Energy and acoustic performances of windows and their correlation

N. Granzotto[1], F. Bettarello[2], A. Ferluga[3], L. Marsich[3], C. Schmid[3], P. Fausti[4], M. Caniato[3,4*]

[1] Industrial Engineering Department, University of Padova, Via Gradenigo, 6/a - 35131 Padova, Italy
[2] AcusticaMente Designers Team, via Garibaldi 13/b, 31015 Conegliano (TV), Italy
[3] Engineering and Architecture Department, University of Trieste, via Valerio 6/a, 34127 Trieste, Italy
[4] Department of Engineering , University of Ferrara, via Saragat 1, 44122 Ferrara, Italy

* corresponding author: mcaniato@units.it

Abstract

Buildings are designed and constructed to use their external envelope to protect people during living, working and sleeping. Nevertheless, although there are several studies on opaque wall insulation, which could reach very good insulating performances, limited research has focused in detail on sound and thermal insulation on transparent elements like windows.

This work analyses these aspects and investigates the effects of every single part of windows like frame, glazing thickness, overall transparent thickness, PVB presence, and so on. The relation between sound and thermal insulation is investigated too. Results show how single components won't influence global thermal insulation whereas acoustic performances are affected by unique constituent. No global relation between thermal and acoustic insulation values was established and finally a new prediction equation for single number sound insulation is proposed.

1 Introduction

High thermal and acoustic insulation as well as air tightness of buildings are needed in order to ensure good living conditions inside dwellings. Many studies have been carried out during recent years, because the performances of the external components of the buildings are the basis of energy saving **Errore. L'origine riferimento non è stata trovata.-Errore. L'origine riferimento non è stata trovata.**, inner comfort **Errore. L'origine riferimento non è stata trovata. - Errore. L'origine riferimento non è stata trovata.** and possible shape and realization solutions **Errore. L'origine riferimento non è stata trovata.**.

Nevertheless, on this topic many other in-depth studies are necessary because these vertical or horizontal partitions are not homogenous and composed by many other big or small components like opaque wall, glazing, air inlet systems, traditional or peculiar shapes and projections.

The performances of opaque vertical and horizontal parts are simple to analyse. The addition of thermal insulation or resilient layers [10], air and water insulations sheaths, aerogel-based finishing **Errore. L'origine riferimento non è stata trovata.**, **Errore. L'origine riferimento non è stata**

trovata. or paintings **Errore. L'origine riferimento non è stata trovata.** are used to improve or restore building technologies.

Thermal insulation of walls, floors and roofs has reached its best performances since the thermal insulation layers have become very thick, **Errore. L'origine riferimento non è stata trovata.**. However an increase in the thickness over 28–30 cm ofa good insulating material (typically with a thermal conductivity< 0.035 W/mK) will not result in further energy saving. Projections are very useful to protect the building from hot sunny weather. They are necessary for sun radiation reduction and help to limit the use of air conditioning [15–17]. On the other hand, glazed windows present different issues to solve. They are an openable component (for natural ventilation) and, as the air tightness may not be perfect, this implies poor thermal and acoustic protection. Moreover, the presence of a see-through component is necessary in order to obtain natural daylight [18]. It is evident that the study of this latter element is very important, due to its particular performances as “barriers” and “holes” at the same time. The European Directives, as well as the Kyoto protocol, invite designers to improve the performances of buildings, in order to increase indoor comfort and energy savings [1]. Such buildings require important design efforts in terms of choice of materials, shape and orientation, global environmental analysis and evaluation of the needs of future occupants. For these reasons, precise and robust technical information about all the products is essential for final result. Window, as a market product, is growing [8], both industrially and technologically. In the 1990s it was almost impossible to find windows with more than double glazing, laminated glass, different type of gas in the cavity, etc. In addition, in recent years it has been possible to find different applications for distinct technologies like thermal [19–26] or acoustic [27,28] insulation.

Window producers always advertise their products as the best ones for acoustic, thermal, lighting, and environmental performances. Concerning this latter factor, a very interesting paper was published [29] where the three principal types of materials and coupling were analysed. The study concludes that wooden windows are the best and the PVC ones are the worst in terms of global environmental pollution, taking into account production methods, life cycles and recyclability. Nevertheless, the study does not take into account possible performances obtainable with these materials.

Glazing has been studied both as single layer glass [30] and as laminated with or without PVB (PoliVinylButyral) [31] and as primary sample [32]. The two parameters globally considered as representative of window performance are sound reduction index R and thermal transmittance Uw.

The former, which represents the global window impedance opposed to sound propagation, can be both measured and calculated (see section 2.1).

The measures are carried out in laboratories according to ISO standards series 10140 [33]. As shown in Fig. 1, the test centre is constituted of two acoustically independent rooms and the sample is included in a high performance filler wall placed in the middle of the laboratory.

Figure 1 – a typical test set-up

The measurement technique avoids flanking transmission and tries to limit workmanship effects; therefore, the results of these measurements can be used both to compare and to choose products for final destination in buildings. Sound reduction index R is requested for the overall standardized sound level difference of fac¸ade D2m prediction (see section 2.1 for details).

Prediction methods are available in international standards [34–36]. Nevertheless, they are able to only forecast Rw weighted sound reduction index levels up to 38 dB or they request the laboratory measured value of primary glass samples.

In the first case, the obtained values are too low to be used in present-day buildings; this method could be suitable in the past when the glazing was very simple (e.g. 4/12/4). Nowadays, this element has improved a lot its thermal and acoustical performances adding PVB layers, laminated glasses, one or more gas gaps and so on. In the second case a laboratory test is needed and consequently few advantages could be gained, since a laboratory test has to be performed in any case.

Consequently, sound reduction index has to be measured, but single results will not show why a specific window has a particular performance, since no mathematical and parametrical model is available [39].

Instead, thermal transmittance can be both measured with laboratory tests or easily calculated using international standard methods (see paragraph 2.2). It represents the global resistance windows would be able to oppose to thermal energy diffusion in cold weather conditions. It is very useful both to compare products and to evaluate energy saving in buildings.

On the other hand, it does not take into account workmanship effect and hot weather conditions since it considers only conductivity (λ [W/mK]) and area parameters (S_i [m^2]) of single components such as glass, frame, type of material and length of the glass seal.

Moreover, acoustical and thermal energy performances of windows are in some way obtained with the same procedures: air tightness and multiple component and layer coupling. Therefore a possible correlation between the two parameters could be investigated and would be greatly appreciated both in research and design.

The aim of the present work is to analyse in detail the relevant literature and then to study windows constituted with different acoustical and thermal insulation characteristics in order to understand if a connection between them may exist, which is the best technology (if any) and finally if there is a possible formulation for the prediction of the sound insulation, in order to avoid laboratory tests in the former step.

Starting from acoustic laboratory results, R and U_w results were analysed and compared in order to understand if there is any connection between their variation and window dimensions, number and type of glazing, cavity number and width, etc.

2. Materials and methods

Over than 45 different kind of windows have been studied and analysed (Table), characterized by diverse construction technologies, in order to investigate performances issues and understand their acoustic and thermal behaviours.

Frames are realized mostly with three different raw materials:

- Wood
- Aluminium
- PVC.

2.1 Sound reduction level

The windows are usually the weakest part of the façade sound insulation. This fact is due to their inner nature of mobile, openable and mountable component, causing a leakage in the external structure and a possible performances loss.

Standardized level difference of façade is a major topic of several studies **Errore. L'origine riferimento non è stata trovata.-Errore. L'origine riferimento non è stata trovata.**. The final predicted value ($D_{2m,nt}$) is calculated with the methods described in international standard **Errore. L'origine riferimento non è stata trovata.** according to equation (1):

$$D_{2m} = R' + 10\log\left(\frac{V}{6 \cdot T_0 \cdot S}\right) + \Delta L_{fs} \qquad (1) \qquad \text{(dB)}$$

where:

V is the volume of the receiving room [m^3]

R' is the composite sound reduction index (dB)

T_0 is the reference reverberation time equal to 0.5 s

S is the total area of the façade as seen from the inside [m^2]

ΔL_{fs} is the level difference due to façade shape (dB)

The apparent sound reduction index is calculated according to equation (2)

$$(2) \qquad R' = -10\log\left(\sum_{i=1}^{n}\frac{S_i}{S}10^{\frac{-Ri}{10}} + \frac{A_0}{S}\sum_{i=1}^{n}10^{\frac{-Dn,e,i}{10}}\right) - K \qquad \text{(dB)}$$

where:

S_i is the area of the single component of the façade [m^2]

R_i is the sound reduction of the single component of the façade (dB)

$D_{n,e,i}$ is the element normalized sound level difference for a small building element (dB)

A_0 is the reference area equal to 10 m^2

K is the flanking transmissions (dB)

Thus, this method requires the knowledge of sound reduction index values R_i of all the single components, i.e. opaque and transparent as well as the $D_{n,e}$ value. For the first ones, many calculation techniques are available **Errore. L'origine riferimento non è stata trovata.-Errore. L'origine riferimento non è stata trovata.**.

On the other hand, no empirical models, tabular data, provisional formula or mathematical models are offered for windows so far, extended to contemporary usable values (R_w > 38 dB) or stratigraphy. The standards **Errore. L'origine riferimento non è stata trovata.** provides only models up to $R_i \approx 38$ dB, as mentioned before; these values are nowadays too low to be used in standard buildings constructions. Databases on primary glass sample laboratory measurements are rare, approximated and with very few references **Errore. L'origine riferimento non è stata trovata.**.

So it is very difficult to estimate with a good and robust process the sound reduction index of façades.

In order to study if some components may influence final values some comparisons were analysed (see paragraph 3). Refer to Table 1 for the symbols used in Figure 7 to Figure 12

Table 1 – legend of symbol for Figure 7 -Figure 12

Symbol	Reference
*	PVB layer
**	Double PVB layer
‘	Double gas inlet

In order to analyse robust results, this investigation is based in first step on sound reduction index values obtained from 5 different laboratories in Europe with all the same features and accredited for ISO 10140 **Errore. L'origine riferimento non è stata trovata.** tests (Sound Reduction R).

Then the weighted sound reduction index R_w, calculated using standard ISO 717-1 **Errore. L'origine riferimento non è stata trovata.** proposed method, is used in order to evaluate and compare different solution.

2.2 Transmittance value

Windows turn up to be a weak component from thermal insulation point of view. For this reasons, the energy passing through this element both in cold and in hot climate must be restricted and limited. In last years many efficient components, such as thermal insulating spacers, low emitting glasses, thicker and multiple inlets, gasses insertion like argon or xenon, were added (Figure 2). This process implied a very good thermal performances achievement, but on the other hand, these technologies reached its top limits. A U_w maximum value of about 0.6 W/m^2K is now possible, with a mean value (in temperate climates) of about 1 W/m^2K.

In this work, the thermal transmittances (U_w) are calculated according to equation (3) **Errore. L'origine riferimento non è stata trovata.**,**Errore. L'origine riferimento non è stata trovata.**:

$$(3) \qquad Uw = \frac{\sum A_g U_g + \sum A_f U_f + \sum l_g \psi_g}{\sum A_g + \sum A_f} \; [W/(m^2 K)]$$

where:

U_g is the heat transfer coefficient related to the glazing $[W/(m^2 K)]$

U_f is the heat transfer coefficient related to the frame $[W/(m^2 K)]$

ψ_g is the linear heat transfer coefficient related to the insulated glazing edge seal [m]

A_g is the area of the glass $[m^2]$

A_f is the area of the frame $[m^2]$

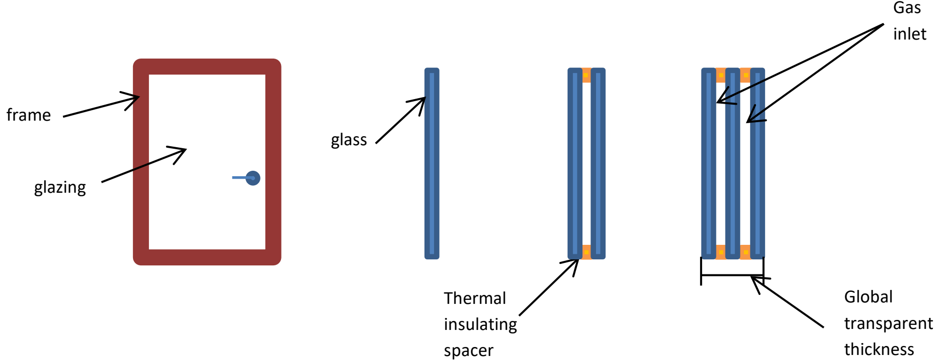

Figure 2 – Schematic representation of window.

Single, double and triple glazing front view and section

For some of the windows a comparison between calculated values and producers declarations was performed. In the 89% of the cases, the two values overlap; in other cases the worst values were considered.

2.3 Samples investigated

The acoustic performances of over 45 types of windows were tested and calculated according to ISO 10140 (standard dimension 1230 mm × 1480 mm) and to Fig. 1 for the type of sample. As it was pointless to calculate the Uw of every samples, some interesting examples were estimated according to ISO 10077 part 1 e 2 [37,38], as reported in Table 1.

Table 1 – description of the studied windows

Wood							
Code	Glazing I [mm]	Inlet [mm]	Glazing II [mm]	Inlet [mm]	Glazing III [mm]	R_w (dB)	U_w [W/m^{2}k]
1	3/PVB/3	16	4	--	--	37	1.3
2	4/PVB/4	12	4	12	3/PVB/3	38	1.1
3	4/PVB/4	14	4	14	4/PVB/4	38	--
4	6	12	4	--	--	38	--
5	3/PVB/3	16	4	16	3/PVB/3	39	0.76
6	3/PVB/3	18	4	18	3/PVB/3	39	--
7	4/PVB/4	15	3/PVB/3	--	--	39	--
8	4/PVB/4	15	3/PVB/3	--	--	39	1.3
9	5/PVB/5	15	3/PVB/3	--	--	39	1.3
10	8/PVB/9	16	6/PVB/6	--	--	39	--
11	3/PVB/3	12	4	--	--	39	--
12	4/PVB/4	16	3/PVB/3	--	--	40	1.3
13	3/PVB/3	15	5	--	--	40	--
14	3/PVB/3	15	4	--	--	40	--
15	4/PVB/4	15	3/PVB/3	--	--	40	--
16	4/PVB/4	15	5/PVB/5	--	--	40	1.3
17	4/PVB/4	9	6	--	--	40	--
18	3/PVB/3	9	3/PVB/3	--	--	41	--
19	4/PVB/4	16	4	16	4/PVB/4	41	0.9
20	4/PVB/4	16	6/PVB/6	--	--	41	1.3
21	4/PVB/4	16	6/PVB/6	--	--	42	1.3
22	4/PVB/4	14	4	14	4/PVB/4	43	0.9
23	4/PVB/4	14	4	14	3/PVB/3	43	--
24	3/PVB/3	14	6	14	3/PVB/3	44	--
25	4/PVB/4	14	4	14	4/PVB/4	44	0.8
26	6/PVB/6	12	6	12	6/PVB/6	44	0.9
27	6/PVB/6	12	6	12	4/PVB/4	44	0.9
28	4/PVB/4	15	4	15	5/PVB/5	44	--
29	4/PVB/4	14	4	14	4/PVB/4	45	0.77
30	6/PVB/6	16	4/PVB/4	--	--	47	1.3
Aluminium							

31	4/PVB/4	20	4/PVB/4	--	--	42	0.9
32	6/PVB/6	20	4/PVB/4	--	--	43	0.9
33	5/PVB/5	16	4/PVB/4	--	--	43	1.6
34	6/PVB/4	12	4/PVB/4	--	--	44	1.1
35	6/PVB/6	20	4/PVB/4	--	--	45	1.6
36	8/PVB/9	15	6/PVB/4	--	--	46	1.1
37	6/PVB/6	24	4/PVB/4	--	--	46	0.9
PVC							
38	4	22	4			35	1.3
39	6	22	4			38	1.0
40	6	20	4	20	4	40	0.7
41	4/PVB/4	20	3/PVB/3			41	1.3
42	4/PVB/4	18	4	18	3/PVB/3	43	0.7
43	4/PVB/4	18	4	15	4/PVB/4	43	0.7
44	4/PVB/4	20	3/PVB/3			44	1.3
45	6/PVB/6	18	4/PVB/4			44	1.3
46	4/PVB/4	18	4	15	4/PVB/4	45	0.7

3 Results and discussion

Using the U_w values, the single windows component influence was analysed in order to understand the influence of every single part on the final value.

The combination effect of frame (material), glass and air thickness was studied but no reliable results were obtained. Therefore they were not included and reported. The aim of these pictures is to generally compare the 3 different material frames with Uw value (Figs. 3–6) and generally compare the Rw and Uw values (Fig. 13).

In Figure 3 glass thickness compared to the U_w value is presented. Glazing itself is the most transmitting part (see Table) as it is the most extensive part in windows. Nevertheless, it is evident that this parameter does not clearly influence final thermal insulation for any frame typology. It is interesting to point out that, for all material frames, overall glass thickness could be double, but with the same U_w value.

Glazing thermal insulation is guaranteed by the low emitting treatments on glasses, as shown in Figure 4. Nevertheless, the low emitting treatment alone would not guarantee optimum thermal insulation.

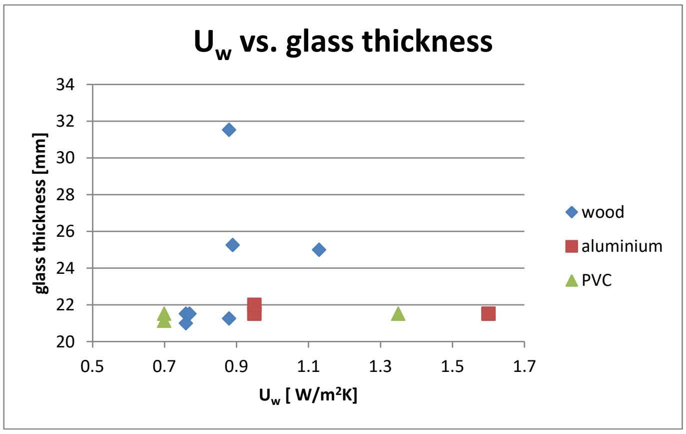

Figure 3 – comparison between U_w value and glass thickness

Table 2 – typical conductivity values for windows components Errore. L'origine riferimento non è stata trovata.

Component	λ [W/mK] **Errore. L'origine riferimento non è stata trovata.**	U [W/m^{2}K] **Errore. L'origine riferimento non è stata trovata.**
Single glass	1	5.8
Insulated aluminium frame	--	2,2-3.8
Wood frame	0.12	2.0
PVC frame	0.16	2.0

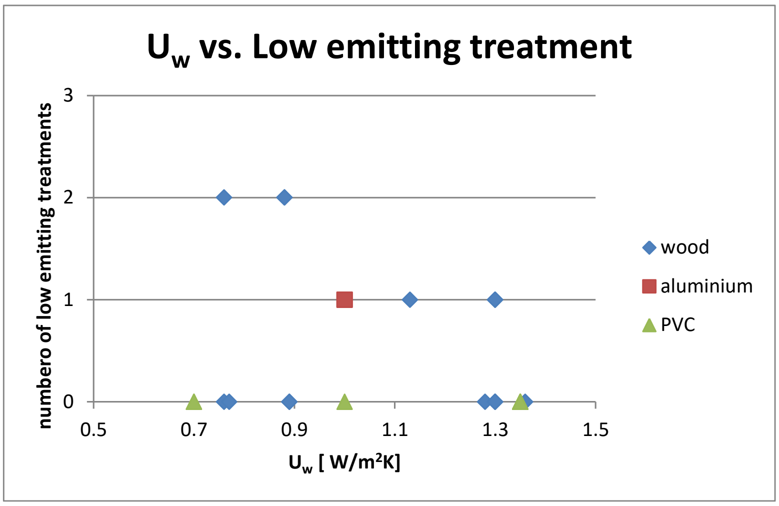

Figure 4 – comparison between U_w value and low emitting treating presence

In Figure 5 frame thickness compared to the U_w value is presented. As for the former case, no evident correlation is possible. Especially for wood frame, thickness influence is homogeneously distributed in all U_w performances.

In Figure 6 overall transparent thickness compared to the U_w value is presented. It is evident that no possible correlation could be found, since for constant transmittance values the transparent component thickness is even 80% higher.

As a consequence for all these analyses it can be concluded that no single part influences the final result but the all parts together contribute to ultimate thermal insulation performance.

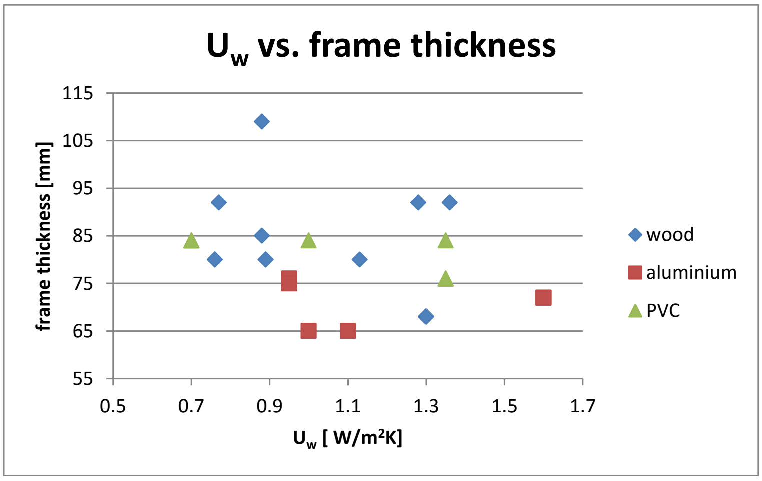

Figure 5 - comparison between U_w value and frame thickness

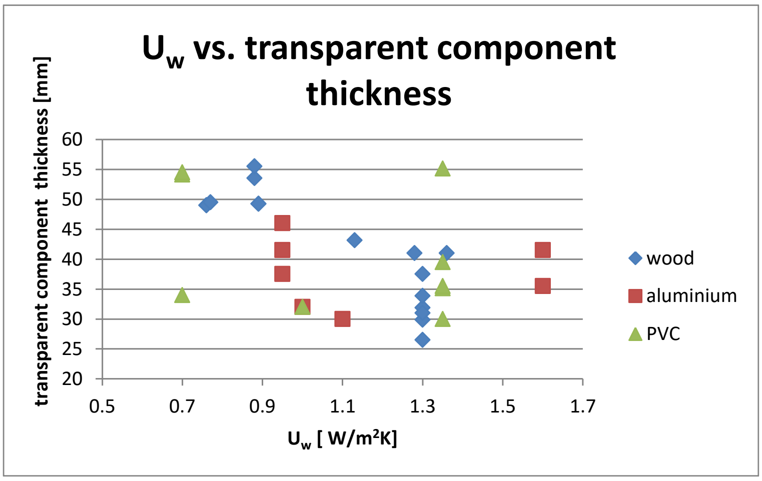

Figure 6 – comparison between overall transparent thickness and U_w value

3.1 Sound Reduction index R

Sound insulation index is of paramount importance for hearing protection. All the analysed parameters influence the R values in frequency domain. As a matter of fact different external sources have different and peculiar frequency emissions **Errore. L'origine riferimento non è stata trovata.-Errore. L'origine riferimento non è stata trovata.**. Though, window selection for buildings applications in noisy soundscapes have to consider all the possible frequency source emission ranges in order to actually reduce human exposure to annoyance and sleeping disturbance. This consideration could not be performed if only a simple index calculation is implemented using the methods proposed in international standards.

As a consequence, frequency sound reduction index R has to be studied for different material frames.

Despite U_w performances, R shows different behaviour for diverse windows technologies. Using the R values, the influence of single windows component was analysed in order to understand the influence of every part on the final value.

On the other hand, the use of R_w is necessary to quickly compare many different solution. In conclusion, both R (for designing purpose) and R_w (for comparison purpose) are essential parameters. Refer to Table 3 for the symbols used in Figs. 7–12.

3.1.1 Wooden frame

In Figure 7 gas inlet was identified as first parameter to influence $R_w < 40$ dB performances in middle frequencies. As reported in many other studies **Errore. L'origine riferimento non è stata trovata.**, **Errore. L'origine riferimento non è stata trovata.**, **Errore. L'origine riferimento non è stata trovata.**, **Errore. L'origine riferimento non è stata trovata.**, PVB presence influences coincidence effect at high frequency range (see for example sample 4 for PVB absence and samples and 11 for only one PVB layer, Figure 7).

In Figure 8 overall glass thickness was identified as second parameter to influence 40 dB $\leq R_w \leq$ 41 dB performances in middle frequencies.

In Figure 9 overall PVB thickness was identified as third parameter to influence 42 dB $\leq R_w \leq$ 48 dB performances in middle and high frequencies.

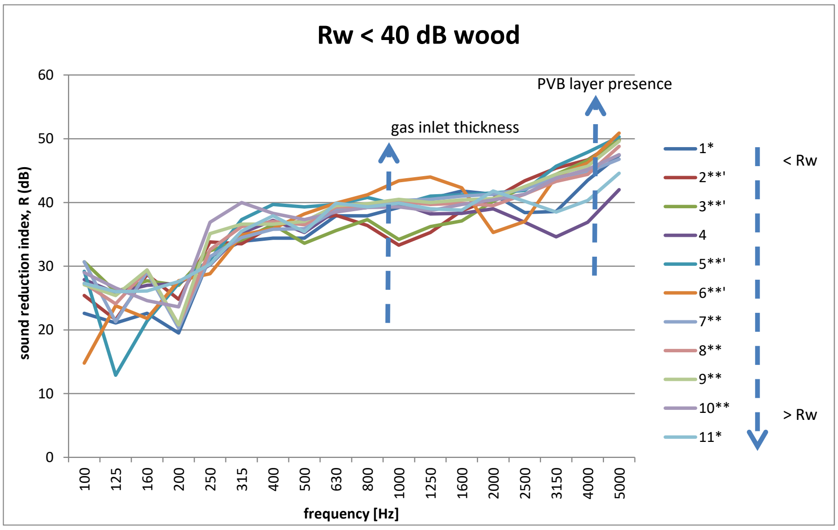

Figure 7 – influence of gas inlet thickness and PVB presence

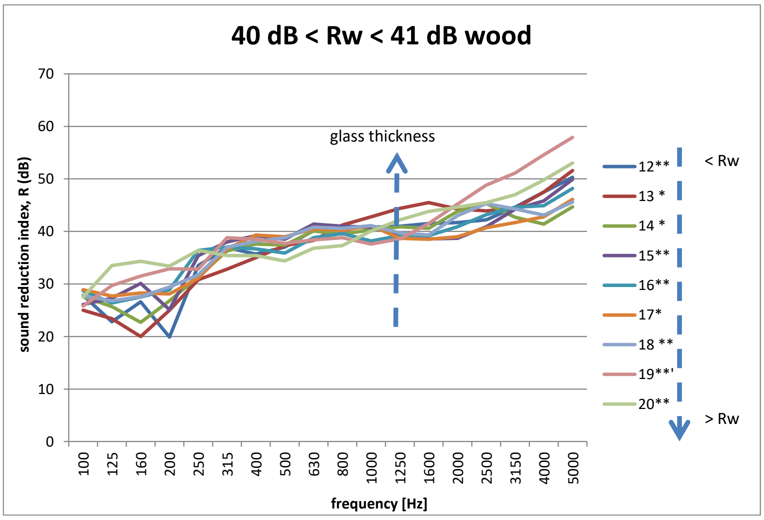

Figure 8 - influence of overall glass thickness

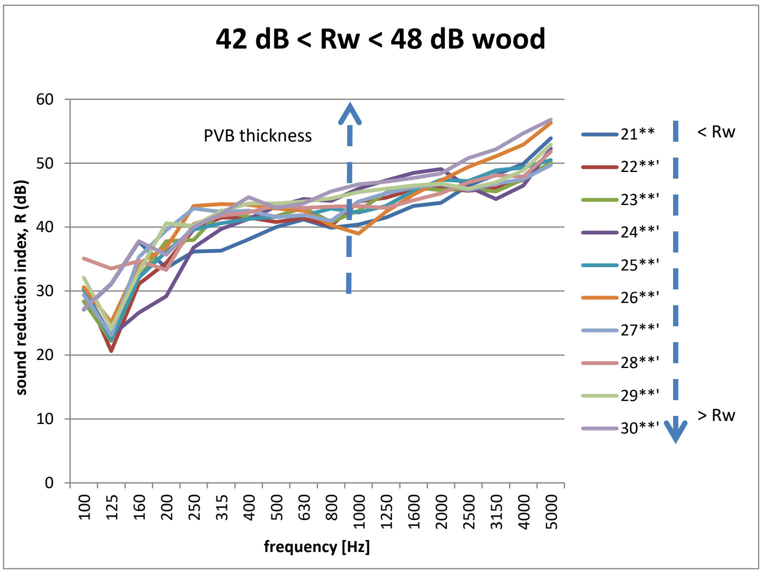

Figure 9 - influence of overall PVB thickness

3.1.2 Aluminium frame

In Figure 10 glass and gas inlet thickness influence is reported in aluminium frame. From middle – low frequency range the behaviour is almost linear and it rises when the thickness of the transparent part increases.

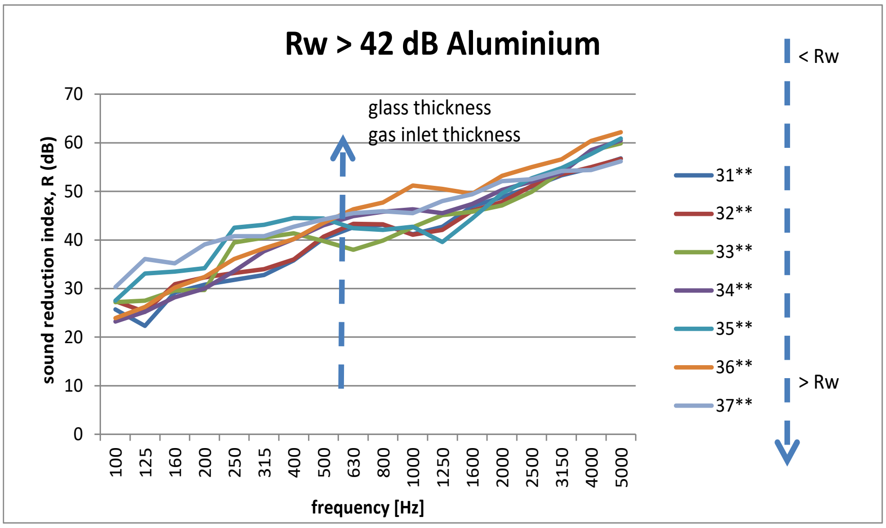

Figure 10 - influence of overall glass and gas inlet thickness

3.1.3 PVC frame

In Figure 11 jointly glass thickness and PVB presence influence is shown in PVC frame. From middle – low frequency range the performances are clearly influenced by the first issue; on the other hand the PVB presence (as for the other frame materials) modifies high coincidence frequencies.

In Figure 12 the only variable is the glass thickness, influencing low and middle-high frequencies. For 46 sample it is worthy to note that the overall structure is able to nullify both resonance and coincidence phenomena.

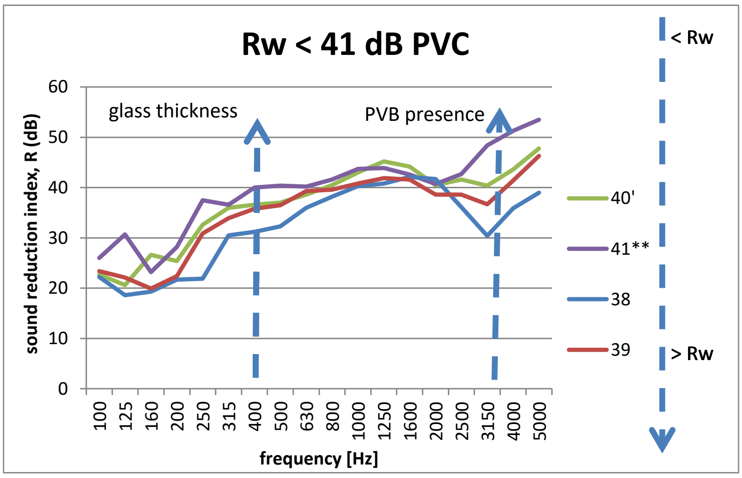

Figure 11 - influence of overall glass thickness and PVB presence

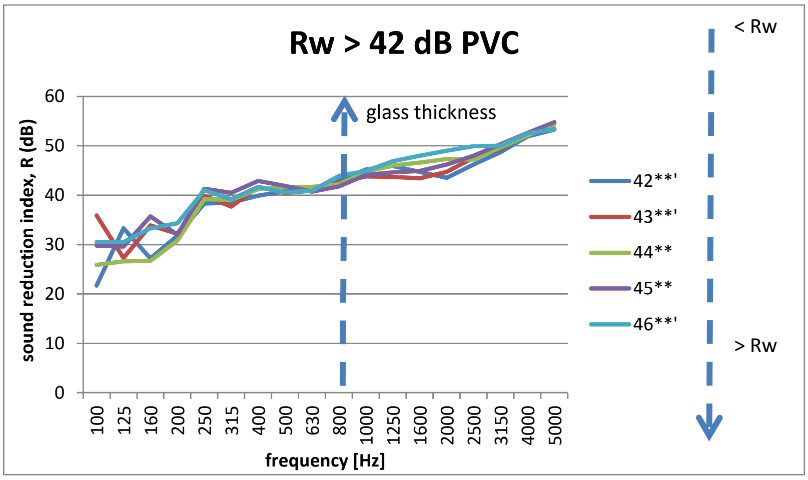

Figure 12 - influence of overall glass thickness

3.2 Thermal vs. Acoustical insulation

From previous paragraphs, it is evident that if a correlation between R and U_w would be possible it could be a great help for researchers, designers, producers and users, because of the easiness in determining those parameters [57-59].

For this reason, a comparison between the two final values was carried out. In order to compare only index results, the weighted sound reduction index R_w determined with ISO 717-1 method **Errore. L'origine riferimento non è stata trovata.** was used.

In Figure 13 the comparison between R_w and U_w values is reported. As an overall overview no direct correlation could be found: high sound insulation index values do not always correspond to low transmittance and vice versa.

So in Figure 14 the wooden frame transmittance value is kept constant while the sound reduction index is compared with overall glass thickness. Here the influence of the overall glass thickness is explicit, and once more, this parameter alone does not imply an increase in transmittance.

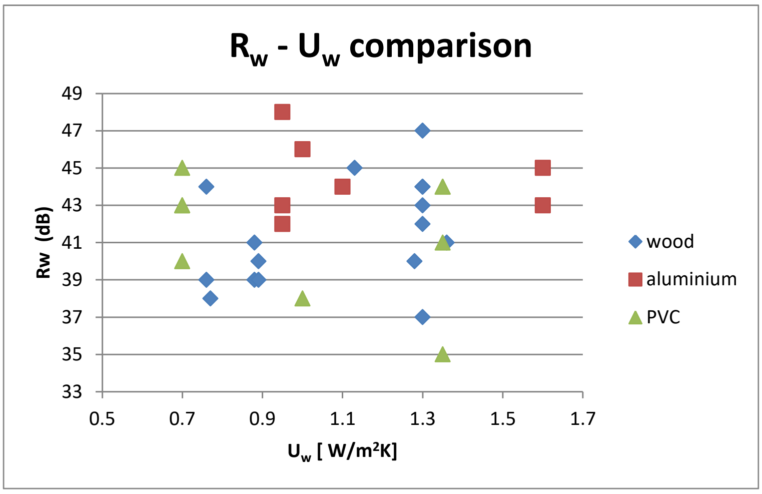

Figure 13 – R_w – U_w comparison for all windows typologies

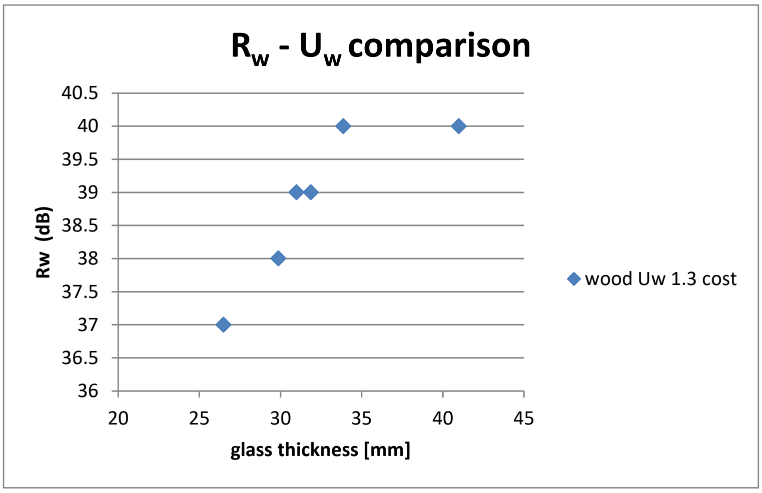

Figure 14 – R_w – U_w comparison for wooden frame at $U_w = 1.3$ W/m^{2}K

In Figure 15, for wooden frame technology, the best U_w values are kept constant, while the R_w parameter shows an increase if the PVB thickness rises. So this latter component acts only as sound insulation improvement, since overall glass thickness is irrelevant from a limit of $U_w \approx 0.9$ W/m^{2}K and $R_w \approx 41$ dB.

In Figure 16 the aluminium frame is analysed. Even if there are very few samples for this analysis, compared towooden ones, for intermediate U_w values, the overall glass thickness improves the sound insulation performances.

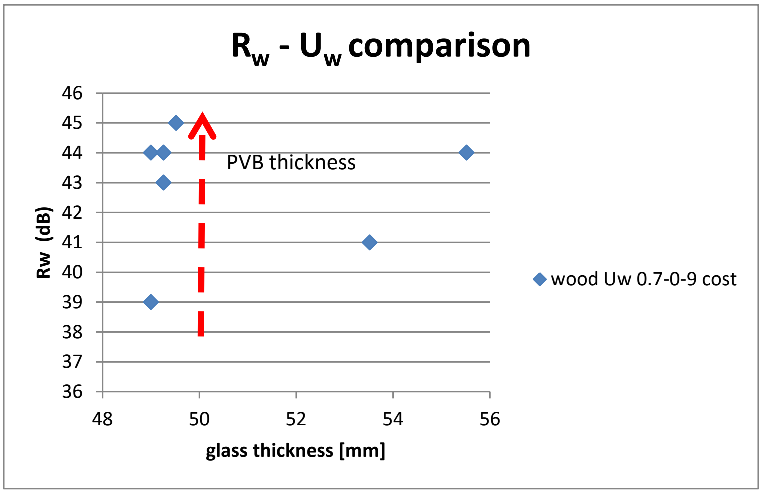

Figure 15 – Influence of PVB thickness on sound insulation improvement with U_w constant

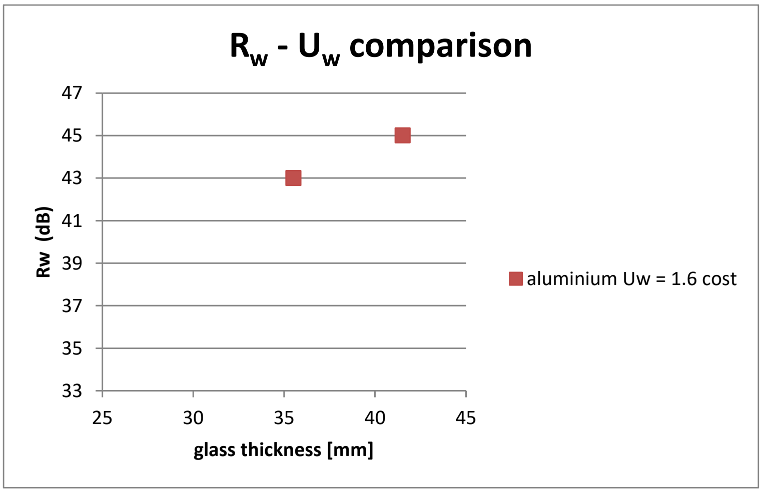

Figure 16 - R_w – U_w comparison for aluminium frame at U_w = 1.6 W/m^{2}K

In Figure 17 for aluminium frame technology, as for wooden frame, U_w values and the R_w parameter are compared, showing an increase if the PVB and overall glass thickness rise and its effect is though only related to sound insulation improvement.

In Figure 18 the PVC frame transmittance is kept constant while the sound reduction index is compared with overall glass thickness. Here once more the influence of the overall glass thickness is explicit, and once more, this parameter alone does not imply an increase in transmittance.

In Figure 19 for PVC frame technology, again the U_w values are kept constant while the R_w parameter shows an increasing under the influence of the PVB thickness. Once more the effect is related only as sound insulation improvement.

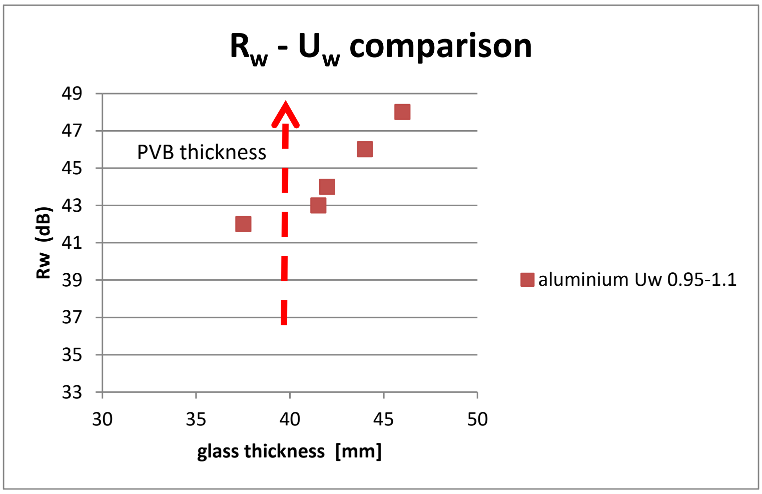

Figure 17 - Influence of PVB and overall glass thickness on sound insulation improvement keeping U_w constant

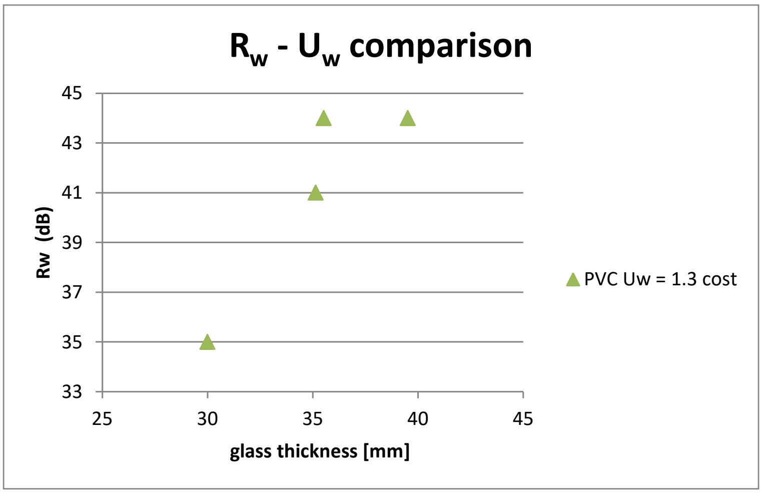

Figure 18 - R_w – U_w comparison for aluminium frame at U_w = 1.3 W/m^{2}K

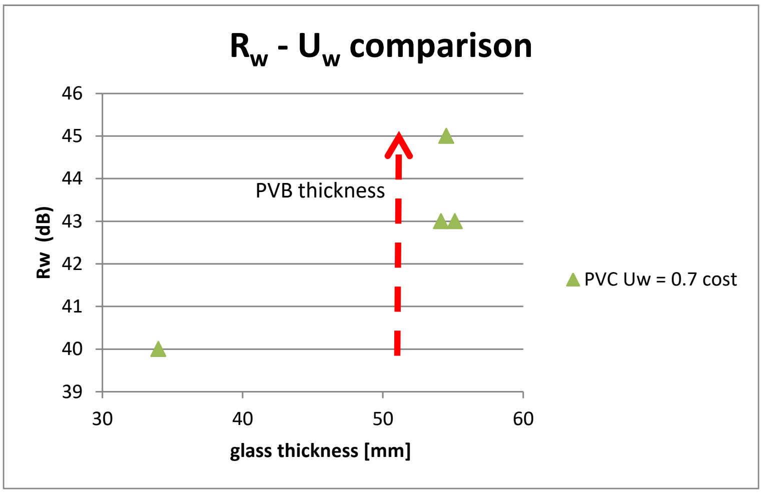

Figure 19 - Influence of PVB thickness on sound insulation improvement with U_w constant

3.3 Sound reduction prediction

After all this considerations, it is evident how glasses, gas inlet(s), PVB presence and thickness influence final R_w result. Nevertheless, no prediction method in literature or in international standards exists so far.

Though, using the available laboratory tests, a prediction method for R_w calculation could be proposed (equation 4).

$$(4) \qquad R_w = 20 \log m' + A \log d_1 + 1.9 \log d_2 - B \log e + 5 \log P + C \qquad \text{(dB)}$$

where:

m' is the glass mass per unit area [kg/m^2];

A,B and C corrective terms are obtained from regression procedure.

For PVC and Aluminium: A = 10 for two gas inlets; 14.5 for single gas inlet; (dB);

for wood: A = 10 for two gas inlets; A = 10 for one gas inlets with no laminated glasses or only one laminated glasses; A = 14.5 for single gas inlet and two laminated glasses both with PVB;

B = 10 for wooden and PVC frame; B= 9 for Aluminium single gas inlet frame; (dB);

C is a corrective term. For PVC frames C= - 10dB when no PVB is present for one gas inlet; for PVC frames C = -6 dB when no PVB is present for two gas inlets; in other cases C= 0; (dB);

d_1 is the first gas inlet dimension [mm];

d_2 is the second gas inlet dimension [mm]. If only one gas inlet is present then $d_2 = 1$;

e is the thicker laminated glass dimension [mm]. e=1 with only 1 laminated glass [mm];

P is ten times the PVB overall thickness sum. It is used only when two gas inlets and two laminated glasses layers are present. In other cases, P=1;

This method shows a very good agreement with laboratory values for all frame typologies, as shown from Figure 20 to Figure 22. For aluminium the prediction works for $R_{w,max}$ value up to 44 dB.

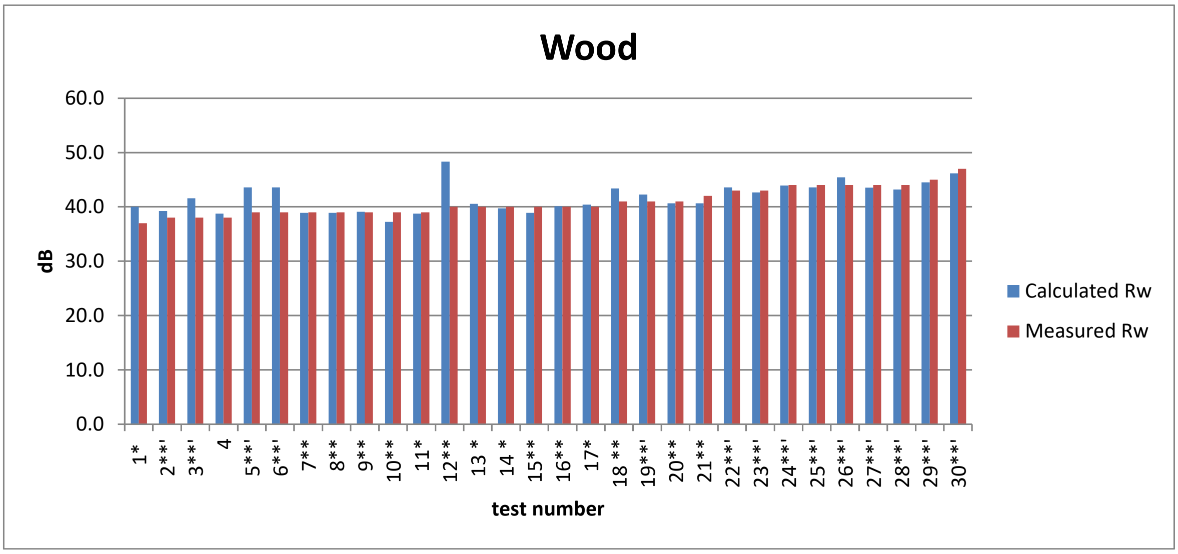

Figure 20 – $R_{w,lab}$ vs. $R_{w,pred}$: results comparison between the two methods for wooden frames

For 1*, 5**’, 7**, 10** and 12** samples there were workmanship as well as poor sample quality effects during laboratory tests. Though, calculated values seem to be more representative than tested values.

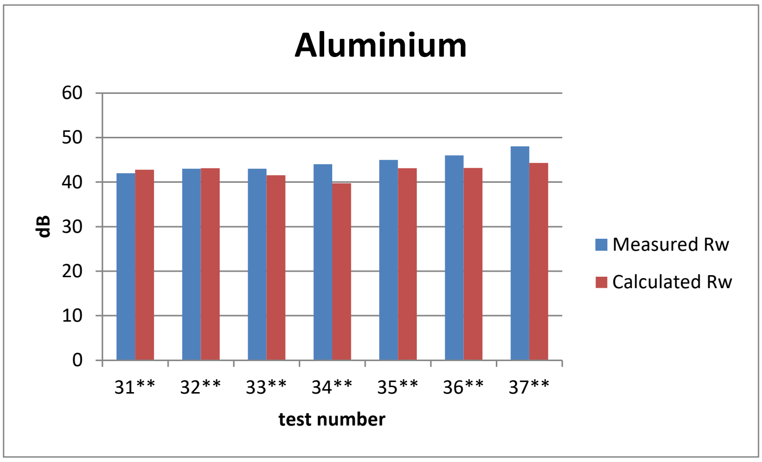

Figure 21 - $R_{w,lab}$ vs. $R_{w,pred}$: results comparison between the two methods for aluminium frames

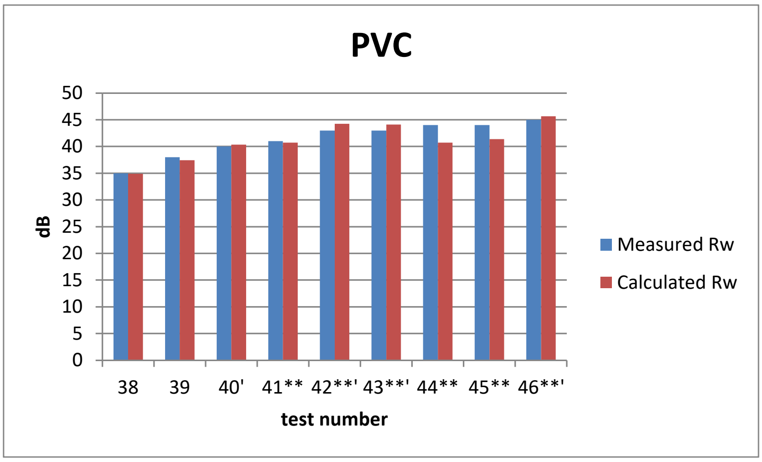

Figure 22 - $R_{w,lab}$ vs. $R_{w,pred}$: results comparison between the two methods for PVC frames

4. Conclusions

An in-depth analysis of more than 45 different frame windows was performed comparing thermal and acoustical insulation. In general terms, for large variations in the thermal and acoustic performance of windows a correlation is present. However, in the present study, in which the range of variation of the properties were limited, the examination of transmittance U_w and sound reduction frequency index R and sound reduction index R_w has shown that correlation is not possible.

From the thermal insulation point of view, results demonstrated that no single windows component could influence final performances, but all constituents participate to final insulation effect. On the other hand, acoustic insulation has shown a dependence on single parameters, such as PVB for coincidence reduction, overall glass and gas inlet(s) thickness to improve middle and, in some case, low frequencies insulation.

Both thermal and acoustic best performances can be obtained with all available material frames. So when choosing the best one, wooden is the less environmental impactful, with higher insulation values.

Finally, a new prediction method was proposed for the R_w estimation; calculated values show a very good agreement with tested ones. This new method could be used to improve international standards in order to help designers and producers to predict final sound reduction index values. This would not replace the fundamental laboratory test, which has to be performed to have a final confirmation.

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