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A global index to evaluate the acoustical and thermal behavior of buildings: first evaluations and applications to common building walls in Italy

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ABSTRACT

In the recent years adequate thermal and acoustic comfort conditions in buildings have received more and more attention. The acoustical and thermal insulation strategies applied to building structures must be based on the correct combination of materials and building construction techniques. The aim is to guarantee comfort and good energy performance of buildings at the same time. The paper therefore proposes a study on the acoustical and thermal behavior of building structures on the basis of the calculations performed on a set of building walls, widely diffused, both in a national and international context. Thermal transmittance and apparent sound reduction index were chosen as representative parameters for thermal and acoustic characteristics definition. The paper objective is to improve the comprehension of thermal and acoustic behavior of existing building walls and to propose a new method to judge such behavior, even for new walls, based on an integrated index. For these reasons the work is divided into two parts. The first part presents a collection of walls (heavy and light kind), characterized by thermal transmittance and apparent sound reduction index values. The second part is devoted to describe a wall classification system, through an integrated index. The performance evaluation is a weighted percentage based on the improvement potential of each analyzed parameter considered. The integrated index considers also the limiting values provided by current rules or laws and technical standards. The integrated index is realized in order to offer a simple instrument to indicate the thermal and acoustic quality with just a single number (positive or negative). Such an index allows to understand immediately if the investigated walls fit, or not, design requirements.

INTRODUCTION

In the last few years the attention of the public opinion and of governments to problems related to energy saving and acoustical confort in buildings is becoming more and more important. It is been a long time since rigorous rules exist with the aim to guarantee acoustical comfort in buildings, which is achieved by proper insulation and sound absorption characteristics of external and internal buildings partitions.

Recently energy saving, too, seems to be one of the primary objectives, in order to reduce fuel consumption and carbon dioxide emissions. Since residential and commercial building are responsible of 40% of the energy waste in Italy and in other world countries, one of the possible interventions is building insulation through the appropriate design of opaque enclosures. Thus, some recent laws impose tight limits for wall thermal transmittance values in new and restructured buildings.

Since thermal and acoustic behaviour of components are not hand in hand, it is important to apply acoustical and thermal insulation strategies to building structures which must be based on a correct combination of materials and building construction techniques, in order to guarantee comfort and good energy performance of buildings at the same time.

The paper therefore presents a study on the acoustical and thermal behaviour of building structures on the basis of some analysis performed on a set of building walls, widely diffused, both in a national and an international context. The paper main objectives are two: on the one hand to improve the comprehension of thermal and acoustic behaviour of existing building walls, and on the other hand to propose an integrated index to evaluate at the same time such performances, for existing and new walls.

The first part presents a collection of heavy and light walls, for which thermal transmittance and apparent sound reduction index were chosen as representative parameters for the definition of thermal and acoustic characteristics. Then the second part of the paper is devoted to describe a wall classification system based on a new integrated index. The performance evaluation is a weighted percentage based on the improvement potential of each analysed parameter, considered as weighted percentage.

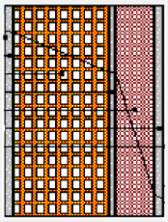
The integrated index has been studied with the purpose to give a simple instrument which can be used in building design to achieve the expected thermal and acoustic quality just evaluating a single number.

The integrated index allows to understand immediately if the wall fits, or not, acoustic and thermal requirements, in conjunction with the limiting values provided by current technical standards and laws.

WALLS DESCRIPTION

In order to develop a whole description and analysis of the integrated index, ten different kind of walls have been considered. They are characterized with different insulation levels and by various acoustic performances. Moreover, five of them can be considered heavy walls (hereafter labelled as H_1, H_2, H_3, H_4, H_5) and the remaining five can be considerate light components (hereafter labelled as L_1, L_2, L_3, L_4, L_5). In this way the set of chosen partition is representative of the more widespread kind of walls in Italy, but also in many other foreign countries. The composition of each wall is shown in Tables from 1 to 4.

Table 1. Wall L_1 and L_2.

Wall	Material	Thickness [cm]	22 cm
L_1	Plaster	1.5	
	Perforated brick	12.0	
	Mortar	1.0	
	Mineral wool	6.0	
	Plaster and finish	1.5	

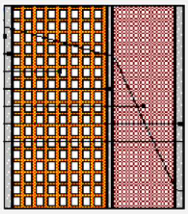
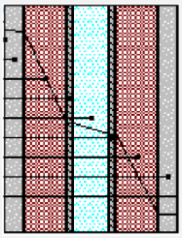
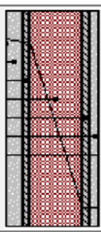
Wall	Material	Thickness [cm]	26 cm
L_2	Plaster	1.5	
	Perforated brick	12.0	
	Mortar	1.0	
	Mineral wool	10.0	
	Plaster and finish	1.5	

Table 2. Wall L_3, L_4 and L_5.

Wall	Material	Thickness [cm]	25 cm
L_3	Plaster and finish	3.0	
	Mineral wool	6.0	
	Prop	1.0	
	Air cavity	5.0	
	Prop	1.0	
	Mineral wool	6.0	
	Plaster and finish	3.0	

Wall	Material	Thickness [cm]	15 cm
L_4	Plaster and finish	2.5	
	Prop	1.0	
	Mineral wool	8.0	
	Prop	1.0	
	Plaster and finish	2.5	

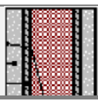
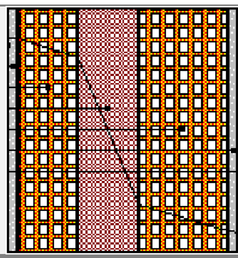
Wall	Material	Thickness [cm]	12.5 cm
L_5	Plaster and finish	2.5	
	Prop	1.0	
	Mineral wool	6.0	
	Prop	1.0	
	Plaster and finish	2.0	

Table 3. Wall $H_1$and H_2.

Wall	Material	Thickness [cm]	31 cm
H_1	Plaster	1.5	
	Perforated brick	8.0	
	Glass wool	8.0	
	Perforated brick	12.0	
	Plaster	1.5	

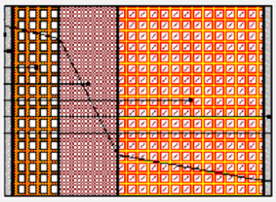
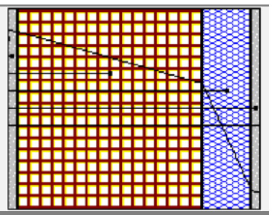
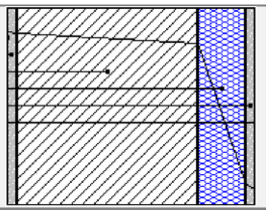
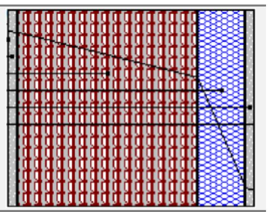
Wal l	Material	Thi-ckness [cm]	46 cm
H_2	Plaster	1.5	
	Perfo-rated brick	8.0	
	Glass wool	10.0	
	Wall block	25.0	
	Plaster	1.5	

Table 4. Wall H_3, H_4 and H_5.

Wal l	Material	Thi-ckness [cm]	41 cm
H_3	Plaster	1.5	
	Insulated brick	30.0	
	Polysty-rene	8.0	
	Plaster	1.5	

Wal l	Material	Thi-ckness [cm]	39 cm
H_4	Plaster	1.5	
	Concrete	30.0	
	Polysty-rene	6.0	
	Plaster	1.5	

Wal l	Material	Thi-ckness [cm]	39 cm
H_5	Plaster	1.5	
	Thermal brick	30.0	
	Polysty-rene	6.0	
	Plaster	1.5	

L_1 and L_2 walls are characterized by perforated brick and different thickness of mineral wool insulation (6 and 10 cm respectively, see Table 1). L_3 wall presents a 5 cm air cavity between 6 + 6 cm of mineral wool. L_4 and L_5 walls are lighter (15 and 12.5 cm, respectively, see Table 2). This set of walls allows to illustrate the usefulness of the proposed integrated index. Concerning with heavy components, H_1 wall is composed by perforated brick (8 + 12 cm) with 8 cm of insulation, instead of H_2 wall which is characterized by a thick wall block and 10 cm of glass wool (see Table 3). H_3, H_4 and H_5 walls have external insulation and the structural part is composed by insulated brick, concrete and thermal brick, respectively (see Table 4).

Thermal and acoustic characteristics are summarized in Table 5. Representative parameters are thermal transmittance and apparent sound reduction index. The indicated values for the apparent sound reduction index have been obtained by laboratory tests and measurements.

Table 5. Thermal and acoustic parameters for the ten selected walls.

Wall	***U*** [W/(m^2 K)]	$\boldsymbol{R_w}$ [dB]
L_1	0.51	52.0
L_2	0.34	54.0
L_3	0.28	60.0
L_4	0.41	56.0
L_5	0.52	54.0
H_1	0.37	51.0
H_2	0.26	52.0
H_3	0.31	58.0
H_4	0.38	47.7
H_5	0.30	49.2

INTEGRATED INDEX DESCRIPTION

One of the main difficulties in building design is to be able to recognise, in an easy and immediate way, if a wall can fit desired thermal performances and at the same time acoustic requirements or limits. The physical main parameters that describe such kind of characteristics are the thermal transmittance and the apparent sound reduction index. The two parameters have different scales, misure units and different nature. The thermal transmittance is the rate of transfer of heat through one square metre of a structure divided by the difference in temperature across the structure (it is expressed in watts per square metre per kelvin, or W/(m²K)).

The second one is an index, expressed in decibel, that drops a bit a physical meaning in order to express in only one number the ability of a partition to reduce the sound energy. The apparent sound reduction index looses information about the behaviour of wall at the different frequencies but allows to fix law limits easily and allows the first step of design. Designers use the apparent sound reduction index for the first evaluation of the different prefabricated partitions or for the choice of the materials of the layers that compose walls, in order to choose something that will fit the acoustic requirements. For the present work an integrated index was developed with a similar purpose: to propose a simple method that allows for an immediate comparison between different walls. The aim is to create an user-friendly instrument useful for the first evaluation of walls and partition from both the principal points of view: the acoustic one and the thermal one. With only one number designers can choose the best solution for the requirements. The integrated index proposed in this work combines the two parameters, thermal transmittance and apparent sound reduc-tion index in a proper mode in order to obtain a number than can help in judgement of wall performances.

The creation of the index is quite easy. The first thing to do is to choose some limits which represent a set of reference values U_{lim} and $R_{\mathrm{w,lim}}$ to compare to the actual value of the thermal transmittance U and the apparent sound reduction index R_{w} of the considered wall type, respectively. There are many different possible choices for the reference values: one of them is to adopt the limits provided by national or international laws or technical standards, and this is the way followed by the authors.

The reference values U_{lim} for the thermal transmittance are reported in Table 6 and they were set corresponding to the limits provided by the Italian law in force. Such limits depend on the climatic zone, on the final use of the building, and on the ratio between thermal dispersion surface area and volume of the building. For the apparent sound reduction index the set of limiting values $R_{\mathrm{w,lim}}$ doesn't belong to a law, but was chosen by a draft standard regarding acoustic classification of buildings that is going to be approved and becoming a standard norm. These reference values are reported in Table 7 and in the next paragraph there's a short explanation of the draft norm.

Starting from the limiting reference values for the thermal transmittance, a parameter a is calculated, which represents the gap between the actual value of the thermal transmittance and the corresponding limit, and is divided by it. In a similar way a second parameter b is derived by calculating the gap between the actual apparent sound reduction index and its limit $R_{\mathrm{w,lim}}$, divided by that reference value.

The integrated index is a score that transposes the percentage of improvement or worsening of wall behaviour related to the fixed set of limits, both for thermal transmittance and for apparent sound reduction index at the same time. Denoting with U the thermal transmittance and with R_{w} the apparent sound reduction index, the procedure to obtain the integrated index is the following:

$$a = 100\,\frac{U - U_{\mathrm{lim}}}{U_{\mathrm{lim}}} \tag{1}$$

$$b \;=\; 10\;\frac{10^{R_w/10} - 10^{R_{\mathrm{w,lim}}/10}}{10^{R_{\mathrm{w,lim}}/10}} \tag{2}$$

$$\begin{cases} \text{if} \quad a \ge 0 \quad \text{and} \quad b \ge 0 \quad \rightarrow \quad x = a + b \\ \text{if} \quad a < 0 \quad \text{and} \quad b < 0 \quad \rightarrow \quad x = a + b - 1 \\ \text{if} \quad a < 0 \quad \text{and} \quad b \ge 0 \quad \rightarrow \quad x = \dfrac{a}{|a| + b + 1} \\ \text{if} \quad a \ge 0 \quad \text{and} \quad b < 0 \quad \rightarrow \quad x = \dfrac{b}{|b| + a + 1} \end{cases} \tag{3}$$

where U_{lim} and $R_{\mathrm{w,lim}}$ are the limiting value, as defined in the next paragraph, for thermal transmittance and apparent sound reduction index, respectively and x is the integrated index.

Note that the function is strictly monotonically increasing and will return zero only if both parameters are exactly those of the limits. If only one of the two parameters doesn't respect the corresponding limit, the integrated index is negative, but it cannot be less than –1. The index is positive if both parameters respect the limits, instead if both parameters don't respect limits, the index is negative and less than –1. In the range between zero and +∞ the function increases proportionally to the percentage of performances. In the range between –1 and $-\infty$ the function trend is proportional to the percentage of worsening.

Chosen limits

In Italy there are six different climatic zones (labelled with capital letters from A to F: the A zone is the warmer one, in the South, while the F zone is the colder, typical of the Alps). The northern part of the country is quite continental, while the southern part is rather hot. Thus Italian law defines different thermal transmittance limits for each climatic zone, in order to guarantee a good insulation for the building envelope [1], [2]. For walls there are six different limits, each one related to a particular climatic zone; their values are reported in the following table.

In order to respect the law, the transmittance value must be equal or less than the fixed corresponding limit. Figure 1 represents thermal transmittance values for the ten considered wall types, with respect to the selected limits.

Table 6. Italian thermal transmittance limits.

Climatic zone	Wall *U* limit [W/(m^2 K)]
A	0.62
B	0.48
C	0.40
D	0.36
E	0.34
F	0.33

Note that all the wall are well insulated, but only four of them (three heavy walls and one light wall) respect the more restrictive limit vale for the thermal transmittance in the F zone, while the reference value for the A Zone is always respected.

Even if limiting values for the thermal transmittance were chosen among those imposed by the Italian law, in the case of the acoustic reference values some technical standard limits were preferred. In Italy there's an existing law (DPCM December 5, 1997) that provides apparent sound reduction index limits for new and refurbished buildings. Those limits vary only in function of the building final use and should be verified with appropriate measurements on finished buildings. But a new norm is going to be approved [3], so that the existing Italian law and the European directive 2002/49/CE will match. That norm introduces a new building classification with new limits, based on the acoustic insulation. Maybe, in the future, this approach will be integrated within the energy evaluation of buildings in order to obtain an integrated classification, and the presented index could be useful for that purpose. Thus, for the presented integrated index, the authors chose the set of limits embodied in the new standard, rather than those provided by the existing law.

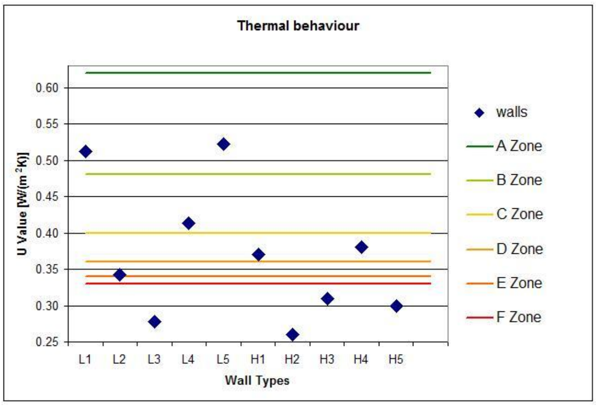


Figure 1. Thermal behaviour of the analised walls.

In the new standard every part of the building is classified in four classes, on the base of the acoustic behaviour, from the first (the best one) to the fourth (the worst one). The following table shows these apparent sound reduction index limiting value related to each class.

Table 7. Italian apparent sound reduction index limits.

Building class	Wall R_w limit [dB]
I	56
II	53
III	50
IV	45

Figure 2 shows the apparent sound reduction index values for the selected ten wall types in comparison to the four classes.

In this case limits are respected if the wall apparent sound reduction index value is equal or higher than the $R_{w,lim}$ value that characterizes the class.

The graph shows that light walls are characterized by an acoustic medium-good answer, while the heavy ones have a worse behaviour. Anyway there are only three components of the ten types (one heavy wall and two light walls) in the first class, but all of them satisfy at least the limit of the fourth class.

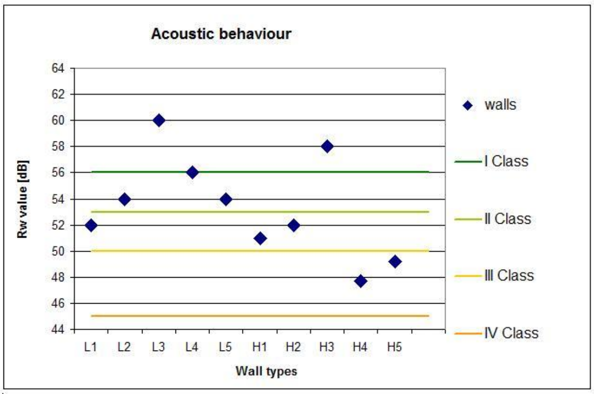


Figure 2. Acoustic behaviour of the analised walls.

Analysing both graphs at the same time, it is possible to know how many walls respect the limits, but it is not easy to give a judgment between two different possible kinds of wall, especially if both respect just one of the two required limits. The purpose of the integrated index is precisely to provide an efficient tool to take into account at the same time both the acoustic performance and thermal behaviour of a wall, in order to judge its quality and if it fits or not design requirements or law limits.

The next section is devoted to the illustration of the performances and classification determined by the application of the integrated index above to the set of ten wall types presented in this paper.

INTEGRATED INDEX CALCULATION

For each of the selected wall, the value of the integrated index was calculated by choosing, one at the time, a climatic zone and by varying the acoustic class requirements. In this way it is possible to evaluate whether every analysed wall fits both the thermal and the acoustic requirements or not.

In the following example a step by step calculation of three of the ten wall types is reported. The hypothesis is that the three solutions have to be embodied in a in a first acoustic class building located in an F climatic zone, so the limits on thermal transmittance and apparent sound reduction index are the following:

- U_{lim} = 0.33 W/(m^2 K)
- $R_{w,lim}$ = 56 dB

In the first case the labelled H_3 heavy solution is considered. Its thermal transmittance and apparent sound reduction index, shown in table 5, are respectively 0.31 W/(m^2 K) and 58 dB. So the two parameters *a* and *b* will be:

$$a = 100\frac{0.33 - 0.31}{0.33} = 6.06 \tag{4}$$

$$b = 10\frac{10^{5.8} - 10^{5.6}}{10^{5.6}} = 5.85 \tag{5}$$

in this case both the parameters are positive, so the integrated index value will be the sum of them:

$$x = a + b = 6.06 + 5.85 = 11.91 \tag{6}$$

In the following calculation the L_4 wall will be shown in order to explain what happens if one of the two limits is not respected. Because L_4 U value is 0.41 W/(m^2 K) and L_4 R_w value is 56 dB the parameters *a* and *b* will be:

$$a = 100\frac{0.33 - 0.41}{0.33} = -25.45 \tag{7}$$

$$b = 10\frac{10^{5.6} - 10^{5.6}}{10^{5.6}} = 0 \tag{8}$$

in this case only one parameter isn't negative, so the integrated index will be calculated according to (3) so its value will be:

$$x = \frac{-25.45}{|-25.45| + 0 + 1} = -0.96 \tag{6}$$

For L4 wall type the integrated index value is nearby –1. That result denotes not only that one of the two parameter does not respect the limit but also that the gap between the actual value of that parameter and its limit is considerable.

The last calculation regards the L2 wall which is characterised by a thermal transmittance value of 0.34 W/(m^2 K) and an apparent sound reduction index of 54 dB. Both parameters do not respect the limits and this is reflected by *a* and *b* values:

$$a = 100\frac{0.33 - 0.34}{0.33} = -3.94 \tag{9}$$

$$b = 10\frac{10^{5.4} - 10^{5.6}}{10^{5.6}} = -3.69 \tag{10}$$

Both the *a* and *b* parameters are negative, so the integrated index value will be:

$$x = -3.94 - 3.69 - 1 = -8.63 \tag{11}$$

The calculation was repeated for the second acoustic class and the results of the integrated index are shown in Table 8:

Table 8. Acoustic classification.

Wall	I	II
L2	–8.63	–0.52
L4	–0.96	–0.70
H3	11.91	27.68

In Figure 3 there is a graph that shows the integrated index trend related to the acoustic class variation.

The H_3 solution is obviously the best one. But it is interesting to observe that the integrated index allows to judge the L_4 wall type better than the L_2 kind when the building is in the first acoustic class, but if the second class is considered, the integrated index shows that the L_2 solution would fit better than L_4 does the requirements.

In Table 9 and 10 the results obtained for two of the most interesting climatic zones (the F one and the C one) are reported. To improve readability, the cells with values between 0 and –1 are coloured in light grey. Negative values lower than –1 are written in darker cells and all negative values are highlighted in Italic. From Table 9, it is apparent that in the F climatic zone there are only two solutions that respect both the thermal transmittance and apparent sound reduction index limits for all the acoustic classes.

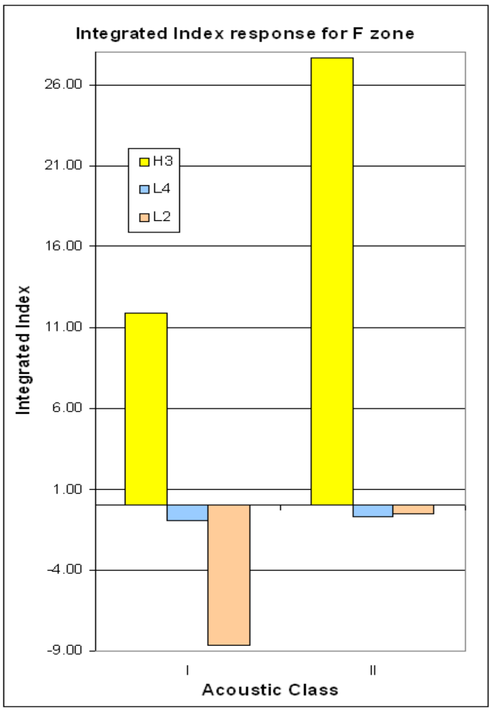


Figure 3. Integrated index response for F zone.

Table 9. Integrated index value for F climatic zone.

	Acoustic classification			
Walls	I	II	III	IV
L1	*–62.17*	*–58.21*	*–0.89*	*–0.57*
L2	*–8.63*	*–0.52*	*–0.20*	*–0.05*
L3	30.88	55.88	105.76	321.99
L4	*–0.96*	*–0.70*	*–0.45*	*–0.18*
L5	*–62.87*	*–0.94*	*–0.78*	*–0.45*
H1	*–19.96*	*–16.81*	*–0.77*	*–0.28*
H2	*–0.21*	*–0.08*	27.06	61.33
H3	11.91	27.68	59.16	195.59
H4	*–24.67*	*–23.20*	*–20.26*	*–0.61*
H5	*–0.44*	*–0.37*	*–0.14*	25.33

Table 10. Integrated index value for C climatic zone.

	Acoustic classification			
Walls	I	II	III	IV
L1	*–35.02*	*–31.06*	*–0.80*	*–0.41*
L2	*–0.19*	16.84	29.37	83.68
L3	45.62	70.62	120.50	336.73
L4	*–0.78*	*–0.24*	*–0.10*	*–0.03*
L5	*–35.19*	*–0.89*	*–0.65*	*–0.30*
H1	*–0.45*	*–0.30*	10.09	37.31
H2	*–0.14*	*-0.05*	40.85	75.12
H3	28.35	44.12	75.60	212.03
H4	*-0.59*	*-0.54*	*-0.41*	13.62
H5	*-0.23*	*-0.18*	*-0.06*	41.24

But if the lowest acoustic performance is admitted for the building (IV class) the number of good solutions increases to four.

In Table 10 the results of the index calculation for the C zone are summarised. In this case it is interesting to compare index values between the two tables in order to underline the fact that some solutions do not fit acoustic and thermal requirements for the F climatic zone, but they do it for the C climatic zone.

From the comparison between the two tables it’s clearly visible that most of the values which are lower than –1 in the first table, increase and turn into values included between 0 and –1 in the second table. This is due to the fact that the thermal transmittance limit for the C zone is more permissive than the corresponding one for the F zone. Indeed for the C climatic zone in the fourth acoustic class almost all the walls have an acceptable acoustic and thermal response. Finally, seven wall types present a positive index value so all those solutions would be acceptable in this case.

It follows that it is easy to make a wall classification, analysing the integrated index results. In particular a graphical representation can help for an immediate evaluation among the different solutions. In Figure 3 the behaviour of the seven wall types with acoustic and thermal characteristics that fit the C zone and the fourth acoustic class is shown.

The graph shows that wall L_1 is the best solution followed by the H_3 wall. It’s interesting to observe that if the building is in the third class then the H_2 solution is better than the L_2 one, but if the building is in the fourth class the judgment would be the opposite. In the fourth class the H_5 solution is more interesting that the H_1 one even if in the third class the H_5 solution isn’t even acceptable. In Table 10 the results of the index calculation for the C zone are summarized. In this case it is interesting to compare index values between the two tables in order to underline the fact that some solutions do not fit acoustic and thermal requirements for the F climatic zone, but they do it for the C climatic zone.

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From these analysis it is apparent that that kind of judgement wouldn’t be so simple if the R_w and U values were evaluated separately. Therefore the integrated index offers a simple instrument to indicate thermal and acoustic quality of a wall with just one meaningful number.

CONCLUSIONS

A new method to judge thermal and acoustic performances for walls has been proposed in this paper. Today the worldwide attention to acoustical comfort and building efficiency is increasing e many laws are elaborated that introduce specific requirements for minimum wall performances. In this work ten wall types were presented and were evaluated from both the acoustic and thermal behaviour. Also an integrated index was presented.

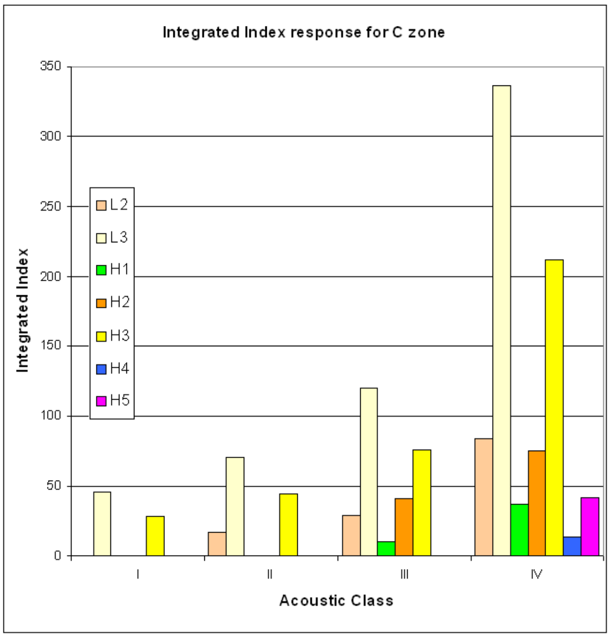

Figure 3. Integrated index value for C climatic zone.

The integrated index takes into account two significant parameters by this point of view: the thermal transmittance and apparent sound reduction index and it combines those values through the calculation of a single parameter which allows to easily and immediately judge both thermal and acoustic quality of a wall. Moreover it allows, during the building design stage, to choose the more convenient between different solutions.

REFERENCES

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