Infiltration Air Flow Variance Analysis in Relation to The Reverberation Time and Weighted Global Noise Level Difference

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Abstract: - The acoustic method for the experimental determination of the air permeability for buildings manages to overcome the disadvantages of other experimental methods or phenomenological modelling. However, the current degree of development of this method is applicable only to a small number of building types. In this research we adapt this method in order to extend its applicability for different types of buildings. To achieve this, we use an experimental approach, completed by numerical simulations for the formation of a database. More specifically, the purpose of this paper is to analyse the variance of the air infiltration flow (Q) considering the different Window Types (WT) for different Reverberation Time (RT_{1000Hz}) of the receiving room and Global Weighted Noise Level Difference (ΔLA). The statistical model 'Analysis of Variance (ANOVA)', offers the possibility to follow the evolution of a phenomenon under different conditions. In this paper, the research objective is to test the hypothesis that Q varies, depending on the four RT_{1000Hz} values for the eight ΔLA values. The article highlights the influence of the two parameters on the infiltrated air flow, as well as the way these parameters must be introduced in a more general model, with wider applicability for different building types.

Keywords: Infiltration air flow, global weighted noise level difference, reverberation time, analysis of variance method.

1. INTRODUCTION

The infiltrated air flow inside the buildings through the window joints is one of the most important parameters to influence the building energy consumption. The characteristic parameter of the building that conditions this infiltration air flow is the air permeability of the windows mounted on the building facade [1, 2]. In addition to energy consumption, air permeability also influences the degree of pollution inside buildings [3] and interior acoustic comfort [4]. Therefore, the air permeability of buildings proves to be one of the most important parameters of the building, and its precise determination is essential.

In general, two approaches are known in order to determine this parameter: physical modelling and experimental measurement. Physical models have some advantages: simplicity and speed of determination, but also have disadvantages in terms of low, uncontrollable accuracy leading to errors as high as 159% [5, 6, 7]. Moreover, the set up for the deterministic models is laborious and they are expensive to develop and maintain, as they use partial differential equations with a large number of physical and chemical interactions. This interaction needs quite a lot of accurate input data, which is not always an easy step. Experimental models have the advantage of high precision, but have the disadvantage of a difficult, long-term approach and require an expensive experimental stand: the method of decreasing concentration [8], the method of overpressure [1, 2], the pulse method [9, 10]. A new experimental method analysed recently in the literature is the acoustic method [11, 12, 13, 14, 15], which is based on the simultaneity of two transfer phenomena (air transfer and sound energy transfer) through the infiltration joints of the windows. So far, the method has proved to be simple, fast, needing an inexpensive experimental stand, therefore overcoming many of the disadvantages of previous methods. Analyses of this method highlighted the dependence of the infiltrated air flow on the difference of the noise level on one and on the other side of a window [15]. The different methods for the outdoor air infiltration indoors are compared by means of qualitative marks in Table 1.

Table 1. Comparison of Air Infiltration estimation methods

Method		Comparison criteria					
		Estimation precision	**Cost**	**Time**	**Difficulty**	**Climatic conditions Influence**	**Applicability**
Prediction models		4/10	10/10	10/10	9/10	10/10	5/10
Known Experimental Methods	**Concentration decay**	9/10	4/10	3/10	3/10	3/10	9/10
	Permeability measurement	9/10	4/10	6/10	5/10	5/10	9/10
New Experimental Method	**Acoustic method**	8/10	8/10	10/10	9/10	8/10	4/10

As it can be expected, the prediction models are the least expensive and the fastest way to predict the air infiltration, their main disadvantage is the decreased precision for specific buildings. Their disadvantage is overpassed by the experimental methods which present excellent precision and can be used for almost any building situation. However, the first two experimental methods are characterized by several disadvantages regarding the price of the experimental devices, the time necessary for the experiment and the raised difficulty of the entire determination. Moreover, they also present a significant technical disadvantage; the measured results are influenced by the climatic condition, mainly by the wind speed. The new experimental method overpasses all the disadvantages of the previously presented methods, but a significant question mark remains regarding its degree of applicability, because this method has been tested on a limited number of buildings with limited variation of building façade characteristics.

The extension of the applicability of this method, for different building types, depends on considering other parameters characteristic for a building.

In this study we continue the investigation in this direction and experimentally analyse whether this influenced air flow depends on certain parameters of the building with an effect on interior acoustics: the reverberant field inside the building and the acoustic characteristics of the facade windows.

In this sense, we will adopt an experimental approach and a statistical method of data processing that, according to our knowledge, until now has not been used in this research direction (variance analysis), but which has successfully been used in similar studies in other fields [16, 17, 18]. The statistical models [19, 20, 21, 22] are mainly based on pattern detection, which is used in a second stage to forecast the variance of the air infiltration flow.

By means of this statistical approach, within this study, we want to answer a few questions:

- Does the reverberant field influence (or not) the mathematical relationship between the two transfer phenomena?
- Does the size of the analysed room represent or not a source of error in such an experimental acoustic determination of the air permeability of the building?
- Can the current model be improved by expanding its applicability for different types of buildings?

Through this study we can answer these questions and understand more clearly the possibility of further research in this direction to determine the air permeability of buildings.

In the following sections the article presents: the experimental approach, the formation of the experimental database and the statistical processing of data through the new investigation method.

2. MATERIALS AND METHOD

2.1. Problem formulation

The first study about analysis of air transfer and sound wave transfer was made, by authors, using correlated analysis method [15].

In this paper the authors simulate several situations of air permeability using several types of windows and frames. For each situation the accuracy of the applied permeability estimation method is verified. The statistical research model applied for the variance analysis uses repeated measurements of type ANOVA-MR two-way [16, 17]. The study utilizes the real permeability value as comparison parameter to validate the results obtained with this new statistical method.

Notations:

- SST- the variance of the individual values of all the researched samples, independent of the group they belong, multiplied with n-1 degrees of freedom;
- SSW-the within-subjects’ variance;

- SSM – the variance of the means of each group – condition of measurement – compared with the total mean considering all values together;
- SSE – the sum of the variances for each condition of measurement.

In such an analysis, the total variance, SST of the values is fully provided by the variance within-subject SSW, which, in its turn, is composed of the variance provided by the levels of the independent variables SSM and the variance of the error, which is not explained by the independent variables SSE. The F ratio describes the model in the statistical test,

$$F = \frac{SS_M}{SS_E} \quad (1)$$

The higher the variance induced by conditions of measurement (SSM) compared to the variance of the unexplained error (SSE), the higher the F value, being able in this way to reach the threshold of statistical significance.

2.2. Experimental approach

The experimental study was conducted in an experimental stand suitable for the study of the phenomenon of sound energy transfer through windows, the field of "airborne noise", according to international standards [23]. The experimental stand consists of two rooms separated by a common wall. Within this experimental wall we placed the analysis window, for which two types of experiments were performed: air permeability experiments (Figure 1) and airborne noise experiments (Figure 2).

The experiment was resumed for nine types of real windows, different both thermally and acoustically:

- TVPVC - triple glazing – PVC
- SL – wooden, simple
- DL – wooden, double
- CL – wooden, coupling
- TL – wooden, triple
- DVL – wooden, double glazing
- DVAL – aluminium, double glazing
- PVC - single-glazing PVC
- DVPVC - double glazing PVC.

For each real window, eight types of joints were experimentally studied: from perfectly sealed (joint under 0.1mm width) to very large joints (20mm width) (Figure 3). Thus, the experimental database contains 9 x 8 = 72 points in the experimental space. For each window and each joint, air permeability and window noise experiments were performed. Air permeability measurements led to the experimental variation of the infiltrated air flow corresponding to the eight types of joints. The airborne noise measurements led to the determination of the noise level difference on one side and the other side of the window for the same eight types of joints.

The noise measurements inside the experimental stand recorded the overlaid effect of two phenomena: the direct propagation of the noise from the noise source (according to EN 717: 2013), and the reverberant acoustic field inside the experimental stand. Thus, the experiments performed are acceptable for rooms or halls with reverberation times of the same order of measurement. To extend the scope of the relationship between the two phenomena, the ODEON Acoustics software was used [24]. Inside this software the reception points were placed inside both the emission and reception room, according to our experimental setup (Figure 4). Two sound source was placed behind the microphones, just like in the real experimental setup. Further, the acoustic absorption coefficients characteristic of the walls, ceiling and floor were changed so that other values were obtained for the interior reverberation time (Figure 4). A total of four reverberation time value spectra were analysed. For these four value spectra the value of the reverberation time at 1000Hz is: 0.8s, 1.2s, 1.6s and 5s.

Thus, the database was amplified four times, now containing 72 * 4 = 288 experimental points.

This way the final database contains simultaneous values of: (1) the infiltrated air flow, (2) of the difference of noise level on one side and on the other side of the window and of the reverberation time. This database was further used in the statistical processing of the data using variant analysis to highlight the effect of reverberation time and noise level difference on the infiltrated air flow.

3. RESULTS AND DISCUSSION

The authors expect that the averages obtained in the four measurements in relation to RT to differ from each other strongly enough to decide that their variance is related to the cumulative effect of the flow induced by the different values of the noise level difference.

We analyse in this paper the flow variance (Q) using different window types (WT) for four values of reverberation time (RT) corresponding to the frequency of 1 KHz and eight values of the weighted global noise level difference (ΔLA).

We normalized the data measured within the PN-III-P2-2.1-PED-2016-1951 research project and processed it in the SPSS program [25] in order to analyze its variance.

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Figure 1. Blower door experimental equipment, mounted in the doorway of the experimental stand

Figure 2. Experimental window (According to EN 717:2013)

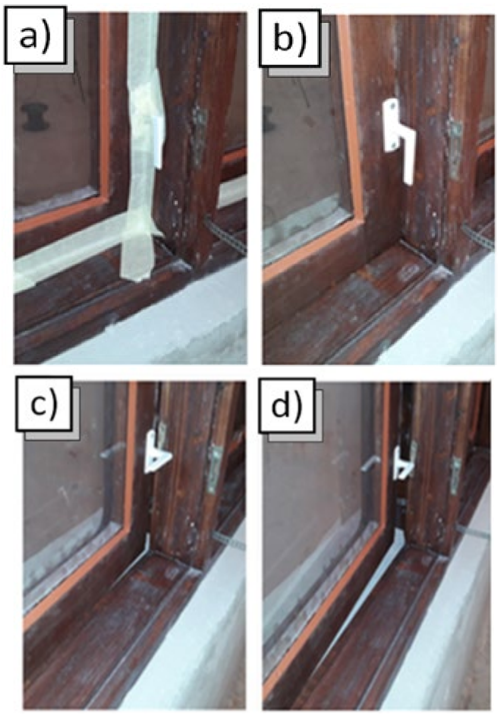

Figure 3. Four different window openings for a simple wooden frame window: a) closed window, sealed joint; b) closed window; c) closed window, small joint; d) closed window larger joint

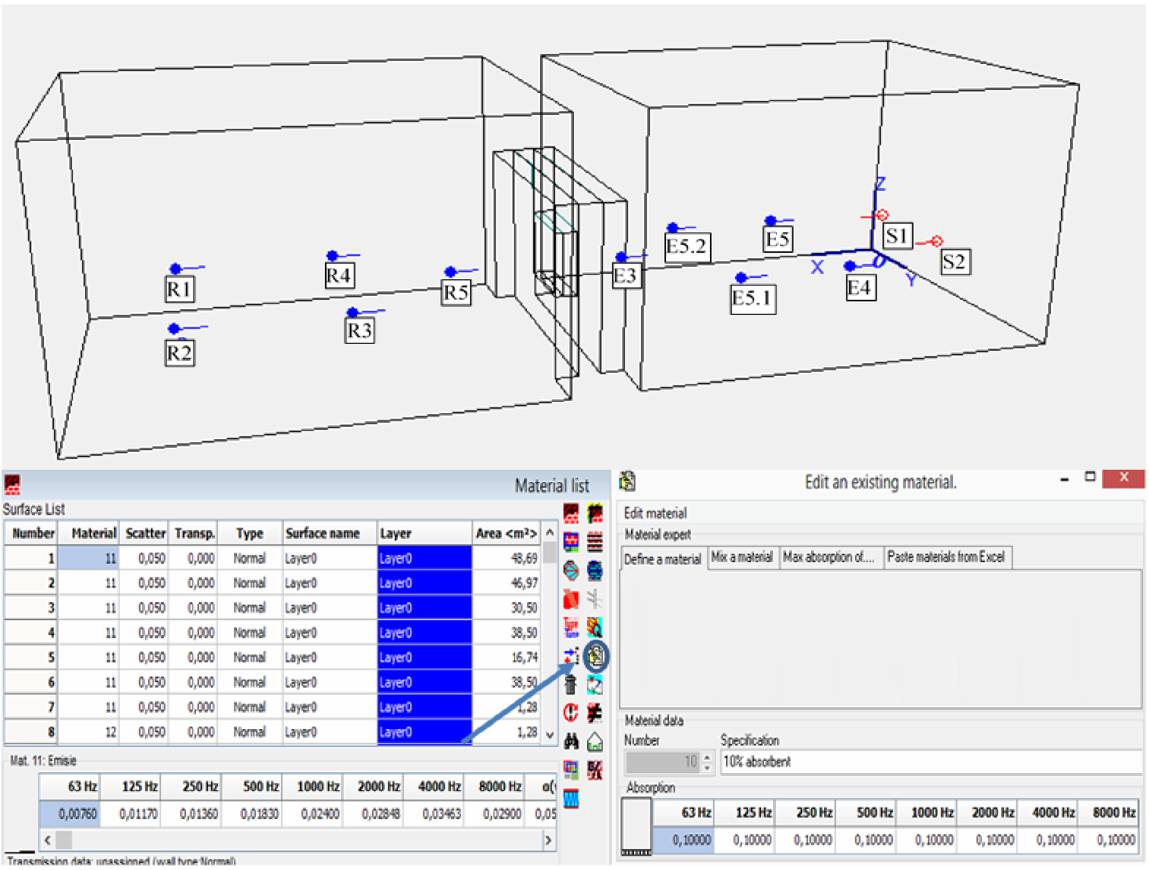

Figure 4. Simulation of different reverberant fields indoors in ODEON Acoustics

We normalized the data measured within the PN-III-P2-2.1-PED-2016-1951 research project and processed it in the SPSS program [25] in order to analyse its variance.

Notations

$Q\_i\_j,\ i \in \{0.6\ , 1.20\ , 1.80\ , 5.10\ \}$

$j \in \{0, 1, \ldots 7\}$ - the flow corresponding to the reverberation time i, respectively to the weighted global noise level difference j.

Table 2. Within-Subjects Factors

RT	ΔLA	Dependent Variable
1	1	Q_060_0
	2	Q_060_1
	3	Q_060_2
	4	Q_060_3
	5	Q_060_4
	6	Q_060_5
	7	Q_060_6
	8	Q_060_7
2	1	Q_120_0
	2	Q_120_1
	3	Q_120_2
	4	Q_120_3
	5	Q_120_4
	6	Q_120_5
	7	Q_120_6
	8	Q_120_7
3	1	Q_180_0
	2	Q_180_1
	3	Q_180_2
	4	Q_180_3
	5	Q_180_4
	6	Q_180_5
	7	Q_180_6
	8	Q_180_7
4	1	Q_513_0
	2	Q_513_1
	3	Q_513_2
	4	Q_513_3
	5	Q_513_4
	6	Q_513_5
	7	Q_513_6
	8	Q_513_7

In this paper, the research objective is to test the hypothesis that Q varies, depending on the four RT values for the eight ΔLA values.

One would expect that the averages obtained in the four measurements in relation to RT to differ from each other strongly enough to decide that their variance is related to the cumulative effect of the flow induced by the different values of the noise level difference.

This research can be integrated in the longitudinal research model, within-subjects, which offer the possibility to follow the evolution of the flow Q, for different types of windows, Table 2.

Table 3. Descriptive Statistics

	Mean	Std. Deviation	N
Q_060_0	.2811	.42191	9
Q_060_1	.2533	.40119	9
Q_060_2	.3489	.43762	9
Q_060_3	.5589	.28959	9
Q_060_4	.7256	.22771	9
Q_060_5	.7411	.16944	9
Q_060_6	.7711	.15366	9
Q_060_7	.8667	.08139	9
Q_120_0	.2811	.42191	9
Q_120_1	.2533	.40119	9
Q_120_2	.3489	.43762	9
Q_120_3	.5589	.28959	9
Q_120_4	.7256	.22771	9
Q_120_5	.7411	.16944	9
Q_120_6	.7711	.15366	9
Q_120_7	.8667	.08139	9
Q_180_0	.2811	.42191	9
Q_180_1	.2533	.40119	9
Q_180_2	.3489	.43762	9
Q_180_3	.5589	.28959	9
Q_180_4	.7256	.22771	9
Q_180_5	.7411	.16944	9
Q_180_6	.7711	.15366	9
Q_180_7	.8667	.08139	9
Q_513_0	.2811	.42191	9
Q_513_1	.2533	.40119	9
Q_513_2	.3489	.43762	9
Q_513_3	.5589	.28959	9
Q_513_4	.7256	.22771	9
Q_513_5	.7411	.16944	9
Q_513_6	.7711	.15366	9
Q_513_7	.8667	.08139	9

The Table 3, Descriptive Statistics, contains the means and standard deviations for the airflow Q for the four values of RT and the eight values of ΔLA.

It is observed that the values of the airflow Q increase with the values of ΔLA, and the increase is the same for each value of RT.

The same can be interpreted from the graphical representation of the normalized airflow Q as a function of the normalized ΔLA, Figure 5: it is observed that the values of Q decrease with the values of ΔLA, and the decrease is the same for each value of the RT. That means for each type of window the curves have the same profile.

Figure 5 presents similar trends for the variation of the normalized infiltration airflow Q (m3/h) as a function of the normalized noise level difference DLA (dB). This resemblance of the variation shape between the two parameters whatever the window type proves the existence of a clear correlation between the infiltration airflow and the noise level difference.

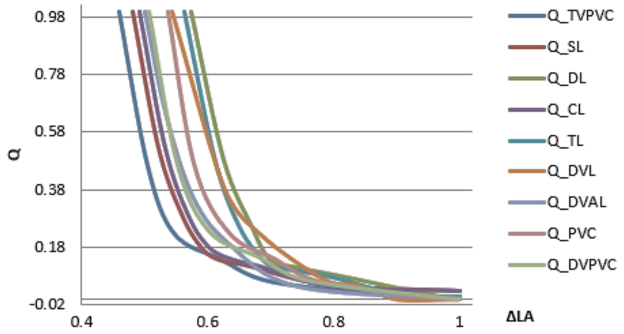

Figure 5. Normalized Q evolution according to the normalized ΔLA for all types of windows

However, the horizontal offset between the curves corresponding to different window types is an indication that the window type influences the noise level difference. This finding is significant; it proves there are multiple ways the sound energy is transferred from one side to the other side of the window. The window acoustic insulation R might also influence the noise recording, and furthermore the relationship between the airflow and the noise level difference.

Our investigation regards mainly the correlation between the air transmission and two parameters: the noise level differences and the indoor reverberation time. The Multivariate Tests table, Table 4, indicates a statistical variation for the airflow Q, not too large, ($p = 0.070$) only as a function of ΔLA.

The table of multiple comparisons, Table 5, shows the significance of the differences between all four pairs of means of Q in relation to RT for all ΔLA values. Statistically significant differences are observed only between the values related to ΔLA.

Table 4. Multivariate Tests [a]

Effect		Value	F	Hypothesis df	Error df	Sig.
RT	Pillai's Trace	.	. [b]	.	.	.
	Wilks' Lambda	.	. [b]	.	.	.
	Hotelling's Trace	.	. [b]	.	.	.
	Roy's Largest Root	.	. [b]	.	.	.
ΔLA	Pillai's Trace	.933	6.955[b]	6.000	3.000	.070
	Wilks' Lambda	.067	6.955[b]	6.000	3.000	.070
	Hotelling's Trace	13.911	6.955[b]	6.000	3.000	.070
	Roy's Largest Root	13.911	6.955[b]	6.000	3.000	.070
RT * ΔLA	Pillai's Trace	.[c]	.	.	.	.
	Wilks' Lambda	.[c]	.	.	.	.
	Hotelling's Trace	.[c]	.	.	.	.
	Roy's Largest Root	.[c]	.	.	.	.
a. Design: Intercept Within Subjects Design: RT + ΔLA + RT * ΔLA						
b. Exact statistic						
c. Cannot produce multivariate test statistics because of insufficient residual degrees of freedom.						

Table 5. Tests of Within-Subjects Contrasts

Measure: MEASURE_1							
Source	**RT**	**ΔLA**	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
RT	Level 1 vs. Level 4		.000	1	.000	.	.
	Level 2 vs. Level 4		.000	1	.000	.	.
	Level 3 vs. Level 4		.000	1	.000	.	.
ΔLA		Level 1 vs. Level 8	3.086	1	3.086	24.881	.001
		Level 2 vs. Level 8	3.386	1	3.386	31.061	.001
		Level 3 vs. Level 8	2.413	1	2.413	16.696	.004
		Level 4 vs. Level 8	.853	1	.853	16.110	.004
		Level 5 vs. Level 8	.179	1	.179	7.059	.029
		Level 6 vs. Level 8	.142	1	.142	10.665	.011
		Level 7 vs. Level 8	.082	1	.082	8.448	.020

The graph below, Figure 6, illustrates the Q means variation for the eight values of ΔLA. The data support and the image illustrate the existence of a statistically significant global variation and also differences from one value to another, with the largest increase 2 to 4 for ΔLA.

Figure 7 shows that Q variation in relation to RT does not exist.

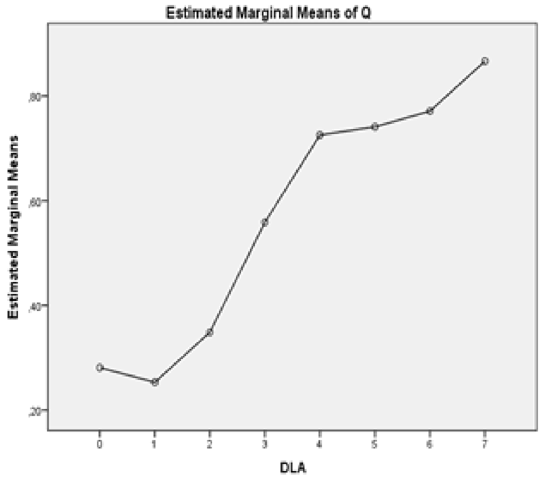

Figure 6. Q variance in relation to ΔLA

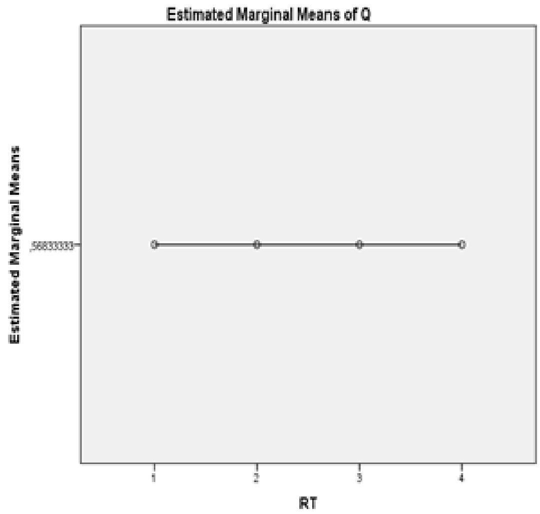

Figure 7. Q variance in relation to ***RT***

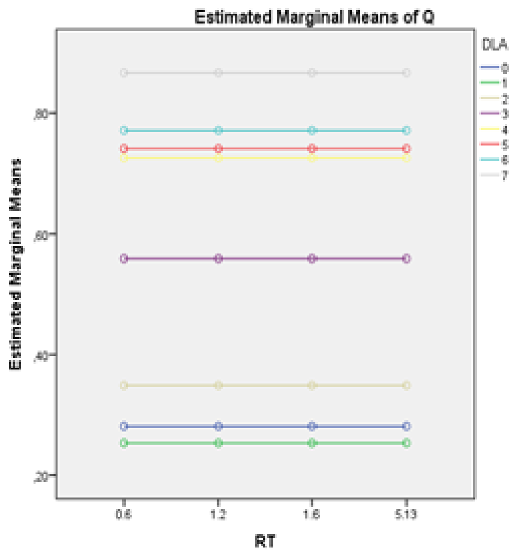

Figure 8. Q variance in relation to RT and ΔLA

Analysing the Q variance using different types of windows for four (4) values of RT (0.6, 1.2, 1.8 and 5.13) corresponding to the frequency of 1 KHz and eight (8) values of ΔLA (0.1, 2, 3, 4, 5, 6 and 7) the paper concludes that the flow is the same regardless of the RT values, and in relation to ΔLA it is sufficient to consider only the following values: 1, 2, 3, 4, 6 and 7. These aspects are illustrated in the figure 8.

Analysing the Q variance in relation to only six values for ΔLA, instead of eight, the results improve considerably. The Multivariate Tests Table, Table 6, indicates a statistically significant variation ($p = 0.030$), with a very high level of effect size (0.914).

Table 6. Multivariate Tests

	Value	F	Sig.	Partial Eta Squared
Pillai's trace	.914	8.467[a]	.030	.914
Wilks' lambda	.086	8.467[a]	.030	.914
Hotelling's trace	10.583	8.467[a]	.030	.914
Roy's largest root	10.583	8.467[a]	.030	.914

Each F tests the multivariate effect of ΔLA. These tests are based on the linearly independent pair wise comparisons among the estimated marginal means.
a) Exact statistic

The graph in Figure 9 illustrates the means variation of Q for the six values of ΔLA, with the largest increase from the value 1 to the value 4 of ΔLA.

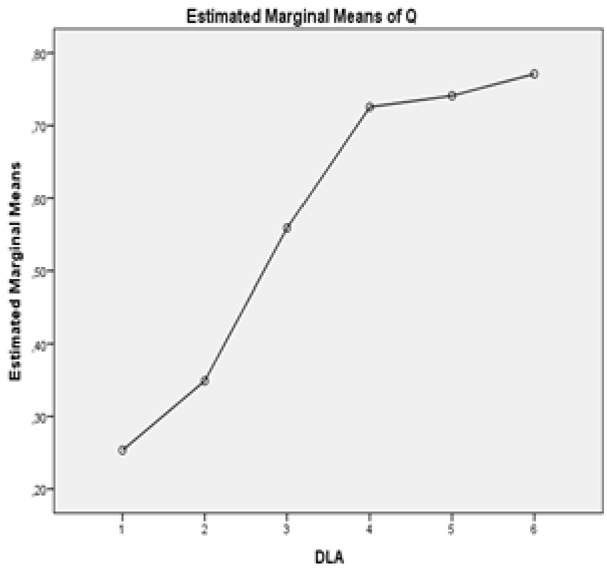

Figure 9. Q variance in relation to six values of ΔLA

The variance analysis leads to the same result obtained from the correlation analysis, namely that the flow rate Q can be determined as a function of ΔLA considering, for example, the measured values for RT = 5.13.

This investigation concerned the relationship between the infiltration air flow that takes place through the window joints and two parameters: (1)

the noise level difference between the two sides of the window and (2) the indoor space reverberation time. This investigation was carried out by the mathematical variance analysis applied on a databased obtained by experiments and Odeon Acoustics simulation.

Our approach led us to the conclusion that the air flow is correlated to the noise level difference but not correlated to the reverberation time. Moreover, a new parameter was found to influence the sound energy transfer: the acoustic insulation parameter of the window R.

Our findings are correct from a physical viewpoint. Indeed, the airflow does not depend on the type of room or its acoustic properties. However, the acoustic measurement of the indoor noise level depends on the reverberation times. Therefore, the in an indirect way the reverberation time still influences the airflow rate because this new acoustic method to determine the air infiltration should consider the indoor reverberation time. This is also in accord with other researches [12, 15].

4. CONCLUSIONS

The variance analysis highlighted the significant dependence between the flow of air infiltrated through the carpentry joints and the difference in noise level on one side and the other side of the window. It was thus shown that the phenomenon of air transfer through the joints of the windows takes place simultaneously with the phenomenon of transfer of sound energy through the same joint of the carpentry.

It was also highlighted that the infiltrated air flow does not depend on the reverberation time of the analyzed room because the statistical research model applied for the variance analysis concludes that the flow is the same regardless of the RT values, as shown in Figures 7 and 8. From a phenomenological point of view, the result of this study is plausible. The acoustic characteristics of the room do not influence the air infiltrations.

However, other experimental studies have shown the influence of reverberation time on infiltrated airflow [12, 15]. Thus, the indoor reverberant field does not directly influence the infiltrated air flow, but through an intermediate parameter that can be measured: the indoor noise level. So, there is no direct link between the infiltrated air flow and the reverberation time, but an indirect link, through the level of sound pressure inside.

We expect the dimensions of the analyzed room, which determines the volume of the interior space, to have a significant influence on the reverberation time and, due to this, to influence the infiltrated air flow.

The results obtained by the ANOVA method are similar to those obtained by the authors, using the method of correlated analysis [15].

The mathematical model of the connection between the two transfer phenomena existing today in the literature [11, 12] can be improved by introducing the reverberation time as a new parameter. Namely, the mathematical relationship between the two phenomena remains a simple relationship (between air flow and noise level difference). However, before applying it, the value of the noise level at the measuring point in the absence of the reverberant field must be determined. This determination is made on the basis of real experimental measurements of sound pressure level and reverberation time. Through its results, this study led to a better understanding of the analyzed phenomenon and of the approach to be adopted in subsequent studies. The result of this study proves that the current acoustic method can be further extended and transformed into a method with wide applicability for different types of buildings.

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