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Selection of low-e windows in retrofit of public buildings by applying multiple criteria method COPRAS: A Lithuanian case

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Abstract

Calculations of building retrofit effectiveness have shown that the replacement of original windows with new ones is not as effective in terms of heat energy saving as are the insulation of a roof, walls and other improvements because the investments are large and take a long time to be repaid. However, in addition to energy saving, window replacement improves the indoor climate of the building, its interior and architectural appearance as well as its market value. The sequence of building operations determines when the replacement of windows should be done. When financial resources are limited, managers of public buildings often begin the renovation of a building's envelope with the replacement of windows. The client faces some problems in choosing among the great variety of windows to satisfy his/her needs, especially with respect to the cost-quality relationship. The method of multiple criteria complex proportional assessment (COPRAS) developed by the authors aims at solving the above-mentioned problems. The solutions based on multicriteria analysis allow for a more rational and realistic assessment of customer's needs as well as cutting down window renewal costs. In this paper, practical example (key-case) of selecting a contractor for the replacement of windows in the main building of Vilnius Gediminas Technical University (VGTU) is presented as a part of its retrofit multivariant design.

Keywords: Public building; Retrofit; COPRAS

1. Introduction

The authors of this paper are participating in the project Framework 6 "Bringing Retrofit Innovation to the Application of Public Buildings" (BRITA in PuBs) (see http://www.brita-in-pubs.com). Public buildings may be of different types, such as colleges, cultural centers, nurseries, student halls of residence, and churches, etc. Public buildings are most suitable for achieving the market's penetration of innovative and effective retrofit solutions to improve energy efficiency and implement renewables, with moderate additional costs. With their help it will be easier to reach groups of differing age and social origin. Public buildings can also be used as engines to heighten awareness and sensitize society on energy conservation.

In all European countries it can be observed that general opinion on the realization of energy saving measures differs greatly between residential and non-residential buildings as well as between new and existing buildings. Most European countries have succeeded in reducing their energy consumption in new dwellings by more than 50% without increasing the building cost and, therefore, energy efficiency concept has reached greater acceptance by the building's owners.

Development is quite different for the non-residential buildings. Energy consumption problems are secondary to the improvement of comfort. Decisions to retrofit a building are often made because of dissatisfaction regarding the comfort level. Therefore, the primary goal is to improve these comfort conditions. Decision makers are often skeptical about measures that aim to reduce energy consumption because they are afraid that these measures could limit the effect of improving the indoor climate and increase costs. The improvement of comfort as the primary aim can be achieved alongside energy saving.

It is, therefore, particularly important to demonstrate the effective solutions of public building retrofit and to make them visible to the wider public. One such project that represents the renovation of a main building at VGTU is considered in this paper.

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Retrofit evaluation of a building is quite difficult to undertake because a building and its environment are complex systems (embracing technical, technological, ecological, social, comfort, aesthetic and other aspects), where all subsystems influence the efficiency of performance and where interdependence between the subsystems plays a significant role. Coherent and effective retrofit scenarios are commonly designed on the basis of knowledge of the degradation state of the building and its obsolescence. A systematic method, based on multicriteria analysis and a constructivist approach are also helpful in designing retrofit scenarios [4].

A methodology for rating buildings or retrofit scenarios according to criteria, such as use of energy for heating, cooling and other appliances, impact on the environment, indoor climate and cost has been suggested [17].

The methodology of a multivariant design and multiple criteria analysis of a building's retrofit enables users to develop thousands of alternatives and to evaluate their economic, technical and architectural, aesthetic and comfort aspects [8].

For the energy saving measures to be profitable, the value of energy saved over the building's life will need to be greater than the capital investment and optimization would involve the selection of all measures with the savings-to-investment ratio (SIR) being more than one [5], where:

$$\mathrm{SIR} = \frac{\text{Present value of the total lifetime energy saving}}{\text{Investment cost}}. \quad (1)$$

The retrofit implementation of the benefits of some energy saving measures is associated not only with the reduction of energy consumption, but also with the improvement of the condition of the building elements, as well as with durability and the market value of a building [12]. Building retrofit also improves the indoor climate in the building, its interior and architectural appearance as well as raising its market value [22].

In terms of real estate market value, the effective retrofit may be described by the following market value ratio (MVR)

$$\mathrm{MVR} = \frac{M_{\mathrm{va}} - M_{\mathrm{vb}}}{C_{\mathrm{r}}}, \quad (2)$$

where M_{va} is the market value of building after retrofit; M_{vb}, the market value of building before retrofit; C_{r}, building retrofit costs. If the implement into retrofit has an MVR greater than 1, it can be regarded as being cost effective with respect to real estate market value. When real estate market is active, the replacement of windows is effective in terms of MVR which is greater than 1.

The efficiency of retrofit implements in the main VGTU building is calculated by determining their SIR (see Fig. 1). As shown in the figure, the most efficient renovation procedures include the upgrading of the heating unit, the reduction of glazed area and the provision of wall and roof insulation. The replacement of windows is not as effective in terms of heat energy saving because it is an expensive and slowly repaid investment (with SIR = 0.66). However, the windows of the VGTU building are old, unsafe, not opening & shutting and poorly insulated. In cold seasons, great heat losses are experienced due to poor insulation and sometimes there are draughts in the spaces. In general, the existing windows do not satisfy standard requirements, their thermal transmittance being $U_{\mathrm{w}} = 2.5\ \mathrm{W/m^2\,K}$.

The renovation of old windows is not reasonable from both technical and economical perspectives. Therefore, the most effective retrofit solution would be the replacement of the original windows with new ones. The building considered was designed and constructed 34 years ago, in the soviet times, when energy saving was not an acute problem. Buildings were designed with large glazed surfaces. Thus, the glazed area of the main VGTU building makes up 27% of the total enclosure surface of the building. Moreover, building renovation is

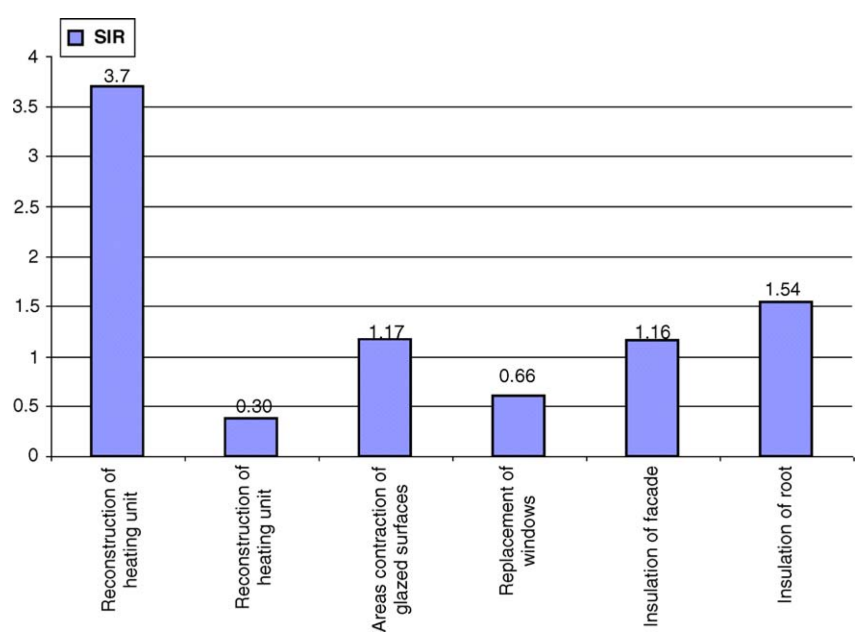

Fig. 1. Savings-to-investment ratios (SIR) for implements of retrofit in the main building of VGTU.

usually done in the following order: first, windows are renovated or replaced and, then, walls are insulated. Therefore, windows should be renovated or replaced prior to carrying out insulation work. As shown by infrared thermovision photographs that were used to determine heat losses of a building, the latter are mostly caused by poorly insulated low-quality windows. Their replacement by low-e windows can cut heating expenses up to 30%.

2. Various types of windows and the problem of making the proper choice

Windows, like doors, walls and the roof, make up an essential part of a building. These also play an important role in forming the façade and the interior of a building. A residential or public building can hardly be imagined without windows. However, about 30% of heat is lost, if windows are poorly insulated.

The main function of windows in a building is to pass light through to the interior and to decorate the building. However, windows are the thinnest elements transmitting cold, heat, noise, harmful ultraviolet rays, etc. into a building. Ordinary glass is mainly responsible for all negative effects because it conducts heat, noise, sunrays (from infrared to ultraviolet spectrum) as well as being fragile and easily broken. Thermal resistance of windows is much lower than that of walls, however, high-quality windows may reduce heat losses to a minimum. Modern technologies can provide windows with very good thermal and noise damping characteristics.

Good performance of windows may be achieved, if they are made of frost resistant glass, with a hermetically sealed frame and if the space in the room is well ventilated and heated. In general, in the process of a building's retrofit the balance between the main three components must be maintained (Fig. 2).

Windows multiple glazing units reduce heat losses through glass, while the emissive glass reflects from 40 to 70% of the heat rays back to room, and further improve the thermal insulation of the units. Multiple glazing units with low-e glass are filled with argon. This also increases their thermal insulation by 20%. Moreover, such windows retain two-thirds of harmful ultraviolet rays and in this way protect walls and furniture from fading. Multiple glazing units of the last generation with a soft emissive glass covering, emit threefold less heat into the atmosphere than ordinary units because their thermal transmittance may be very low, with $U_g = 1.1$ W/m^2 K.

Currently, used plastic windows may have profiles of three to eight chambers. Their thermal transmittance U_p ranges from 1.8 to 0.9 W/m^2 K. Eight closed air chambers of the frame profile can provide the best heat insulation characteristics. A special structure of plastic and aluminum reinforces the profiles as well as improving their insulation, by not using steel reinforcement as in an ordinary unit and, therefore, avoid cold air crossing.

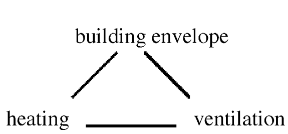

Fig. 2. The main retrofit components of a building.

Noise problems can be solved in various ways: thicker windowpanes or sheets of various thicknesses may be used for this purpose. The spacing between glass sheets can be enlarged or gases heavier than air, of two-chamber glazed units or laminated glass sheets with transparent acrylic rubber, etc. may also be used. Windows are divided into six classes according to their acoustic performance, while their weighed sound reduction index R_w can range from 25 to 50 dB [2]. Noise may be of high or low frequency or of a wide acoustic spectrum. Noise frequency should be determined prior to using any damping technique otherwise it would not provide the desired effect.

Multiple glazed units provide protection from hot solar rays with an external glass sheet made from reflective glass, which is more effective than dimmed glass. It reflects heat and light rays, and therefore, the illumination intensity in the room is lower. In fact, modern glass used in glazed units looks like ordinary transparent glass, but it can effectively reduce heat in summer and help to preserve heat in winter. To protect room from harmful ultraviolet radiation, reflective as well as laminated glass covered with PVC film or transparent acrylic rubber (from the inside), that allows only a very small percentage of ultraviolet radiation into the premises, is used.

According to resistance to wind load test pressure P1, windows are divided into six classes, i.e. from 400 Pa to more than 2000 Pa, while, according to frame deflection, they are divided into three classes: A ($\leq$1/150), B ($\leq$1/200), C ($\leq$1/300).

Windows should be watertight (weather resistant). According to the water-tightness test method A, windows are divided into 10 classes, i.e. water pressure may range from zero to more than 600 Pa. According to the test method B, windows may be divided into seven classes, with water pressure ranging from zero to more than 300 Pa.

According to air permeability, windows may belong to one of four classes, and under maximum test pressure it may range from 150 to 600 Pa. At 100 Pa, air permeability may range from 50 to 3 m^3/(m^2 h).

According to mechanical strength, windows are divided into four classes, while, according to resistance to repeatedly being opened and closed windows are divided into three classes (from 5000 to 20,000 cycles).Burglar resistance can be provided by laminated glass consisting of two 4-mm thick glass sheets and four layers of 1.52-mm thick film between them, by considerably increasing impact resistance of windows. According to this characteristic, windows are divided into five classes, with a drop height ranging from 200 mm to 950 mm, respectively.

According to reaction to fire, windows are grouped into seven classes.

Depending on a particular manufacturer, windows can also differ considerably in such characteristics as resistance to snow, permanent load and dangerous substances as well as radiation properties (i.e. solar factor g and light transmittance τ_v), ventilation (i.e. air flow exponent n and air flow characteristic K), explosion and burglar resistance, etc.

To ensure good window performance and to avoid weeping, windows should be properly installed and insulated. Proper installation accounts for 50% of a window's quality. An efficient ventilation system should also be provided. Special limit stops that adjust a window's position in opening and closing are used for providing microventilation. There are a great number of air vents aimed at allowing fresh air into spaces that can even have noise damping characteristics. Recently, air vents provided with humidity sensors that react to air humidity fluctuation in the premises have emerged on the market. When relative humidity exceeds the admissible level, the air vent is opened automatically to allow in some fresh air. To provide the required ventilation, the inflow and outflow of air should be ensured.

Today, various types of windows including wooden, plastic and aluminum windows are offered in the market. Modern windows should be selected and based on their quality and operational characteristics. The windows characteristics are associated with the type of building (residential or administrative), a particular district—the Old Town or a new district (with modern multistory buildings), etc. Nowadays, more than 200 enterprises produce modern windows in Lithuania, of which about 50 produce plastic windows made from a plastic profile and are manufactured both in Lithuania and abroad. There is a great offering of windows of various shapes made from various kinds of glass, e.g. transparent, dimmed, smoked, plate glass, etc. as well as limit stops, ventilation and hinging systems, etc.

Therefore, given the wide variety of windows, it is not easy, even for a specialist, to make a decision, as to what type of windows to choose, especially, when the quality of the products also differs considerably.

3. Contractor selection using COPRAS, a multicriteria decision making method

Selection of a retrofit contractor is a decision characterized by multiple objectives. Owners want to minimize the likely cost of projects, but they also want contractors to maintain schedules as well as to achieve acceptable quality standards [6]. Contractor selection is often based on the lowest bid that is made. However, the choice can be ineffective in terms of quality standard and lifetime. Contractors trying to win a contract often reduce the bid price. This may result in many changes, poor quality work, delays or perhaps all of these. From a client's point of view, such contractors are risky. Many countries have defined the criterion to limit the lowest bid price. In the USA and Canada, in the public sector, the "lowest bidder" is selected, but a bid bond in an amount equal to 10% of the bid price also has to be provided. In Denmark, the two highest and the two lowest bidders are excluded, while preference is given to a bidder suggesting an average bid price. The public sector system of bid evaluation, concentrating as it does solely on the bid price, is one of the major causes of project delivery problems. Most clients, especially those in the public sector, necessarily have to be accountable for their decisions and this becomes more difficult when selecting bidders other than the lowest.

A single criterion cannot give a full expression of the goals pursued by various clients. In most cases, the alternative versions provide a different degree of satisfaction to the client, i.e. bidders have different utility degrees [20]. Apparently, for selecting a contractor one such method based on utility theory should be used because award of contract should be made to the responsible contractor whose proposal provides the best overall value to the client. In the determination of the best value, other technical factors and the bid price should be separately ranked. A number of criteria relating to contractors and technical products need to be considered in selecting contractors. For this purpose, multicriteria decision methods can be used.

In Lithuania, the main characteristics of building products are described in technical specifications and provided together with the bidding documents. This helps to ensure fair competition as well as allowing for alternative engineering solutions to be considered. The client can reject a bid if the product does not meet the specification. Bids are assessed and based on the following criteria [10]:

(1) The lowest bid price.
(2) Economically effective bid chosen by considering a number of product characteristics, i.e. quality standard, price, aesthetic and operational characteristics, environmental and technical characteristics, maintenance costs, efficiency, warranty period and technical support, project delivery time, etc.

The client asks for determination of a relative weight for the criteria of every economically effective bid and in addition, he/she should evaluate the technical characteristics of the bids and inform the contractors about the evaluation results. Then, basing him/herself on the bid price, the client makes a general assessment of the bids. If the bid price is too low, the client should ask the contractor to give reasons for it. If the client is not satisfied with the reasons provided, he/she may reject the bid. The price is considered to be too low, if it is lower by 15% than the average price that is suggested by all the potential contractors.

For public procurement of construction works, the model of theory–bimatrix games may be applied [14].

Selection of a building renovation contractor can be performed in three stages [15]:

1. Selecting the criteria relating to a contractor and his/her product.
2. Pre-qualification of contractors, where the bid price is not one of the criteria.
3. The selection of construction and Project Manager of the renovation.

A variety of criteria have been proposed to date for contractor selection: in addition to the bid price, there are such criteria as financial soundness, technical ability, management capabilities, safety performance and reputation of a firm [6]. Examples of technical information that Metropolitan Washington Airports Authority may be requested to submit include [13]:

(i) recent experience with contracts of similar value;
(ii) evidence that they have the required specific technical capability and experience;
(iii) a technical proposal that describes how they will satisfy the client's requirements;

(iv) schedule of their current contracts;
(v) breakdown of their available equipment and workforce resources;
(vi) the firm's latest financial statement; and
(vii) evidence, such as a letter from an acceptable surety showing that the firm will be able to obtain bonds in the required amounts.

Therefore, a contractor's selection should be based not only on past experience and capabilities of the candidate but should also take into consideration quantitative and qualitative characteristics of the product, i.e. thermal transmittance of windows, weighed sound reduction index R_w, durability, etc. In this case, the problem of price and quality ratio arises. A low price cannot ensure quality standards that are expected by the client because the contractor can reduce costs at the expense of the product's quality.

For this purpose, a pre-qualification of contractors is made and is based on multicriteria analysis of the contractor's bidding for a window replacement's project. The choice of the project is made fully satisfying the client's needs at minimum cost [1]. Technical evaluation will normally be made without the technical evaluator(s) having access to the pricing data. Further, technical information, and the technical criteria alone can be used to establish a competitive range of proposals. A pre-qualification of contractors helps the client to identify contractors with whom the client could enter into a contract. The main goal in contractor pre-qualification is to establish a set of decision pre-qualification criteria (PQC) through which the capabilities of contractors are measured and judged. The choice of PQC depends on two factors: clients' objectives and the decision-maker's perceptions [15].

The client should decide on the type of windows he/she needs, especially, as regards to low thermal transmittance or high sound insulation windows. In general, the client should be aware of the available technical solutions of renovation [16]. He/she may get the necessary information from experts or in contractor pre-qualification. If the client is not sufficiently qualified to make a decision, it affects his/her choice of contractor.

A number of retrofit professionals were asked to elicit the utility functions needed to retrofit the main building of VGTU. Prior to performing a contractor's pre-qualification for the main building of VGTU windows replacement, window specialists, manufacturers, suppliers and researchers were consulted. The evaluation criteria were chosen taking into account the fact that VGTU is a public sector client. The type of client is an important factor that influences a contractor's bidding behavior [3]. Significant differences exist between the public and private sector's clients. PQC for a public client are more stringent and well defined so as to eliminate any imprudent inclusion of contractors.

Improvement of comfort in public buildings as the primary aim should be combined with measures for energy saving. Therefore, the selection of PQC for window replacement in VGTU was based on these two most important factors. To reduce heat energy losses and to provide comfortable conditions in the main building of VGTU, the sufficiently stringent minimal requirements of PQC were established. For example, they included thermal transmittance of the window profile $U_p \leq 1.4$ W/m^2 K, thermal transmittance of double glazing unit $U_g \leq 1.2$ W/m^2 K, emission ability of low emissive glass coating $\varepsilon \leq 0.1$, weighed sound reduction index $R_w \geq 32$ (-2, -5) dB, and light transmittance of double glazing unit $\tau_v \geq 78\%$, etc. (see Table 1). In general, the criteria had to satisfy 14 requirements.

One of the major tasks is to determine the weights of the criteria. To determine the weights of the criteria, the expert's judgment method is applied [9], which has been successfully used in research by the authors since 1987 [18,21]. This expert judgment method was implemented in the following stages:

- calculation of values t;
- calculation of weights q;
- calculation of values S;
- calculation of values T_k;
- calculation of values W;
- calculation of values χ^2;
- testing the statement $\chi^2 > \chi^2_{tbl}$.

The values t_{jk} for statistical processing were obtained by interviewing respondents. A survey of experts, based on

Table 1
PQC and minimal requirements for new windows

No.	PQC	Units of measurement	Minimal requirements
1.	Mechanical strength and stiffness	[a]	Conformity to standard GOST 24033-80
2.	Reliability	Cycles	≥10,000
3.	Thermal transmittance U_p of profile	W/m^2 K	≤1.4
4.	Thermal transmittance U_g of double glazing unit	W/m^2 K	≤1.2
5.	Emission ability of low emissive glass coating ε	[a]	≤0.1
6.	Weighed sound reduction index R_w	dB	≥32 (−2, −5)
7.	Air permeability, when pressure difference $\Delta p = 50$ Pa	(m^3/m^2 h)	≤0.5
8.	Water-tightness	Pa	≥250
9.	Warranty period	Years	≥5
10.	Durability	Years	≥30
11.	Light transmittance τ_v of double glazing unit	%	≥78
12.	Duration of work	Days	≤60
13.	The number of windows with two opening positions (horizontal and vertical) (in percent of the total area of windows)	%	≥25
14.	The number of windows with closing infiltration air vent or the third opening position (in percent of the total area of windows).	%	≥25

[a] There is no unit for criterion measurement.

questionnaires, was conducted to elicit data on the significance of criteria. The criteria provided for evaluation were actually similar to those used at the pre-qualification step, though they had been given much earlier than when this procedure was performed. All experts (interested parties) were subdivided into six categories: experts over 35 years of age, experts under 35, and students. Then, the experts were divided into two groups consisting of males and females. Teachers that were acquainted with the discussed window's problems, administration staff and students studying in the main building of VGTU represented the experts. About 30 questionnaires were filled and processed with the aim of finding the alternative of the type of windows that would meet the requirements of all interested parties. The evaluation scale ranged from 1 to 10 points: 1, 2: insignificant criterion; 3, 4: the criterion is of little significance; 5, 6: the criterion is of average significance; 7, 8: significant criterion; and 9, 10: very significant criterion. The average criterion value $\bar{t}_j$ was calculated by the formula:

$$\bar{t}_j = \frac{\sum_{k=1}^{r} t_{jk}}{r}, \quad (3)$$

where t_{jk} is the ranking of the jth criterion by the kth respondent; r, the number of respondents.

The weights of the criteria were calculated by dividing the sum of the criteria's average values by the average value of each criterion:

$$q = \frac{\sum_{j=1}^{n} \bar{t}_j}{t_j}. \quad (4)$$

Table 2
Bids of 5 contractors for pre-qualification in window replacement

PQC	Units of measu-rement	[a]	Weights of criteria	Ltd 1	Ltd 2	Ltd 3	Ltd 4	Ltd 5
Mechanical strength and stiffness	[b]	+	0.06875	1	1	1	1	1
Reliability	Cycles	+	0.07275	10,000	10,000	10,000	10,000	10,000
Thermal transmittance U_p of profile	$W/m^2 K$	−	0.091	1.2	1.4	1.4	1.4	1.4
Thermal transmittance U_g of double glazing unit	$W/m^2 K$	−	0.108	1.1	1.2	1.1	1.1	1.14
Emission ability of low emissive glass coating ε	[c]	−	0.0575	0.05	0.1	0.05	0.05	0.05
Weighed sound reduction index R_w	dB	+	0.08275	34	33	34	33	32
Air permeability, when pressure difference Δp = 50 Pa	$(m^3/m^2 h)$	−	0.0615	0.18	0.15	0.18	0.3	0.31
Water-tightness	Pa	+	0.0755	600	300	600	250	250
Warranty period	Years	+	0.0755	10	5	5	5	5
Longevity	Years	+	0.07725	35	30	50	40	30
Light transmittance τ_v of double glazing unit	%	+	0.055	81	78	81	79	78
Duration of works	Days	−	0.05625	60	50	60	60	60
The number of windows with two opening positions (horizontal and vertical) (in percent of the total area of windows)	%	+	0.05375	78.5	100	37	100	27.43
The number of windows with closing infiltration air vent or the third opening position (in % of the total area of windows)	%	+	0.0645	78.5	100	37	100	27.43

[a] The sign z_i (+/−) indicates that a higher/lower criterion value satisfies a client.
[b] Does it meet the specification requirements (if so, =1).
[c] There is no particular unit for criterion measurement.

The total weight of the criteria must be equal to one:

$$\sum_{j=1}^{n} \frac{\sum_{j=1}^{n} \bar{t}_j}{\bar{t}_j} = 1.0 \tag{5}$$

The reliability of the data can be expressed by the coefficient of concordance (agreement) of the respondents' opinions by describing the extent of proximity of individual views. In the cases with reiterated ranks for the same parameters, as in this case, the coefficient of concordance is:

$$W = \frac{12S}{r^2(n^3 - n) - r\sum_{k=1}^{r} T_k}, \quad W \in [0; 1] \tag{6}$$

where S total square deviation of the rankings of each criterion; T_k, the index of reiterated ranks in the r rank; n, the number of evaluation criteria.

The deviation of the criterion ranking is as follows:

$$S = \sum_{j=1}^{n}\left[\sum_{k=1}^{r} t_{jk} - \frac{1}{n}\sum_{j=1}^{n}\sum_{k=1}^{r} t_{jk}\right]^2, \tag{7}$$

where t_{jk} is the rank conferred by the kth respondent to the jth criterion.

However, the calculated value W is stochastic, meaning that the significance of the concordance coefficient has to be calculated. Kendall has shown that, when $n > 7$, then the value $\chi^2 = Wr(n - 1)$ has a distribution with degrees of freedom $\nu = n - 1$. It has also been proved that if the calculated value χ^2 is larger than the critical tabular value χ^2_{tbl} for the pre-selected level of significance (e.g. $\alpha = 0.05$), then the hypothesis on the agreement of independent experts' judgments is not rejected. In our case, we have $n = 14$, $\nu = 13$ and the pre-selected level of significance is $\alpha = 0.05$, therefore, the above-mentioned conditions are satisfied.

The significance χ^2 of the concordance coefficient is calculated as follows:

$$\chi^2_{\alpha,\nu} = Wr(n-1) = \frac{12S}{rn(n+1)(-1/n-1)\sum_{k=1}^{r} T} \tag{8}$$

If $\chi^2_{\alpha,\nu} > \chi^2_{tbl}$, the significance of the concordance coefficient exists at α level, then the agreement of experts' opinions is satisfactory and a group's opinion is established. Otherwise, when $\chi^2_{\alpha,\nu} < \chi^2_{tbl}$ is obtained, the respondents' opinions are not in agreement, implying that they differ substantially and the hypothesis of the rank's correlation cannot be accepted.

The concordance coefficient based on the criteria weights is $W = 0.87$. The value of $\chi^2_{\alpha,\nu}$ calculated by formula (8) is equal to 26.36. This value should be greater than χ^2_{tbl}, which depends on the degrees of freedom ν and the pre-selected level of significance α. In this case, the tabular value was taken from Fisher and Yates statistical tables. When the degrees of freedom $\nu = 13$ and pre-selected level of significance is $\alpha = 0.05$ (or error probability $P = 5\%$), then we have the value of χ^2_{tbl} equal to 23.685. Since $26.36 > 23.685$, when $\alpha = 0.05$, and $\nu = 13$, then, the assumption is made that the coefficient of concordance is significant and expert rankings are in concordance with 95% probability. The significances of the criteria obtained by this method are presented in Table 2.

The best-known Lithuanian firms were invited to take part in the pre-qualification for window replacement. Two of firms could not meet the requirements needed to provide sufficient thermal transmittance of the profile and light transmittance of double-glazing unit. Finally, five firms remained which submitted their bids (see Table 2).

The first bidder offered windows that had the best qualities according to the following criteria: thermal transmittance of profile $U_p = 1.2$ W/m^2 K, thermal transmittance of double glazing unit $U_g = 1.1$ W/m^2 K, emission ability of low emissive glass coating $\varepsilon = 0.05$, weighed sound reduction index $R_w = 34$ dB, light transmittance of double glazing unit $\tau_v = 81\%$, water-tightness $p = 600$ Pa, warranty period 10 years. However, these windows were worse according to these criteria: longevity—35 years, duration of work—60 days, the amount of windows with two opening positions—78.5%, the number of windows with closing infiltration air vent or the third opening position (in % of the total area of windows) 78.5%. It is hardly possible to choose the best alternative based only on a visual inspection of products without using any mathematical methods.

The MCDM method COPRAS was first announced in 1994 [19]. This method assumes direct and proportional dependence of the significance and utility degree of investigated versions on a system of criteria adequately describing the alternatives and on values and weights of the criteria. Determination of significance, the priority order and utility degree of the alternatives is carried out in five stages [8]:

1. Forming the weighted normalized decision-making matrix D (see Table 3).
2. Calculating the sums of weighted normalized indices describing the jth alternative.
3. Determining the significances Q_j of the compared alternatives describing the advantages S_{+j} and disadvantages S_{-j} of the alternatives.
4. Calculating the utility degree N_j of alternative a_j.
5. Determining the priority order of the alternatives.

The results of multiple criteria evaluation of five window replacement versions for the pre-qualification of bidders shows that the first alternative is the best with respect to the utility degree that equals 100%, the third version is the second best in the utility degree that equals 86.35%, the second version is the third best in the utility degree that equals 71.15, etc. This shows that the first alternative is more useful than the third alternative by 13.65%, and is more useful than the second alternative by 28.85%.

The next stage in the final choice of a contractor includes the consideration of bids by the candidates who satisfied the pre-qualification requirements. At this stage, an additional criterion, i.e. bid price, is considered alongside the criteria of technical specifications. Once technical evaluation is complete, price proposals of contractors on the final short-list will be combined with the technical score in making the final selection of a contract's award.

Table 3
The data obtained in multiple criteria analysis of five contractors' bids in pre-qualification for window replacement in the main building of VGTU

PQC	Weighted normalized values of the criteria describing the compared alternatives (matrix D)				
	Ltd 1	Ltd 2	Ltd 3	Ltd 4	Ltd 5
Mechanical strength and stiffness	0.0138	0.0138	0.0138	0.0138	0.0138
Reliability	0.0177	0.0177	0.0177	0.0018	0.0177
Thermal transmittance U_p of profile	0.0161	0.0187	0.0187	0.0187	0.0187
Thermal transmittance U_g of double glazing unit	0.0211	0.023	0.0211	0.0211	0.0218
Emission ability of low emissive glass coating ε	0.0096	0.0192	0.0096	0.0096	0.0096
Weighed sound reduction index R_w	0.0169	0.0165	0.0169	0.0165	0.016
Air permeability, when pressure difference $\Delta p = 50$ Pa	0.0099	0.0082	0.0099	0.0165	0.017
Water-tightness	0.0226	0.0113	0.0226	0.0094	0.0094
Warranty period	0.0252	0.0126	0.0126	0.0126	0.0126
Longevity	0.0146	0.0125	0.0209	0.0167	0.0125
Light transmittance τ_v of double glazing unit	0.0112	0.0108	0.0112	0.0109	0.0108
Duration of works	0.0116	0.0097	0.0116	0.0116	0.0116
The number of windows with two opening positions (horizontal and vertical) (in % of the total area of windows)	0.0123	0.0157	0.0058	0.0157	0.0043
The number of windows with closing infiltration air vent or the third opening position (in % of the total area of windows)	0.0148	0.0188	0.007	0.0188	0.0052
Total sum of maximizing normalized indices S_{+j}	0.1491	0.1297	0.1285	0.1162	0.1023
Total sum of minimizing normalized indices S_{-j}	0.0683	0.0788	0.0709	0.0775	0.0787
Alternative's significance Q_j	0.2308	0.2005	0.2072	0.1882	0.1732
Alternative's degree of efficiency N_j	100%	86.87%	89.77%	81.54%	75.04%
Priority order of alternative	1	3	2	4	5

In assessing the economic effect of bids and stating the priorities, bid prices and relative weights of values should be determined. For this purpose, Holt et al. combine the so-called P2 points (symbolizing the information collected about a bid) with P3 points (referring to the bid price) to make a single criterion. Holt et al. set the weight of 0.40 to P2 and 0.60 to P3 [7]. The Finnish Road Administration applies the price points (with a relative weight of 0.75) and quality points (with a relative weight of 0.25) [11] in choosing the contractor. The relative weight of the construction's cost in Lithuania can be 0.60, while the sum of the relative weights in the evaluation of operational characteristics and maintenance costs may reach 0.40. The relative weight of 0.60 is specified when the price and three or more other criteria are evaluated. Therefore, the relative weight of the price was taken to be equal to 0.6, while the relative weight of operational-maintenance characteristics was 0.4 [10]. Contractors offered the following prices for window replacement (see Table 4).

We can see that Ltd 1 offered the lowest bid price, while was Ltd 4 offered the highest price. According to pre-qualification results, Ltd 1 was first in the list of priorities, while Ltd 3 was the second and Ltd 2 was the third.

The final choice of a low-e window's contractor was made by using the MCDM method COPRAS. According to the calculation's results, Ltd 1, which was the best in pre-qualification, offered windows that have the highest utility for a client in terms of technical characteristics and a good price for the product. The first alternative is also the best in terms of its utility degree that equals 100%. Low-e windows offered by the first bidder have the following technical characteristics: thermal transmittance of the profile $U_p = 1.2$ W/m^2 K, thermal transmittance of double glazing unit $U_g = 1.1$ W/m^2 K, emission ability of low emissive glass coating $\varepsilon = 0.05$, weighed sound reduction index $R_w = 34$ dB, light transmittance of double glazing unit $\tau_v = 81\%$, water-tightness $p = 600$ Pa, warranty period 10 years, longevity 35 years, duration of works—60 days, the number of windows with the third opening position (in % of the total area of windows) 78.5%.

Table 4
Contractors' bid prices for window replacement

Contractor bids (USD)	
Ltd 1	72,116
Ltd 2	101,896
Ltd 3	84,176
Ltd 4	115,072
Ltd 5	92,166

Fig. 3. A view of the main building of VGTU with replaced windows.

However, the priority order of other firms (contractors) changed after the final evaluation. Thus, Ltd 1, 2 and 3 retained their positions that were obtained in pre-qualification, while Ltd 4 and 5 changed places in the list of priorities.

The windows in the main building of VGTU were replaced according to the results obtained by using the MCDM method COPRAS (Fig. 3).

4. Conclusions

In order to realize an effective selection of low-e windows in a building's retrofit, it is necessary to carry out an exhaustive investigation of all possible solutions. The efficiency level of a particular window's replacement alternative depends on a large number of factors, including cost of the project, energy savings gained after renovation, tentative pay-back time, thermal transmittance of the profile and double glazing unit, emission ability of low emissive glass coating, weighed sound reduction index, light transmittance of double glazing unit, water-tightness, warranty period, longevity, the number of windows with the third opening position, and duration of work, etc.

On the other hand, the evaluation of the retrofit also benefits in respect to heat energy savings as was shown in the main building of VGTU in that the replacement of the original windows with the new ones is not so effective as other improvements (SIR = 0.66). However, in addition to energy saving, window replacement improves the indoor climate of the building, its interior and architectural appearance as well as raising its market value. When the financial resources are limited, managers often resort to window replacement as the first step in a building's retrofit.

The MCDM method COPRAS provides an opportunity to select a low-e windows contractor. The selection of a low-e windows contractor by using this method allows for a more precise assessment of a customer's needs as well as cutting down the window replacement's costs.

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