the heating degree days. For each zone, there is a corresponding different annual heating period and number of hours of daily operation. In addition, a series of minimum U-values are provided for each zone. Central Italy, where the reference building is located, is involved in the “E” zone, which corresponds with a heating period from 15 October to 15 April. The specific location of the building presents a minimum temperature of -4 °C, as stated in the UNI 10349 standard. This data is required to calculate the energy performance of the building under the worst-case conditions. Then a dynamic hourly-based method is applied to provide the energy consumptions over a year. The first step for the energy performance calculation is the energy determination of the U-values of all vertical and horizontal, opaque and transparent structures. The U-value is a function of the thickness and type of each material of the stratification. The thermal conductivity is taken from the UNI 10351 standard for homogeneous materials and the UNI 10355 for heterogeneous ones. In the absence of reliable data, the U-value of opaque and transparent structures can be estimated as a function of the year of construction of the building. When data are collected, U-values can be determined. In Tables 1, 2, 3, 4 the stratifications and the thermal and acoustic performance of the opaque structures are presented.

Table 1 – Stratification of the front vertical facade

<b>Total thickness [cm]</b>	50		
<b>Surface mass [kg/m<sup>2</sup>]</b>	1296		
<b>U-Value [W/(m<sup>2</sup> °C)]</b>	2,02		
<b>Rw [dB]</b>	54		
<b>Layer</b>	<b>Thickness [cm]</b>	<b>Thermal conductivity [W/(m °C)]</b>	<b>Density [kg/m<sup>3</sup>]</b>
Gypsum plaster	2	0.35	1200
Dolomite stone	48	1.8	2700

Table 2 – Stratification of the external vertical wall

<b>Total thickness [cm]</b>	44		
<b>Surface mass [kg/m<sup>2</sup>]</b>	560		
<b>U-Value [W/(m<sup>2</sup> °C)]</b>	1.1		
<b>Rw [dB]</b>	51		
<b>Layer</b>	<b>Thickness [cm]</b>	<b>Thermal conductivity [W/(m °C)]</b>	<b>Density [kg/m<sup>3</sup>]</b>
Gypsum plaster	2	0.35	1200
Perforated brick	40	1.8	2700
Cement mortar	2	1.4	2000

Table 3 – Stratification of the floor

<b>Total thickness [cm]</b>	32		
<b>Surface mass [kg/m<sup>2</sup>]</b>	354		
<b>U-Value [W/(m<sup>2</sup> °C)]</b>	1.64		
<b>Rw [dB]</b>	52		
<b>Layer</b>	<b>Thickness [cm]</b>	<b>Thermal conductivity [W/(m °C)]</b>	<b>Density [kg/m<sup>3</sup>]</b>
Ceramic tiles	2	1	2300
Cement mortar	4	1.4	2000
Floor brick	26	0.74	1185

Table 4 – Stratification of the ceiling

<b>Total thickness [cm]</b>	24		
<b>Surface mass [kg/m<sup>2</sup>]</b>	55		
<b>U-Value [W/(m<sup>2</sup> °C)]</b>	0.20		
<b>Rw [dB]</b>	48		
<b>Layer</b>	<b>Thickness [cm]</b>	<b>Thermal conductivity [W/(m °C)]</b>	<b>Density [kg/m<sup>3</sup>]</b>
Wood panel	1.3	0.12	450
BARRIER 100	0.1	0.35	950
Rock wool	1.6	0.035	40
Waterproofing	0.1	0.17	1200
Air	5	0.32	1
Roof tiles	1.5	1	2000

The U-values of the transparent components range from 2.8 W/(m<sup>2</sup> °C), consisting of aluminum frame without thermal break and double glazing, to 5 W/(m<sup>2</sup> °C) for the oldest ones, consisting of metallic frame and single glazing.

Then the performance of the building was evaluated. Energetically, the building was modeled on MC4software, whose representation is shown in Fig. 3.

For the acoustic characterization of the unoccupied classrooms, forecast calculations were carried out according to the current technical regulations. These can be determined with the aid of performance and functional criteria. The forecast calculations and assessment methods are described in UNI 11532-2.

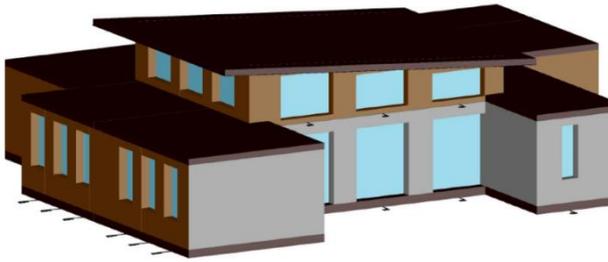


Fig. 3 - 3D model reconstruction for building simulation

The sound insulation performances of typical Italian classrooms were investigated in terms of indoor sound pressure level transmitted through the school façade, reverberation time and sound emitted by technological systems. The estimation of the indoor sound pressure level,  $L_2$ , due to the sound from outdoor is obtained with Eq. (1), based on the ISO 12354-3.

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

where  $L_{1,2m}$  is the outdoor sound pressure level 2 m in front of the façade (dB),  $D_{2m,nT}$  is the standardized level difference of façade insulation,  $T$  is the reverberation time (s) and  $T_0$  is the reference reverberation time (0.5 s).

The prediction method for calculating the Reverberation Time is described in EN 12354-6, while for the  $L_{pu,c}$  index the reference standard is the EN 12354-5. Based on the energy efficiency interventions, the acoustic performance of the school has been calculated in parallel as the interventions varied.

A list of intervention has been hypothesized, involving both the building envelope and the thermal plant. Each specific building can require certain interventions. In this work general interventions are proposed, to remain valid in most of the cases. In Table 5 the interventions are listed.

Table 5 – List of interventions

Code	Intervention
GL1	Substitution of glazing
IN1	Insulation of vertical walls
IN2	Insulation of floor and addition of radiant heat floor
L1	Substitution of traditional lighting system with LED-based one
TP1	Substitution of traditional heat generator with heat pump
TP2	Introduction of a photovoltaic plant
TP3	Introduction of mechanic ventilation system

The substitution of glazing (GL1) allows a reduction of the U-value of the transparent components. Triple glass of thickness 5 mm with 12 mm of air gap has been chosen, with an aluminum frame and thermal break. The respective U-value turns out to be in the range 2.8 W/(m<sup>2</sup> K) and 5 W/(m<sup>2</sup> K), depending on the size of the window. The insulation of vertical walls (IN1) consists in the addition of a layer of thermal insulation, to increase the thermal resistance. An expanded polystyrene (EPS100) has been chosen, with a thermal conductivity of 0.035 W/m K and a density of 20 kg/m<sup>3</sup>. A layer of 12 cm, placed externally to the wall stratification, has been provided for the brick-based wall. The front façade instead, has been insulated with 6 cm of the same polystyrene but placed internally, to maintain the aesthetics of the faced stone. The U-value of the two walls becomes 0.2 and 0.5 W/(m<sup>2</sup> K), respectively.

The intervention on the lighting system (L1) consists in the replacement of traditional lamps with LED ones. The latter reduce the expense of electricity for lighting, considering that a traditional lamp produces 62 lm/W compared to 95 lm/W of a LED one. The number of LED lamps to be installed in each room (n) has been evaluated with the Eq. (2):

$$n = \frac{\phi_t}{m h \phi_l} \quad (2)$$

where  $\phi_t$  is the luminous flux of the lamp, m is a coefficient of utilization in function of the shape of the lamp, h is the net height of the room and  $\phi_l$  is the luminous flux on the target area.

The substitution of traditional heat generator for heat pump (TP1) increases the heat generation and

distribution efficiency by decreasing the working temperature of the water. In addition, this is a switch from natural gas to electricity. Consequently, the installation of a photovoltaic plant (TP2) is a fundamental step towards exploiting a local renewable energy source to cover the lighting and heat pump energy demand. The last intervention is the mechanical ventilation system (TP3), which improves the indoor air quality of the classrooms. The system is composed of a single machine, to be installed in each room, which provides an air ventilation rate proportional to the CO<sub>2</sub> percentage in the room. Then the single interventions were combined each other to maximize the energy performance of the building and the energy saving. Different scenarios, later called “packages”, have been simulated (Table 6).

Table 6 – Combination of interventions

Package	Building envelope		Lighting		Thermal plant		
	GL	IN	L1	L2	TP1	TP2	TP3
P0	-	-	-	-	-	-	-
P1	GL1	-	-	-	-	-	-
P2	-	IN1	-	-	-	-	-
P3	GL1	IN1	-	-	-	-	-
P4	GL1	IN1	IN2	-	TP1	-	-
P5	GL1	IN1	IN2	L1	TP1	TP2	-
P6	GL1	IN1	IN2	L1	TP1	TP2	TP3

### 3. Results and Discussions

The parameters for the indoor conditions of the rooms were calculated separately for the thermal, acoustic and visual conditions. Energetically, the parameters are the global performance index and the CO<sub>2</sub> emitted. The first one, indicated with “EP<sub>gl,nren</sub>” and expressed in kWh/m<sup>2</sup>yr, considers the amount of energy for the air conditioning over one year, normalized per meter square. This is a useful parameter for comparing different buildings. In addition, the index differentiates the fuel used, applying a higher coefficient for non-renewable ones and neglecting the share of local energy productions

from renewable sources. The CO<sub>2</sub> emitted considers the typology of fuel and its relative emissive factor, while for the electricity from the grid the factors are estimated based on the national energy mix. Results are shown in Fig. 4 and Fig. 5, for the global performance index and the CO<sub>2</sub> emitted, respectively. The reference case is characterized by a global performance index of 407.6 kWh/m<sup>2</sup> yr and 38037 kg of CO<sub>2</sub> emissions. Both parameters decrease, while the number of interventions increase. The best scenario allows a reduction of the CO<sub>2</sub> emissions of 88.5 %, 4354 kg, and the global performance index of 85.2 %, 60.3 kWh/m<sup>2</sup> yr.

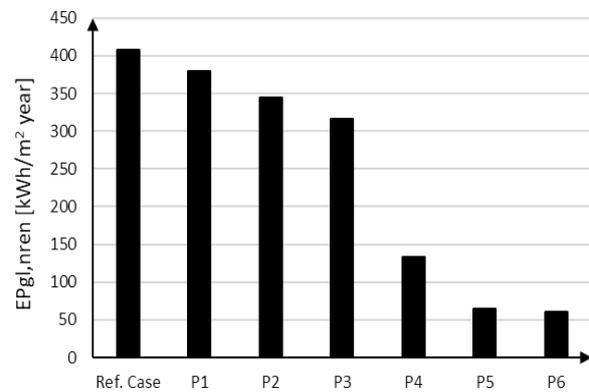
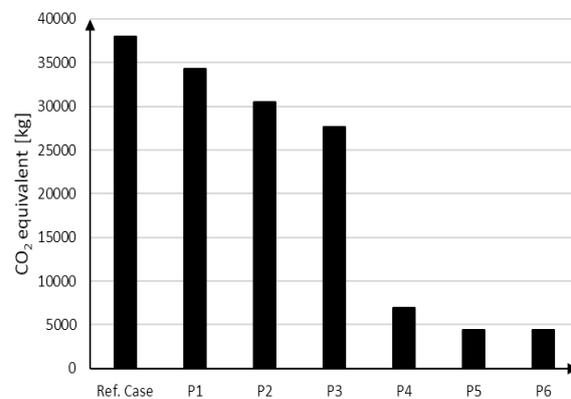


Fig. 4 – Global energy performance index for each scenario

Fig. 5 – CO<sub>2</sub> emissions for each scenario

The payback period (PB) was chosen as economic index. It provides information about the time necessary to recover the initial costs, by means of the annual energy saving of the improved scenario. The lower the PB is, the more the scenario becomes a priority. Table 7 summarizes the initial cost and the PB for each scenario analyzed. The best scenario turns out to be the combination of all interventions

except for the mechanical ventilation system, with a payback period of 13 years and 10 months.

Table 7 – Initial cost and payback period of the simulated scenarios

Intervention	Cost [€]	PB [years]
P1	27605	24 years 6 months
P2	37161	14 years 4 months
P3	64766	15 years 6 months
P4	217234	17 years 6 months
P5	283336	13 years 10 months
P6	303336	14 years 9 months

For the acoustic scenarios, results refer to the prediction values of façade sound insulation, to the reverberation time and to the calculated values of unoccupied indoor sound pressure level. Table 8 shows the average values of results of D2m,nT,w and DnT,w calculations for all classrooms, respectively. Results concerning corridors, gyms and closets were excluded from this analysis.

Table 8 – Acoustic performance ante and post operam

	Result	Limit value
Ante Operam Average	D2m,nT,w [dB]	D2m,nT,w [dB] D.P.C.M 5/12/97
	33	48
	DnT,w [dB] Between two classrooms	DnT,w [dB] high performance UNI 11367
	45	50
Post Operam Average	D2m,nT,w [dB]	D2m,nT,w D.P.C.M 5/12/97
	52	48
	DnT,w [dB] Between two classrooms	DnT,w high performance UNI 11367
	54	50

Schools with single-glazed windows have typically lower insulation performances. The improvement of acoustic performances is evident because of the better air thickness of the new windows and the insulation of vertical walls.

Fig. 6 shows the average reverberation time calculated in octave bands in all the classrooms.

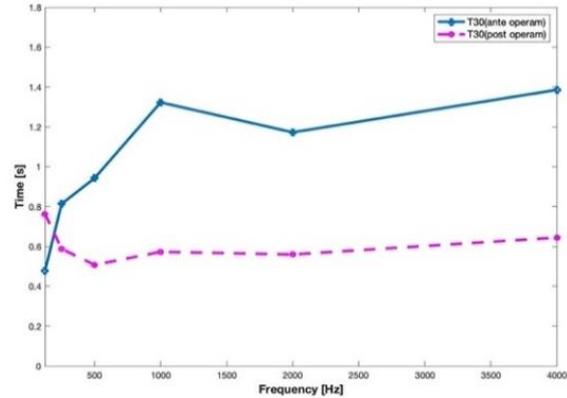


Fig. 6 – Reverberation time in pre (blue) and post operam (pink)

Reverberation time values averaged between the 500 Hz and 1 kHz octave bands, resulting in 1,02 s (ante operam) and 0,59 s (post operam).

The optimal value set by Italian law [16] is a function of the classroom volume. Averaging the volume of the examined classrooms (100 m<sup>3</sup>), the optimal average value is 0,47s.

For each façade, the outdoor noise levels (L<sub>1,2m</sub>) were calculated. A weighted outdoor level equal to 60 dB (that is the maximum noise emissions level permitted by the law DCPM 14/11/97) was assumed. Results were compared to the limit values set by Italian legislation or by other relevant national or international references. The analysis of indoor SPL shows that, after the treatments of the façades, the main acoustic problem of the selected classrooms is the indoor reverberation time and it is not the noise from outdoor sources.

A subsequent statistical analysis was performed for the case study. The first correlation model is based on a multivariate regression between the representative thermal parameters and weighted on the non-renewable global energy performance index of the school (Fig. 7). The regression was calculated considering the results obtained by the seven scenarios.

The model is based on the following Eq. 4:

$$Model(x, y) = a + bx + cy + dx^2 + ey \quad (4)$$

where *a, b, c, d, e* represent the partial regression coefficients (with 95 % confidence bound).

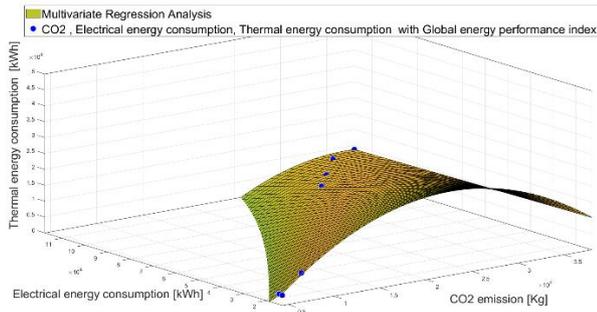


Fig. 7 – Multivariate regression (CO2 emission [kg], electrical energy consumption [kWh], thermal energy consumption [kWh] weighted on the global energy performance index). Several noteworthy results were:  $R^2=0.99$ ,  $R=0.97$ , Dfe 2

The second correlation model aims to determine the impact of the acoustic and energetic interventions on processing costs. The model was defined as the weighted sum of the acoustic and thermal resulting parameter. The weights were assigned arbitrarily considering increasing weights to the acoustic performance and subsequently decreasing to the thermal one. The optimization model is represented by the following equation (Eq. 5):

$$opt = b \cdot \%EP_{gl,nren} + a \cdot \%RT + a \cdot \%SA \quad (5)$$

where  $a = [0.2 \ 0.4 \ 0.6 \ 0.8]$ ,  $b = [1-a]$ , and the  $EP_{gl,nren}$ , RT (reverberation time (T30)) and SA (sound absorption) are expressed as percentages of saving compared to the reference case.

Results of the polynomial regression are shown in Fig. 8, while Table 9 summarizes the percentage of reduction of the global impact at the various weights.

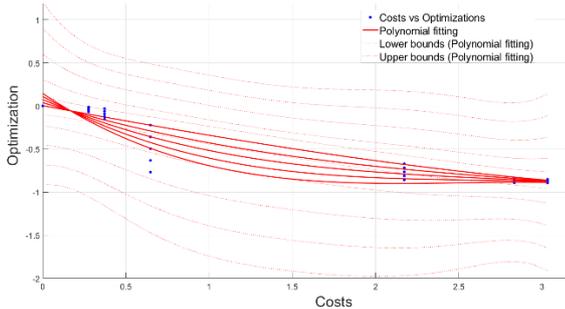


Fig. 8 – Results of linear regression between Thermal-Acoustic optimization and Costs (Euro). Several noteworthy results were:  $R^2=0.85$ ,  $R=0.70$ , Dfe 3

Table 9 - Thermal-acoustic optimization vs costs of intervention at the different weights ( $w_0$ ,  $w_1$ ,  $w_2$ ,  $w_3$ ,  $w_4$ )

Intervention	$w_0$	$w_1$	$w_2$	$w_3$	$w_4$
P1	6.9%	5.6%	4.2%	2.8%	1.4%
P2	15.5%	12.3%	9.2%	6.1%	3.0%
P3	22.3%	35.9%	49.5%	63.2%	76.8%
P4	67.1%	71.8%	76.5%	81.1%	85.8%
P5	84.2%	85.4%	86.7%	87.9%	89.2%
P6	85.2%	86.2%	87.3%	88.3%	89.4%

## 4. Conclusions

This paper proposes a methodology for a combined optimization of the thermal and acoustic performance of a school building. A primary school building located in the center of Italy was chosen as case study. Firstly, the thermal and acoustic performance of the reference building were simulated. Then the proposed methodology was applied. A list of interventions was hypothesized, involving both the building envelope and the thermal and lighting plants. Different interventions were combined in packages, to optimize the overall performance of the building and to find the best scenario. Results show that the optimal scenario, combining all the interventions, reduces the CO<sub>2</sub> emission of 88.5 % (4354 kg, while it is 38037 kg for the reference case) and the global performance index of 85.2 % (60.3 kWh/m<sup>2</sup> yr, while it is 407.6 kWh/m<sup>2</sup> yr for the reference case). The acoustic treatment of façades, consisting of the replacement of windows and the insulation of vertical walls, produces good results in the abatement of indoor noise level (19 dB). The average reverberation time is reduced by about 0.40 s, which turns out to be a good result but still not compliant with the optimal time defined by the standards. However, the mechanical ventilation system negatively affects the intelligibility and, in general, the acoustic comfort in a classroom (Serpilli et al., 2022). Consequently, a combined plan between the façade refurbishment and the interior acoustic treatment of the classrooms is recommended. As regard the economic analysis, the best scenario turns out to be the combination of all interventions except for the mechanical ventilation system. This scenario returns the shortest payback period (13 years and 10

months). The combined optimization shows that the best scenario is obtained by weighting the acoustic performance 80 % and the thermal one 20 %, and ensures a global impact reduction of 89.2 %, compared with the reference case. Further research, under analysis, will be proposed extending the presented methodology to other school buildings, to validate the statistical approach and compare the results obtained.

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