Research Paper

The Acoustic Effect of Windows Installed in a Wood Frame Façade

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The acoustic effect of windows installed in a prefabricated wood frame façade was considered. Windows inserted into a lightweight wall modify its structural scheme. The research aimed to investigate the possible interaction of the façade's main components and their actual contribution to the total sound insulation. The principal research question involved the prediction of the acoustic performance of the complete prefabricated panel from the performance of its basic elements, an opaque part and windows. As the frequency-dependent characteristics of the elements differ substantially, the use of single number values for prediction and accuracy was of particular interest. The study is based on laboratory measurements. Initially, two full-scale samples of an opaque wall and four windows were tested separately. Then, several variants of the façade consisting of various combinations of these elements were examined. The results of measurements were juxtaposed and compared with calculated values. The frequency-dependent experimental results were fairly consistent with calculations. The estimations based on single number quantities were also in good agreement with measurements. Thus, it may be concluded that the façade elements did not interact significantly, and the single number calculations give reliable results that can be used in practice.

Keywords: sound insulation; lightweight frame building; prefabricated façade; windows; protection against noise.

1. Introduction

The marked trend of lightweight, prefabricated residential buildings is evidently growing, so panelised and modular homes have become increasingly popular. The frame structure is beneficial in respect to construction, building physics, and energy conservation. Besides, these buildings are widely perceived as consistent with the sustainable development concept and providing good indoor environment quality (ŠUJANOVÁ *et al.*, 2019; LIEBL *et al.*, 2013). In this context, the acoustic performance of the façade is of primary importance particularly in the case of multi-storey dwellings situated in noisy areas. The review of the literature concerning acoustic properties of lightweight timber buildings, however, showed that the sound insulation of their envelope was rarely investigated and the major contribution was from analytical studies (CANIATO *et al.*, 2017). For prefabricated buildings, the façade panel, consisting of different components, becomes a final product placed on the market. The acoustic performance should then be determined for the entire panel, especially with regard to the vision of an open building system and open manufacturing (NURZYŃSKI, 2007). Testing each possible combination of the opaque part and windows, however, seems impractical. Generally, the acoustic performance of a complex partition may be estimated from the performance of its elements. The formula for total sound insulation applies well to traditional massive buildings, but the structure of lightweight façade is very different. In acoustic terms, the components may interact making the estimations inadequate or imprecise.

The sound insulation of a window is usually determined empirically in the laboratory for a specific product of a specific type and dimensions, consisting of a strictly defined frame, the glazing, and sealing system. Extensive data based on laboratory measurements already exist for numerous products and may be used for the prediction of total sound insulation of a complete façade. The window, however, when tested in the laboratory is installed in a heavy massive partition so the mounting (edge) conditions differ considerably from the practical assembly in a lightweight façade, which may influence the results (Utley, Fletcher, 1969). Theoretical models, on the other hand, that may be used for calculating the sound insulation of windows, concentrate basically on the glazing (Quirt, 1982; 1983). In fact, other components of the window, mainly the frame and sealing also play an important role in the entire system performance. As the components mutually interact (Nurzyński, 2020), the results of simplified calculations usually differ significantly from the experimental data (Tadeu, Mateus, 2001).

The acoustic performance of the opaque wall, in turn, depends on its main structure (Bradley, Birta, 2001; Davy *et al.*, 2019) but also largely on various details, dividers, and connections (Quirt *et al.*, 1992; Ljunggren, Ågren, 2011). The installation of a window modifies the structural scheme of the wall as the studs, faces, and other elements are partly removed. Finding any experimental research work focused on the acoustic effect of these modifications or numerical simulations, however, is really difficult (Caniato, 2020). Articles on the façade sound insulation mostly concern field measurements (Kim, Kim, 2007; Buratti *et al.*, 2014), the reduction of external noise annoyance (Ryu, Song, 2019; Amundsen *et al.*, 2011) and the low-frequency behaviour (Keränen *et al.*, 2019; Scrosati *et al.*, 2016).

The paper concentrates on the sound insulation of lightweight prefabricated façades and, in particular, the acoustic effect of windows installed in the opaque element. The basic research question concerned the possibility of predicting the acoustic performance of a complete panel based on the performance of basic components. As the frequency-dependent characteristics of an opaque element and a window differ substantially, the use of single number values for prediction and accuracy was of particular interest. Two samples of an opaque wall and four windows were tested separately in the laboratory. Then, complete façades composed of these elements were examined. Finally, the empirical sound insulation of the entire panels was juxtaposed and compared with the results of estimations.

Basic terms and symbols used in the article: R_w is the weighted sound reduction index [dB]; C is the spectrum adaptation term corresponding to spectrum no. 1 (ISO 717-1:2020, 2020) [dB]; C_{tr} is the spectrum adaptation term corresponding to spectrum no. 2 (ISO 717-1:2020, 2020) [dB]; f_c is the coincidence frequency [Hz].

2. Samples and materials

2.1. Opaque elements

The acoustic performance of the opaque part depends on its basic structure, details, and additional layers, i.e., external thermal insulation and internal technical cladding (Di Bella *et al.*, 2014). Two samples of the wall, 4220 × 2760 mm, with the same basic structure and internal cladding but different thermal insulation were considered. The basic wall was supported with a frame constructed of wood studs, 180 × 60 mm, spaced at 600 mm, firmly secured on a perimeter framing. Faces, made of fire-resistant 12.5 mm plasterboards, were screwed on both sides to the studs. The plenum inside was filled with mineral wool. The technical cladding was made of 12.5 mm plasterboards supported with wooden battens (studs), 50 × 60 mm, fastened rigidly to the main frame. The plenum was filled with 50 mm of mineral wool (Fig. 1). Technical data on facing boards is presented in Table 1.

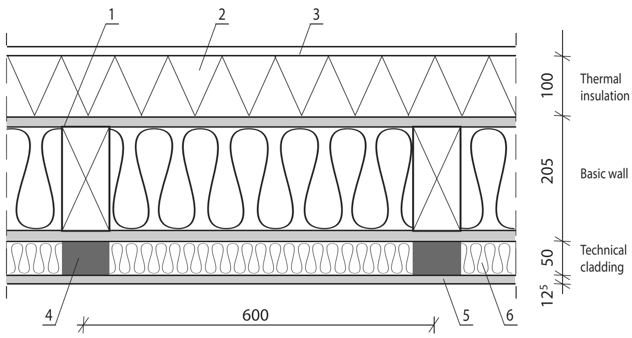

Fig. 1. Sample no. 1, façade with ETICS: 1) basic wall; 2) mineral wool 100 mm (lamella boards); 3) rendering; 4) studs; 5) boarding; 6) mineral wool 50 mm.

Table 1. Technical data on facing boards.

Board	Thickness [mm]	Density [kg/m^3]	Surface mass [kg/m^2]
Fire-resistant plasterboard	12.5	810	10.1
Fibre-cement board	8	1925	15.4

The first sample was equipped with an external thermal insulation composite system (ETICS), which in general reduces sound insulation in a certain frequency range due to the mass-spring-mass resonance (Weber, 2003; Santoni *et al.*, 2017). Several typical lightweight walls with ETICS made of mineral wool (MW) and expanded polystyrene (EPS), 100 mm and 120 mm thick, were initially examined to select the sample for further investigations. The results are presented in Fig. 2. The sound insulation characteristics were quite similar despite the different wall structures and various dynamic stiffness of the insulation. The values of the $R_w + C_{tr}$ index were within the range of 41–43 dB (Nurzyński, 2022). The wall with ETICS consisted of 100 mm of mineral wool (lamella boards) and a thin rendering was finally selected as fairly representative of the wide range of lightweight façades of such a type (Fig. 1).

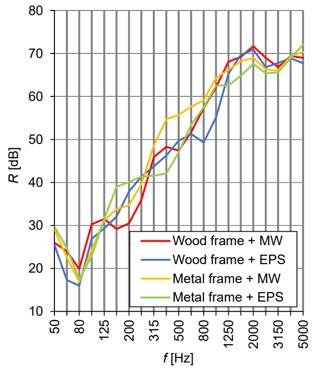

Fig. 2. Sound insulation of lightweight frame façades with ETICS, $R_w + C_{tr}$ = 41–43 dB.

The second sample consisted of the same basic wall and had the same technical cladding but different thermal insulation. This was supported by a grid made of timber battens providing 30 mm ventilating cavity (Fig. 3). The cavity was opened by making two 30 mm slots in the external fibre-cement boarding along the bottom and upper edges of the test opening. Thermal insulation of such a type provides significantly better sound insulation and is recommended in the case of higher levels of outdoor noise.

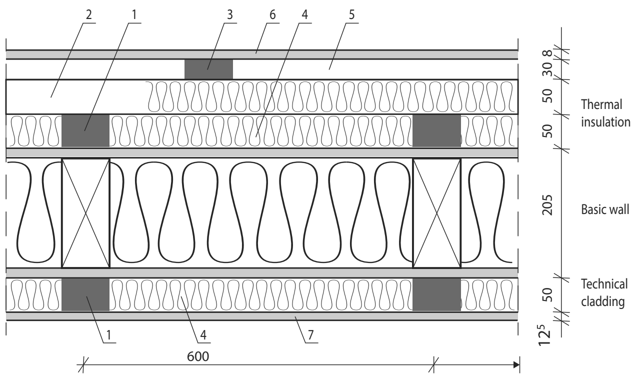

Fig. 3. Sample no. 2, façade with thermal insulation with a venting cavity: 1) studs; 2) horizontal battens; 3) vertical grid; 4) mineral wool 50 mm; 5) venting cavity 30 mm; 6) fibre-cement board 8 mm; 7) plasterboard 12.5 mm.

2.2. Windows

Four single-wing PVC windows, 1230 × 1480 mm, were tested individually in the laboratory. The windows were of the same system and manufacturer, had the same dimensions but different glazing. Single- and double-chamber insulated glass units (IGU) were used, respectively:

- Window A: double chamber IGU 4/16/4/16/4;
- Window B: double chamber IGU 10/12/4/12/6;
- Window C: double chamber IGU 44.1Si/12/4/12/44.1Si;
- Window D: single chamber IGU 66.2Si/24/86.2Si.

The glass units consisted of monolithic panes, 4, 6, and 10 mm thick, and laminated glass, 44.1Si, 66.2Si, 86.2Si, composed of two panes bonded with one or two layers of PVB ductile film (e.g., 66.2Si means two 6 mm panels bonded with two layers of laminate). The distance between panels in the unit was 12, 16, and 24 mm, respectively (see the denotation of samples).

2.3. Façades

The windows were installed successively in the opening made in the examined opaque element, and the installation was in accordance with field practice (Fig. 4). The openings were cut out in the elements after completing the first series of sound insulation measurements. The arrangement was representative for small rooms of about 12 m^2 of floor area (bedrooms).

Fig. 4. Sample of the façade installed in the laboratory.

3. Testing methods

The samples of the façade were tested in a facility consisting of two reverberant rooms of irregular shape so that the opposite surfaces were not parallel. The volume of the sending and receiving rooms was 100 m^3 and 93 m^3, respectively. In order to suppress flanking transmission, the rooms were separated by an acoustic break. Additionally, a sound insulating lining was applied on the walls and ceiling in the receiving room. The samples were installed in accordance with ISO standard (ISO 10140-2:2021, 2021), and the external face of the wall was on the sending room side. The windows were tested in another facility consisting of two smaller reverberant rooms, 88 m^3 and 52 m^3 for the sending and receiving rooms, respectively. The rooms were separated by an acoustic break, and a sound insulating lining was applied in the receiving room. The windows were installed in a double, massive filler wall constructed of calcium silicate blocks 250 mm + 200 mm, separated with vibration brake filled with mineral wool. The windows were fastened in the opening and sealed on the perimeter. The facilities, measurement procedures and the equipment complied with the requirements of respective ISO standard (ISO 10140-4:2021, 2021). A dual channel analyser and rotating microphones were used for the measurements. Average sound pressure levels in 1/3 octave bands were measured in the source and receiving rooms, and integrated over time and space.

4. Results of measurements and discussion

4.1. Windows

The windows were tested successively in the test opening provided in the heavy filler wall between both rooms of the laboratory. The values of the $R_w + C_{tr}$ index ranged from 31 dB to 45 dB with an average step of 5 dB (Table 2). This covers a comprehensive performance spectrum of commonly used windows equipped with typical insulated glass units (Miskinis *et al.*, 2015). The frequency-dependent characteristics were very different due to the IGU structure, the type of panes, the mass per unit area and the distance between them (Fig. 5). The fundamental resonance of the double (triple) glazing system and the coincidence of single panels determined the shape of the sound insulation plots.

Table 2. Sound insulation of windows (single number values).

Window	R_w [dB]	$R_w + C$ [dB]	$R_w + C_{tr}$ [dB]
A (4/16/4/16/4)	36	35	31
B (10/12/4/12/6)	40	39	36
C (44.1Si/12/4/12/44.1Si)	45	43	39
D (66.2Si/24/86.2Si)	47	47	45

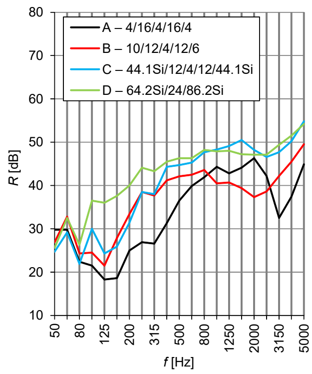

Fig. 5. Sound insulation of windows with different glazing, results of measurements.

4.2. Opaque elements

Two samples of the opaque element were examined. The measurements were taken in three different phases of their construction, i.e., for the basic wall without any insulating layers, with insulation but without external finishing (i.e., without the rendering in the sample no. 1 and the fibre-cement board in the sample no. 2), and finally for the complete façades. The sound insulation characteristics of the first sample are presented in Fig. 6. The insulating layers applied to the basic wall (without finishing) increased greatly the sound insulation at middle and high frequencies. Due to low frequency behaviour and whole structure resonance,

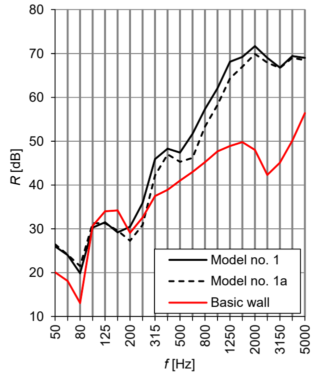

Fig. 6. Sample no. 1. Sound insulation measured in different phases of construction (model no. 1a without rendering).

however, the single number value of $R_w + C_{tr}$ did not improve at all. This equals 40 dB with and without insulation (Table 3). Implementation of the rendering, that is applying just the thin external finishing of ETICS, slightly moved the mass-spring-mass resonance towards low frequencies (Fig. 6) and, in effect, the single number quantity increased by 2 dB.

Table 3. Sound insulation of opaque elements (single number quantities).

Opaque element	R_w [dB]	$R_w + C$ [dB]	$R_w + C_{tr}$ [dB]
Basic wall	44	43	40
Sample no. 1a (without rendering)	47	44	40
Sample no. 1	50	47	42
Sample no. 2a (without external face)	53	51	46
Sample no. 2	60	58	54

The thermal insulation system with a venting cavity applied in the second sample was significantly more effective, particularly at low and middle frequencies (Fig. 7). The application of a bare insulation made of mineral wool was highly beneficial only at middle

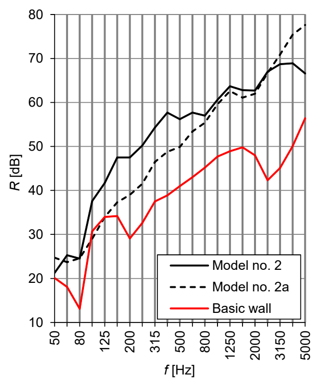

Fig. 7. Sample no. 2. Sound insulation measured in different phases of construction (model no. 2a without external faces).

and high frequencies, while the fibre-cement faces improved sound insulation considerably in the range of 100–630 Hz. Surprisingly, however, a pronounced lowering was observed in the range of 800–2500 Hz, where the sound insulation of the complete façade is quite the same as that of the façade without external finishing made of fibre-cement boards. This was probably caused by the ventilating slots made in the faces that opened the cavity along the upper and lower edges of the façade. The $R_w + C_{tr}$ index without external faces was 46 dB, whereas for the complete façade it was 54 dB (Table 3). The coincidence effect of a fibre-cement board, 8 mm thick, was observed in the high frequency range (theoretically calculated f_c = 5200 Hz), whereas low frequency behaviour was determined by the fundamental resonance of the basic wall (Fig. 7). The examined samples of opaque elements are fairly representative of a comprehensive range of lightweight external walls used in real life in prefabricated residential buildings.

4.3. Complete façades

The frequency-dependent characteristics of windows and opaque elements tested separately were very different (Figs. 5–7). This means that both components contribute to the total sound insulation of the entire façade in different ways. The measurement results for sample no. 1 examined in various wall–window configurations are shown in Fig. 8. Generally, the window determined the total sound insulation at middle and high frequencies. In the range beneath 800 Hz, the characteristics of sample 1B, 1C, 1D (with windows) were practically the same as for the stand-alone opaque part of the façade. However, the differences observed above 800 Hz did not significantly influence the single number quantities; the values of the $R_w + C_{tr}$ index gained 41–42 dB regardless of the window's presence and the type of glazing (Table 4). Thus, the final effect expressed in terms of $R_w + C_{tr}$ was approximately the same, which clearly indicates the need for optimisation in the façade designing process.

Table 4. Total sound insulation of complete façades with different windows (single number quantities).

Sample no.	R_w [dB]	$R_w + C$ [dB]	$R_w + C_{tr}$ [dB]
1	50	47	42
1A	43	42	37
1B	46	44	41
1C	49	46	41
1D	49	47	42
2	60	58	54
2A	44	43	39
2B	48	47	44
2C	52	50	46
2D	52	51	48

The result obtained for the modified variant 1C without internal technical cladding (1Cx) is interesting as the removal of the cladding practically had no acoustic effect (Fig. 8). This confirms that such a supplementary layer, when rigidly fastened to the main structure of the lightweight frame wall, does not improve its sound insulation (Nurzyński, 2022). The arrangement 1A had a window of lower sound insulation and, consequently, lowering in total sound insulation may be observed nearly across the entire frequency range (Fig. 8). The value of the $R_w + C_{tr}$ index dropped by 5 dB in comparison with the standalone opaque element.

The acoustic performance of the second sample was utterly determined by windows. Subsequent to their assembling, the total sound insulation decreased dramatically in almost the entire frequency range (Fig. 9). It is interesting, however, that the installation of windows brought about some slight improvements at low frequencies. The $R_w + C_{tr}$ index of samples 2B, 2C, and 2D dropped by 6–10 dB compared to the standalone opaque element. The differences between subsequent samples were relatively small, measuring just 2 dB (Table 4). The use of the window A seems impractical, as in this case the index dropped by 15 dB.

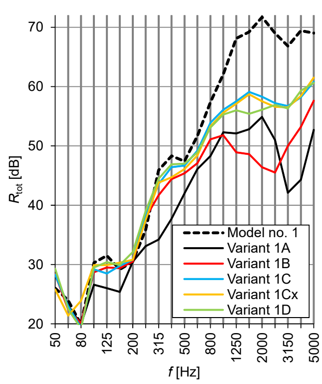

Fig. 8. Sample no. 1. Total sound insulation of complete façade with different windows.

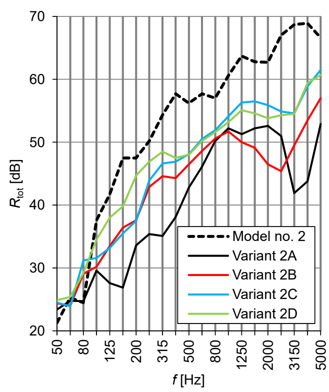

Fig. 9. Sample no. 2. Total sound insulation of complete façade with different windows.

The differences between single number quantities for respective variants of both samples, with a different opaque part but the same window, are presented in Table 5. The results confirm the need for façade optimisation, as the use of a highly insulated opaque element had rather limited effects compared to a wall equipped with common ETICS. The optimal wall–window configuration should be determined in reference to local requirements (Rasmussen, Rindel, 2010; Rasmussen, 2010), while the development of a uniform acoustic categorisation for the whole prefabricated panels would be helpful for designers, manufacturers, and other stakeholders referring to existing acoustic classification schemes for residential buildings (Nurzyński, 2007; Casini *et al.*, 2016).

Table 5. Differences in single number values for respective variants of both samples.

Variant no.	ΔR_w [dB]	$\Delta(R_w+C)$ [dB]	$\Delta(R_w+C_{tr})$ [dB]
2A–1A	1	1	2
2B–1B	2	3	3
2C–1C	3	4	5
2D–1D	3	4	6

5. Estimations versus empirical results

Empirical sound insulation of the façade elements, opaque parts, and windows, was used for calculating total sound insulation of the complete façade:

$$R_{\text{tot}} = -10\log\left(\sum_{i=1}^{n}\frac{S_i}{S}10^{-0.1R_i}\right), \qquad (1)$$

where R_{tot} is the total sound insulation of the complete façade [dB], S is the total area of the façade [m^2], R_i is the sound insulation of part i of the façade [dB], S_i is the area of a part i of the façade [m^2].

The results of calculations were fairly consistent with the experimental values for practically the entire frequency range (Fig. 10). This consistency is somewhat surprising, especially as the opaque elements and windows were tested in two distinctly different test facilities.

The estimations based directly on single number quantities were also in good agreement with the results of measurements. The calculated values rounded to an integer; in almost all cases, they were the same as measured. The sample 2D, however, formed an exception, as the calculated indices were higher by 2–3 dB. This was probably caused by window assembly failures that brought about tiny cracks locally decreasing the airtightness of the system. Some interaction between the wall and the window, however, can also be a reason for this discrepancy.

6. Conclusions

The acoustic effect of windows installed in lightweight frame façades was examined. The study investigated the acoustic interaction of façade components and aimed to verify whether the formula for the total sound insulation of a complex partition is applicable in this case. The frequency-dependent experimental results for the entire façade panels were fairly consistent with calculated values. The estimations based on single number quantities were also in good agreement with measurements. Thus, it may be concluded that

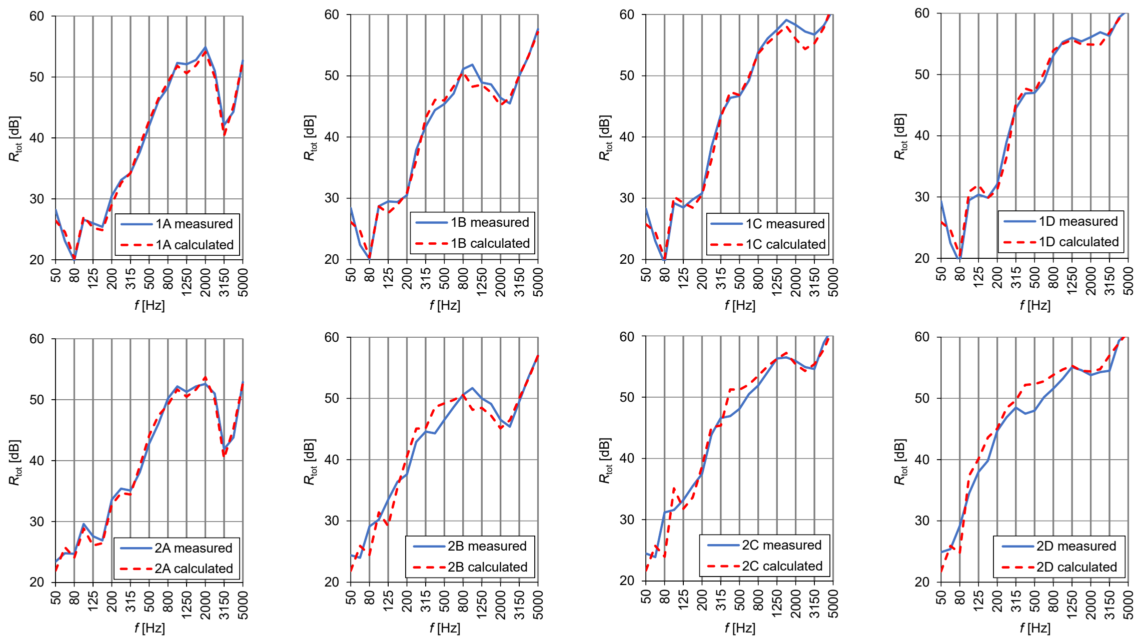

Fig. 10. Total sound insulation of complete façades with different windows: comparison of experimental and calculated values.

the façade elements did not interact significantly and that the single number calculations give reliable results that can be used in practice. This conclusion provide directions for the further work on the assessment of prefabricated frame buildings and may be useful while optimising their acoustic performance. The development of an acoustic categorisation and the marking scheme for prefabricated façade panels considered as final building products would be a helpful tool for manufacturers and designers.

The windows and opaque elements influenced total sound insulation in a different frequency range. The installation of windows B, C, and D in the opaque wall with ETICS (sample no. 1) reduced sound insulation considerably in the high frequency bands, mostly above 800 Hz. Due to low and medium frequency behaviour, however, the single number values of $R_w + C_{tr}$ were practically the same. The acoustic performance of the second sample was utterly determined by windows. Surprisingly, however, their installation brought about some improvements at low frequencies. The removal of the technical cladding in the sample no. 1 had practically no acoustic effect, which confirms that such a supplementary layer, when rigidly fastened to the main structure of a lightweight frame wall, does not improve sound insulation. These observations and conclusions may be useful for designers and engineers working on external wall structures. Future research should be focused on the acoustic effect of another technical elements installed in façade panels such as slot ventilators, shutter boxes, air transfer devices, electrical raceways, etc.

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