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Multivariant design and multiple criteria analysis of building refurbishments

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Abstract

In order to design and realize an efficient building refurbishment, it is necessary to carry out an exhaustive investigation of all solutions that form it. The efficiency level of the considered building's refurbishment depends on a great many of factors, including: cost of refurbishment, annual fuel economy after refurbishment, tentative pay-back time, harmfulness to health of the materials used, aesthetics, maintenance properties, functionality, comfort, sound insulation and longevity, etc. Solutions of an alternative character allow for a more rational and realistic assessment of economic, ecological, legislative, climatic, social and political conditions, traditions and for better the satisfaction of customer requirements. They also enable one to cut down on refurbishment costs. In carrying out the multivariant design and multiple criteria analysis of a building refurbishment much data was processed and evaluated. Feasible alternatives could be as many as 100,000. How to perform a multivariant design and multiple criteria analysis of alternate alternatives based on the enormous amount of information became the problem. Method of multivariant design and multiple criteria of a building refurbishment's analysis were developed by the authors to solve the above problems. In order to demonstrate the developed method, a practical example is presented in this paper.

Keywords: Building refurbishment; New method; Multiple criteria analysis

1. Introduction

The authors of this paper participated in the project Framework 6 "Bringing Retrofit Innovation to the Application of Public Buildings" (BRITA in PuBs). The BRITA proposal on Eco-buildings aims at increasing the market penetration of innovative and effective retrofit solutions so as to improve energy efficiency and to implement renewables, with moderate additional costs. In the first place, this will be realized by the exemplary retrofit of nine demonstration public buildings (see http://dss.vtu.lt/renovacija/index_educational.asp). One of the project's goals was to develop the method of multivariant design and multiple criteria analysis of a building's refurbishment and on that basis, developed a Decision Support System for building refurbishment. The method developed and the problem solved is presented in the paper in Sections 4 and 5. Section 2 presents decision-making models and methods that were used in the building refurbishment. Section 3 discusses the collection of initial data for a multiple criteria analysis.

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2. Decision-making models and methods

A thorough building's refurbishment evaluation is quite difficult to undertake, because a building and its environment are complex systems (technical, technological, ecological, social, comfort, esthetical, etc.), where all sub-systems influence the total efficiency performance and where the interdependence between sub-systems play a significant role.

Many decision-making models and methods (cost–benefit analysis [2], multiple criteria analysis [1], the lattice method for global optimization [4], predict a building's habitability index [3] and energy rating systems for existing houses [7], etc.) have been developed in the world for solving the above-mentioned and other problems.

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Goodacre et al. [2] use a cost–benefit analysis framework to assess the potential scale of some of the benefits from the comprehensive upgrading of heating and hot water energy's efficiency in the English building stock. Goodacre et al. [2] attempted to evaluate the potential scale for societal costs that are associated with poor levels of domestic space heating and hot water energy's efficiency in the English building sector. The basic premise of this paper has been that an appraisal of these costs should be evaluated against a wider range of potential benefits, not only the direct benefits (micro-economic) and current government monetary appraisals [2].

The TOBUS method aims at offering a tool for selecting office building's upgrading solutions with respect to multiple criteria. One of the key elements to reach this goal is an assessment of the degree of physical degradation, extent of any degradation, extent of the necessary work to renovate the building and the costs [1].

The energy performance in buildings is a complex function of the building's form and structure, heating system, occupancy pattern, operating schedules, and the external climatic conditions. To carry out a multi-parameter analysis for the optimization of the building's energy performance, the lattice method for global optimization was used [4].

Kasuda [3] would like to see the extension of the predicted building habitability index (PIHI) as an integrated evaluation criterion for a building's performance in which the simulated hourly energy consumption, comfort index and system's economic factors were weighted (in accordance to specific application requirements) and were algebraically summed up to arrive at an index for determining the building's air conditioning needs. This PIHI concept can be extended to include other elements such as lighting, acoustics, moisture condensation, plumbing, etc. [3].

According to [7], different approaches have been developed to evaluate the energy performance of houses, by using a simple index and they are known under the generic term of home energy rating systems (HERS) which can be classified in the following three main categories: the points system, which evaluates the energy performance of a house by giving points of performance or scores to each subsystem such as exterior walls, roof or heating system; the performance system, which assigns an index of performance in terms of the annual heating energy consumption or cost; and the awareness system, which recommends the total annual and heating site's energy consumption, and the corresponding costs, in terms of the year the house was constructed and its climatic zone and the source of energy.

As one can see, the above-mentioned research has enabled the authors to solve a majority of problems in a complex way as far as a building's renovation is concerned. However, one of the weakest aspects of the above research was the formation and multiple criteria analysis of alternative variants of the whole building. The authors of this paper have developed a method of multivariant design and multiple criteria analysis of a building's refurbishment to tackle these problems.

3. Collection of initial data for multiple criteria analysis

The determination of the building refurbishment's utility degree and the establishment of the order of priority for its implementation has less difficulty if the criteria values and weights are obtained and when multiple criteria decision-making (MCDM) methods are used.

All criteria are calculated for the whole project. The decision tree of criteria decomposes the refurbishment problem at hand, into sub-problems (criteria) that are, in their turn, decomposed into sub-problems and so on until the problem is represented as a decision tree of criteria. The process for determining the system of criteria, numerical values and initial weights of the qualitative criteria of the project under investigation, are based on the use of various experts' methods.

The results of the comparative analysis of projects are presented as a grouped decision-making matrix where columns contain n alternative projects, while all quantitative and conceptual information pertaining to them is found in Table 1. Any alternative that has a criterion value worse than the required level is rejected.

In order to perform a complete study of the project, a complex evaluation of its economic, qualitative, technical, technological, ecological, climatic and social conditions, traditions and for better satisfaction of customer requirements is needed. Quantitative and conceptual descriptions provide this information. The diversity of aspects being assessed should include a variety of presented data that are needed for decision-making. Therefore, the necessary conceptual information may be presented in numerical, textual, graphical (schemes, graphs, diagrams, drawings), equation formats and audio or as videotapes. The criteria used for conceptual descriptions, their definitions and reasons for the choice of the criteria's system, their values and weights should all be analyzed. Conceptual information about the possible ways of doing a multivariant design is needed to make a more complete and accurate evaluation.

Quantitative information is based on criteria systems and subsystems, units of measure, values and initial weights of the projects' alternatives.

Conceptual information is a more flexible and less accurate means of expressing estimates than numbers. Quantitative information is more accurate and reliable and allows one to use multiple criteria decision-making methods.

The information's grouping in the matrix should be performed so as to facilitate the calculation process and to express their meaning. The criteria system here is formed from criteria describing the building's refurbishment as expressed in a quantitative form (quantitative criteria) and

Table 1
Grouped decision-making matrix of refurbishment project's multiple criteria analysis

Criteria describing the project	[a]	Weights	Measuring units	Comparable projects					
				1	2	...	j	...	n
Quantitative criteria									
X_1	z_1	q_1	m_1	x_{11}	x_{12}	...	x_{1j}	...	x_{1n}
X_2	z_2	q_2	m_2	x_{21}	x_{22}	...	x_{2j}	...	x_{2n}
...	...	...	...	...	...	...	...	...	...
X_i	z_i	q_i	m_i	x_{i1}	x_{i2}	...	x_{ij}	...	x_{in}
...	...	...	...	...	...	...	...	...	...
X_m	z_m	q_m	m_m	x_{m1}	x_{m2}	...	x_{mj}	...	x_{mn}
Qualitative criteria									
X_n	z_n	q_n	m_n	x_{n1}	$x_{n\ 2}$	...	$x_{n\ j}$	...	$x_{n\ n}$
...	...	...	...	...	...	...	...	...	...
X_q	z_q	q_q	m_q	x_{q1}	x_{q2}	...	x_{qj}	...	x_{qn}
...	...	...	...	...	...	...	...	...	...
X_t	z_t	q_t	m_t	x_{t1}	x_{t2}	...	x_{tj}	...	x_{tn}
Conceptual information relevant to projects (i.e. text, drawings, graphics, video tapes)									
C_f	C_z	C_q	C_m	C_1	C_2	...	C_j	...	C_n

[a] The sign z_i (±) indicates that a greater/lesser criterion value corresponds to a greater weight for a client.

the criteria describing the building's refurbishment that cannot be expressed in a quantitative form (qualitative criteria).

The qualitative criteria values should be put into a numerical and comparable form. They must be comparable because a ''medium'' value for one qualitative criterion needs to receive approximately the same numerical values as ''medium'' values of other qualitative criteria.

4. A method of multivariant design and multiple criteria analysis of a building's refurbishment

According to the method developed by authors, the determination of significance, priority and utility degree of alternatives is carried out in the first six stages [5,6]. These stages assume direct and proportional dependence of significance and the utility degree of investigated versions on a system of criteria that adequately describes the alternatives, and values and weights of the criteria. A decision maker by using the best practices of similar situations and experts' methods determines the system of criteria and calculates the values and initial weights of qualitative criteria. Multivariant design and multiple criteria analysis of the whole building refurbishment are carried out in next six stages.

4.1. Determination of the significance, utility degree and priority of all the renovation elements of a building

While carrying out building renovations it is rational to analyze all its possible combinations. In order to create possible combinations, the efficiency of separate elements (windows, walls, thermal units, roof, etc.) of building renovations should be analyzed. The efficiency of these separate elements of building renovations is estimated during the first five stages.

Stage 1: The weighted normalized decision-making matrix D is formed (see Table 2) at this stage. The purpose here is to receive dimensionless weighted values from comparative indexes. When the dimensionless values of the indexes are known, all criteria can be compared. The following equation is used for this purpose:

$$d_{ij} = \frac{x_{ij} q_i}{\sum_{j=1}^{n} x_{ij}}, \quad i = \overline{1,m}; \quad j = \overline{1,n}, \tag{1}$$

where x_{ij} is the value of i criterion in j alternative of a solution; m the number of criteria; n the number of the alternatives compared; q_i weight of i criterion.

The sum of dimensionless weighted index values d_{ij} of each criterion x_i is always equal to the weight q_i:

$$q_i = \sum_{j=1}^{n} d_{ij}, \quad i = \overline{1,m}; \quad j = \overline{1,n}. \tag{2}$$

In other words, the value of weight q_i of the investigated criterion is proportionally distributed among all alternative versions a_j according to their value x_{ij}.

Stage 2: The sums of weighted normalized indexes describing the jth version are calculated. The versions are described by minimizing indexes S_{-j} and maximizing indexes S_{+j}. The lower the value of minimizing indexes, such as the price of a building's refurbishment, the better the attainment of goals. The greater the value of maximizing indexes, such as comfort and aesthetics, the better attainment of goals.

Sums are calculated according to:

$$S_{+j} = \sum_{i=1}^{m} d_{+ij}; \qquad S_{-j} = \sum_{i=1}^{m} d_{-ij}, \quad i = \overline{1,m}; \quad j = \overline{1,n}. \tag{3}$$

Table 2
Building's refurbishment multiple criteria analysis results

Criteria under evaluation	Measuring units	[a]	Weights	Comparable projects (matrix D)					
				1	2	...	j	...	n
X_1	m_1	z_1	q_1	d_{11}	d_{12}	...	d_{1j}	...	d_{1n}
X_2	m_2	z_2	q_2	d_{21}	d_{22}	...	d_{2j}	...	d_{2n}
...	...	...	...	...	...	...	...	...	...
X_m	m_m	z_m	q_m	d_{m1}	d_{m2}	...	d_{mj}	...	d_{mn}
...	...	...	...	...	...	...	...	...	...
X_t	m_t	z_t	q_t	d_{t1}	d_{t2}	...	d_{tj}	...	d_{tn}
The sums of weighted normalized maximizing indices of the project				S_{+1}	S_{+2}	...	S_{+j}	...	S_{+n}
The sums of weighted normalized minimizing indices of the project				S_{-1}	S_{-2}	...	S_{-j}	...	S_{-n}
Significance of the project				Q_1	Q_2	...	Q_j	...	Q_n
Project's priorities				Pr_1	Pr_2	...	Pr_j	...	Pr_n
Project's utility degree (%)				N_1	N_2	...	N_j	...	N_n

[a] The sign z_i ($\pm$) indicates that a greater/lesser criterion value satisfies a client.

The greater the value S_{+j}, the more satisfaction of the stakeholders. The lower the value S_{-j}, the better the attainment of goals of stakeholders. S_{+j} and S_{-j} express the degree of goals attained by the stakeholders in each project. In any case, the sums of 'pluses' S_{+j} and 'minuses' S_{-j} of alternative projects are always, respectively, equal to sums of weights of maximizing and minimizing criteria:

$$S_{+} = \sum_{j=1}^{n} S_{+j} = \sum_{i=1}^{m}\sum_{j=1}^{n} d_{+ij},$$
$$S_{-} = \sum_{j=1}^{n} S_{-j} = \sum_{i=1}^{m}\sum_{j=1}^{n} d_{-ij}, \quad i = \overline{1,m}; \quad j = \overline{1,n}. \tag{4}$$

In this way, the calculations may be additionally checked.

Stage 3: The significance of comparative alternatives is determined on the basis of describing positive projects' characteristics S_{+j} and negative projects characteristics S_{-j}. The relative significance Q_j of each project a_j is found according to (see Table 2):

$$Q_j = S_{+j} + \frac{S_{-\min}\sum_{j=1}^{n} S_{-j}}{S_{-j}\sum_{j=1}^{n} S_{-\min}/S_{-j}}, \quad j = \overline{1,n}. \tag{5}$$

Stage 4: Determination of building refurbishment's priorities (Q_j). The greater Q_j, the higher is the priority of the project. The significance Q_j of a building's refurbishment a_j indicates the satisfaction degree of demands and goals pursued by the stakeholders. In this case, the significance $Q_{\max}$ of the most rational project will always be the highest. The significance of all remaining projects is lower, compared to the most efficient building refurbishment. Total demands and goals of stakeholders will be satisfied to a smaller extent than in the case of the best project.

Stage 5: It is assumed that people can measure values of various projects, in terms of the so-called *utility*. Each project has its consumer or other stakeholder utility. In the proposed method, the utility of alternatives is measured quantitatively.

The degree of the project's utility is directly associated with the quantitative and conceptual information that is related to the building's refurbishment. If one project is characterized by the highest comfort level, aesthetics, lowest price indices, while other projects show better maintenance characteristics, having obtained the same significance values as a result of multiple criteria evaluation, it means that their utility degree is also equal. With the increase/decrease of the significance of a building's refurbishment, its degree of utility also increases/decreases. The degree of project utility is determined by comparing the analyzed projects with the most efficient project. All the values of the utility degree related to the analyzed projects will range from 0% to 100%.

Utility degree N_j of building refurbishment a_j is calculated as follows:

$$N_j = (Q_j : Q_{\max}) \times 100\%. \tag{6}$$

where Q_j and $Q_{\max}$ are the significance of projects obtained from Eq. (5).

Stage 6: Determination of the significance, utility degree and priority of all building renovation elements. Further on, one repeats the first five stages till the significance, utility degree and priority of all the renovation elements of a building are estimated (see Table 3).

4.2. Multivariant design and multiple criteria analysis of the whole building's refurbishment

Much data had to be processed and evaluated in carrying out the multivariant design and multiple criteria analysis of a building refurbishment. Numbers of feasible alternatives can be as large as 100,000. Each of the alternatives may be described from various perspectives, e.g. by conceptual and quantitative information. The problem arises as how to perform design and multiple criteria analysis of the alternatives, based on this enormous amount of information. To solve this problem, multivariant design and multiple criteria analysis of the whole building refurbishment are carried out in stages 7–12. These stages are briefly described below.

Table 3
Most efficient solution alternatives set according to priorities (priority table)

Solutions considered	Significance of solutions	Priority of the best alternative solutions						
		1	2	3	...	j	...	p
1. Window alternatives	Q_1	a_{11}	a_{12}	a_{13}	...	a_{1j}	...	a_{1p}
2. Wall alternatives	Q_2	a_{21}	a_{22}	a_{23}	...	a_{2j}	...	a_{2p}
...	...	...	...	...	...	...	...	...
i. Thermal unit alternatives	Q_i	a_{i1}	a_{i2}	a_{i3}	...	a_{ij}	...	a_{ip}
...	...	...	...	...	...	...	...	...
t. Roof alternatives	Q_t	a_{t1}	a_{t2}	a_{t3}	...	a_{tj}	...	a_{tp}

Stage 7: Rejection of potentially inefficient versions. When determining possible building refurbishment alternative versions, 10 alternatives are considered for any 10 solutions and then until ten billion combinations of building refurbishments can be obtained. It is evident that in this and similar cases, it is hardly possible to analyze all the versions from various perspectives. Therefore, it is advisable to reduce their numbers as follows. If a building refurbishment of t solutions having n_i alternatives allows k combinations (see Eq. (7)) by using multiple criteria analysis methods, p most efficient versions should be chosen from every solution for further consideration (see Table 3). This stage involves removing non-rational alternatives before entering further phases. Any alternatives passing this sieve become candidates for further evaluation. In this way, inefficient alternatives are removed. The best alternatives for solutions are obtained then grouped according to priorities. In Table 3, a_{i1} is a code of the best variant of i solution, while a_{ip} is a code of its weakest version.

That is, the alternatives are arranged in descending order of priority in the table. There is also the total weight (Q_i) and refers to their total significance, the given total utility and the price in the context of all the building's renovation.

Stage 8: Development of codes of building refurbishment's alternative solutions with conceptual and quantitative information. In order to reduce the amount of information used in the multivariant design, codes of alternative solutions are used. Any i solution of j alternative is given a_{ij} code providing thorough system of criteria, units of measure, weights and values. As well, conceptual (text, drawings, graphics, videotapes) information about the alternative being considered (see Table 4) is presented. The use of codes for alternative solutions in multivariant design reduces the volume of information and provides a better insight into the physical meaning of computations.

Development of the table of building refurbishment alternative solutions' codes includes the formation of the alternative codes and conceptual and quantitative data provided with their help. Codes, providing conceptual and quantitative information, are used for describing all available alternative building refurbishment solutions. The total number of code forms the table of codes of building refurbishment alternatives, allowing one to get the alternative versions in a more simple way. Table 4 shows t solutions of a building refurbishment (windows, walls, thermal units, roof, etc.) of the n_i alternative versions codes.

Any i line of the code table represents the codes of A_i solution and a_{ij} alternatives. If the information relating to the solutions in the code table of building refurbishment alternatives is represented by codes, then the code contains quantitative and conceptual information (see Table 4). Here n_i alternatives of any i solution are considered when

Table 4
Codes of building refurbishment alternative solutions with conceptual and quantitative information

Solutions considered	The codes of the alternative solutions considered						
	1	2	3	...	j	...	n_i
1. Window alternatives	a_{11}	a_{12}	a_{13}	...	a_{1j}	...	a_{1n}
2. Wall alternatives	a_{21}	a_{22}	a_{23}	...	a_{2j}	...	a_{2n}
...	...	...	...	...	...	...	...
i. Thermal unit alternatives	a_{i1}	a_{i2}	a_{i3}	...	$\mathbf{a_{ij}}$	...	a_{in}
...	...	...	...	...	...	...	...
t. Roof alternatives	a_{t1}	a_{t2}	a_{t3}	...	a_{tj}	...	a_{tn}
The information provided by code a_{ij} of i solution j alternative							
Conceptual information	Information						
	Cost, X_1	Aesthetics, X_2	Comfort, X_3	...	X_j	...	Quality, X_n
C_{ij}	$x_{ij\,1}$	$x_{ij\,2}$	$x_{ij\,3}$	...	$x_{ij\,j}$	...	$x_{ij\,n}$
Units of measure	USD	Points	Points	...	$u_{ij\,j}$	...	Points
Weights	$q_{ij\,1}$	$q_{ij\,2}$	$q_{ij\,3}$	...	$q_{ij\,j}$	...	$q_{ij\,n}$
*	$z_{ij\,1}$	$z_{ij\,2}$	$z_{ij\,3}$	...	$z_{ij\,j}$	...	$z_{ij\,n}$

*The sign z_i (+/−) indicates that a greater/lesser criterion value satisfies a client.

Table 5
Development of building refurbishment alternatives based on codes of solution variants

Solutions considered	Development of building refurbishment alternatives based on codes of solution alternatives											
	1	2	3	...	p	$p+1$	$p+2$	$p+3$	...	$2p$	...	K
1. Window alternatives	a_{11}	a_{11}	a_{11}	...	a_{11}	a_{11}	a_{11}	a_{11}	...	a_{11}	...	a_{1p}
2. Wall alternatives	a_{21}	a_{21}	a_{21}	...	a_{21}	a_{21}	a_{21}	a_{21}	...	a_{21}	...	a_{2p}
...	...	...	...	...	...	...	...	...	...	...	...	...
i. Thermal unit alternatives	a_{i1}	a_{i1}	a_{i1}	...	a_{i1}	a_{i1}	a_{i1}	a_{i1}	...	a_{i1}	...	...
...	...	...	...	...	...	...	...	...	...	...	...	...
$t-1$	$a_{t-1\ 1}$	$a_{t-1\ 1}$	$a_{t-1\ 1}$	...	$a_{t-1\ 1}$	$a_{t-1\ 2}$	$a_{t-1\ 2}$	$a_{t-1\ 2}$	...	$a_{t-1\ 2}$	...	$a_{t-1\ p}$
t. Roof alternatives	a_{t1}	a_{t2}	a_{t3}	...	a_{tp}	a_{t1}	a_{t2}	a_{t3}	...	a_{tp}	...	a_{tp}

developing the alternative versions of a building refurbishment. The maximum number of projects obtained may be calculated as follows:

$$k = \prod_{i=1}^{t} n_i \qquad (7)$$

where t is the number of solutions considered in determining a building refurbishment; n_i the number of i solution alternatives to be used in developing a building refurbishment.

Stage 9: Development of building refurbishment alternatives based on codes of solution alternatives. Building refurbishment alternatives are developed and based on the efficient p alternatives of chosen c solutions. At the beginning, this process should involve the codes of alternative solutions. The first building refurbishment variant is obtained by analyzing the best solution alternatives according to a priority (see Table 5). In the process of forming possible versions the compatibility of separate variants of complex renovation is taken into account. The best alternatives of renovated building elements frequently are not compatible, which is encountered in practice. A null variant of building renovation is also being analyzed, when a building is not renovated at all. Maybe the market value of this building is comparatively low, and the building is not worth to be renovated? The last variant is based on solution versions from the end of the priority table (see Table 3). Intermediate alternatives are obtained with an account of versions and are also found on this table. The first building refurbishment version is based on a_{11} window, a_{21} wall, a_{i1} thermal unit, a_{t1} roof alternatives. The last building refurbishment's version takes into account alternatives a_{1p} window, a_{2p} wall, a_{ip} thermal unit and a_{tp} roof alternatives. Combinations are obtained by using p alternatives from any t solutions. Therefore, the maximum number of building refurbishment alternatives obtained may be determined as follows:

$$k = \prod_{i=1}^{t} p, \qquad (8)$$

where t is the number of solutions used in determining a building refurbishment; p represents the number of best

Table 6
Development of building refurbishment alternatives based on conceptual and quantitative information

Solutions used in developing building refurbishment alternatives	Information related to building refurbishment versions							
	Conceptual	Quantitative						
		Cost, X_1 (US$)	Aesthetics, X_2 (points)	Comfort, X_3 (points)	...	X_j	...	Quality, X_n (points)
Information related to refurbishment of first building								
1. Window, a_{11}	C_{11}	$x_{11\ 1}$	$x_{11\ 2}$	$x_{11\ 3}$	...	$x_{11\ j}$	...	$x_{11\ n}$
2. Wall, a_{21}	C_{21}	$x_{21\ 1}$	$x_{21\ 2}$	$x_{21\ 3}$	...	$x_{21\ j}$	...	$x_{21\ n}$
...	...	...	...	...	...	...	...	...
i. Thermal unit alternatives, a_{i1}	C_{i1}	$x_{i1\ 1}$	$x_{i1\ 2}$	$x_{i1\ 3}$	...	$x_{i1\ j}$	...	$x_{i1\ n}$
...	...	...	...	...	...	...	...	...
t. Roof, a_{t1}	C_{t1}	$x_{t1\ 1}$	$x_{t1\ 2}$	$x_{t1\ 3}$	...	$x_{t1\ j}$	...	$x_{t1\ n}$
...	...	...	...	...	...	...	...	...
Information related to refurbishment of K building								
1. Window, a_{1K}	C_{1K}	$x_{1K\ 1}$	$x_{1K\ 2}$	$x_{1K\ 3}$	...	$x_{1K\ j}$	...	$x_{1K\ n}$
2. Wall, a_{2K}	C_{2K}	$x_{2K\ 1}$	$x_{2K\ 2}$	$x_{2K\ 3}$	...	$x_{2K\ j}$	...	$x_{2K\ n}$
...	...	...	...	...	...	...	...	...
i. Thermal unit alternatives, a_{iK}	C_{iK}	$x_{iK\ 1}$	$x_{iK\ 2}$	$x_{iK\ 3}$	...	$x_{iK\ j}$	...	$x_{iK\ n}$
...	...	...	...	...	...	...	...	...
t. Roof, a_{tK}	C_{tK}	$x_{tK\ 1}$	$x_{tK\ 2}$	$x_{tK\ 3}$	...	$x_{tK\ j}$	...	$x_{tK\ n}$

Table 7
Summarized decision-making table of all building refurbishment versions obtained and the overall related conceptual and quantitative information

The obtained versions of building refurbishment	Information related to versions of building refurbishment							
	Conceptual	Quantitative						
		Cost, X_1	Aesthetics, X_2	Comfort, X_3	...	X_j	...	Quality, X_n
1. Building refurbishment's version	C_1	x_{11}	x_{12}	x_{13}	...	x_{1j}	...	x_{1n}
2. Building refurbishment version	C_2	x_{21}	x_{22}	x_{23}	...	x_{2j}	...	x_{2n}
...	–	...	...	...	...	...	...	...
i. Building refurbishment version	C_i	x_{i1}	x_{i2}	x_{i3}	...	x_{ij}	...	x_{in}
...	–	...	...	...	...	...	...	...
K. Building refurbishment version	C_K	x_{K1}	x_{K2}	x_{K3}	...	x_{Kj}	...	x_{Kn}
Weights of criteria		q_1	q_2	q_3	...	q_j	...	q_n
Criteria's measuring units		US$	Points	Points	...	u_j	...	Points

alternatives of every solution used in developing a building refurbishment.

The variants developed during this stage in which elements are not compatible are not analyzed hereinafter.

Stage 10: Development of building refurbishment alternatives based on the conceptual and quantitative information. In Table 5, the development of building refurbishment alternatives was based on codes of solution alternatives. Table 6 presents conceptual and quantitative information about the alternatives, instead of the codes. When a particular building refurbishment is being considered, the values relating to various solutions but based on the same criterion are recalculated into a single reduced value.

Stage 11: Development of a summarized decision-making table of all building refurbishment versions obtained and the overall related conceptual and quantitative information. When reducing the same criterion e.g. cost and comforts values of various solutions, to a single one, it is necessary to appraise the weights of these solutions. For example, noise level inside and outside the building is not of equal importance to inhabitants. The same applies to paying money and this depends on whether it should be done now or in the future. Using experts, financial analysis and other methods determine the above weights of the solutions. The weights should be made compatible in two directions: horizontally (among criteria) and vertically (among solutions). In this way, Table 6 transforms into a summarized decision-making table (Table 7) containing all building refurbishment versions and the overall related information.

Stage 12: Determination of building refurbishment significances, priorities and utility degree (see Table 2). Further, after the formation of decision-making matrix (see Table 7), the possible most rational versions of a whole building's refurbishment are determined and grouped according to their priority (see stages 1–5). The greater the priority of a version, the higher is the efficiency of the building refurbishment. Significance Q_i of a project indicates the satisfaction degree of demands and goals pursued by clients—the greater the Q_i, the higher is the efficiency of the building's refurbishment. In this case, the significance Q_{max} of the most rational project will always be the greatest. The significances of all remaining projects are lower when compared with the most rational one. This means that demands and goals of the stakeholders will be satisfied to a lesser extent than would be the case of the best building refurbishment.

However, in practice, the customers are more concerned not with the priority of the surveyed building refurbishment, but with their utility degree and costs. In other words, a customer is mostly interested in a project that will satisfy its demands and goals to the greatest extent and will be the cheapest and render the least infringement of interests of other parties participating in the project. The results of this assessment are expressed by the project utility degree concept (see Table 2).

5. Example illustrating the efficiency boost of building refurbishment

5.1. Description of renovated building

The example considered is the main, public building from Vilnius Gediminas Technical University (VGTU) (see Fig. 1). The configuration of a rectangular, comprises of the shape of the building with the measurements 74.30 m ×

Fig. 1. The main building of Vilnius Gediminas Technical University.

Table 8
Decision-making matrix of windows

No.	Criteria under evaluation	Measuring units of criteria	*	Weights of criteria	Ltd 1	Ltd 2	Ltd 3	Ltd 4	Ltd 5
1	Price	US$	–	0.6	72116	101896	84176	115072	92166
2	Mechanical strength and stiffness	[a]	+	0.0275	1	1	1	1	1
3	Reliability	Cycles	+	0.0291	10000	1000	10000	1000	1000
4	Thermal transmission coefficient λ of profile	$W/m^2 K$	–	0.0284	1.2	1.4	1.4	1.4	1.63
5	Thermal transmission coefficient λ of double glazing unit	$W/m^2 K$	–	0.0322	1.1	1.2	1.1	1.1	1.14
6	Emission ability of low emissive glass coating ε	[b]	–	0.023	0.05	0.1	0.05	0.05	0.05
7	Parameter Rw of air sound isolation	dB	+	0.0259	34	33	34	33	32
8	Air leakage, when pressure difference D_p = 50 Pa	$m^3/m^2 h$	–	0.0246	0.18	0.15	0.18	0.3	0.31
9	Waterproof-ness	Pa	+	0.0302	600	300	600	250	100
10	Guarantee period	Years	+	0.0302	10	5	5	5	5
11	Longevity	Years	+	0.0309	35	30	50	40	30
12	Light transmission of double glazing unit	%	+	0.022	81	78	81	79	78
13	Pay-back period	Years	–	0.0262	13.2	40	30	45	25.9
14	Duration of works	Days	–	0.0225	60	50	60	60	60
15	Quantity of windows with two opening positions (horizontal and vertical) (in percent of the area of all windows)	%	+	0.0215	78.5	100	37	100	27.43
16	Quantity of windows with closing infiltration air vent or the third opening position (in percent of the area of all windows)	%	–	0.0258	78.5	100	37	100	27.43

[a] Does it meet the requirements for the norms (if so, t.i. 1).
[b] There is no unit for criterion measurement.

17.22 m. The floor-area totals 8484.20 m^2. The main building was built in 1971. It includes several departments and lecture halls and seats from 50 to 100 students. Number of storeys is 7.

The substructure of the building is made from frame pillar with UK type columns. The walls of the building have ferroconcrete frame and three-layer ferroconcrete panels (60/90/90). A glass area occupies the biggest part of the

Table 9
Window refurbishment's multiple criteria analysis results

Criteria under evaluation	Measuring units of criteria	*	Weights of criteria	Weighted normalized values of criteria of the comparable alternatives				
				Ltd 1	Ltd 2	Ltd 3	Ltd 4	Ltd 5
Price	US$	–	0.6	0.093	0.1314	0.1085	0.1483	0.1188
Mechanical strength and stiffness	**	+	0.0275	0.0055	0.0055	0.0055	0.0055	0.0055
Reliability	Cycles	+	0.0291	0.0127	0.0013	0.0127	0.0013	0.0013
Thermal transmission coefficient λ of profile	$W/m^2 K$	–	0.0284	0.0048	0.0057	0.0057	0.0057	0.0066
Thermal transmission coefficient λ of double glazing unit	$W/m^2 K$	–	0.0322	0.0063	0.0069	0.0063	0.0063	0.0065
Emission ability of low emissive glass coating ε	***	–	0.023	0.0038	0.0077	0.0038	0.0038	0.0038
Parameter Rw of air sound isolation	dB	+	0.0259	0.0053	0.0051	0.0053	0.0051	0.005
Air leakage, when pressure difference D_p = 50 Pa	$(m^3/m^2 h)$	–	0.0246	0.004	0.0033	0.004	0.0066	0.0068
Waterproof-ness	Pa	+	0.0302	0.0098	0.0049	0.0098	0.0041	0.0016
Guarantee period	Years	+	0.0302	0.0101	0.005	0.005	0.005	0.005
Longevity	Years	+	0.0309	0.0058	0.005	0.0084	0.0067	0.005
Light transmission of double glazing unit	%	+	0.022	0.0045	0.0043	0.0045	0.0044	0.0043
Pay-back period	Years	–	0.0262	0.0022	0.0068	0.0051	0.0077	0.0044
Duration of works	Days	–	0.0225	0.0047	0.0039	0.0047	0.0047	0.0047
Quantity of windows with two opening positions (horizontal and vertical) (in percent of the area of all windows)	%	+	0.0215	0.0049	0.0063	0.0023	0.0063	0.0017
Quantity of windows with closing infiltration air vent or the third opening position (in percent of the area of all windows)	%	+	0.0258	0.0059	0.0075	0.0028	0.0075	0.0021
The sums of weighted normalized maximizing indices of the windows, S_{+j}				0.0645	0.0449	0.0563	0.0459	0.0315
The sums of weighted normalized minimizing indices of the windows, S_{-j}				0.1188	0.1657	0.1381	0.1831	0.1516
Windows's significance, Q_j				0.2534	0.1803	0.2188	0.1684	0.1795
Windows's degree of efficiency, N_j (%)				100	71.15	86.35	66.46	70.84
Windows's priority				1	3	2	5	4

*The sign (+/–) indicates that a greater/lesser criterion value satisfies a client.

Table 10
Four best versions of solutions under consideration

The solutions considered	Significance of solutions	The numeration of versions			
		3	4	1	2
Renovation of					
Walls	0.302	1	3	2	5
Windows	0.419	1	3	2	4
Roof	0.145	3	4	1	2
Entrance door	0.048	3	1	4	2
Thermal unit	0.086	3	4	1	2
Priority of versions		1	2	3	4

external sectors partitioned off in the main facades. All window glass is placed by wooden or aluminium profile frameworks. The windows of the main building are very old. Closing windows and lack of tightness are of major inconvenience. Current construction of the windows does not correspond to modern window requirements and does not ensure proper inside comfort conditions. The roof is flat and the covering is made from the roll.

5.2. Determination of the significance, utility degree and priority of all the renovation elements of a building

Referring to the task of the Framework 6 project Brita in PuBs the walls, windows, roof, entrance door and thermal unit had to be renovated of the building of VGTU. Further on, the determination of the significance, utility degree and priority of the renovated windows (see stages 1–6) will be analyzed in brief as an example. Alternative windows of five companies according to 16 indicators (see Table 8) were analyzed. Values of these criteria are different. For instance, the offered prices of building renovation by five companies range from US$ 72,116 to 115,072.

For a better understanding of the stated facts mentioned above, let us make a comparison of the first alternative with the fourth one. The cost of thermal renovation in the first version is lower while longevity of fourth version is more favorable. The first alternative, however, differs from the fourth one in possessing better quality characteristics (i.e. reliability, thermal transmission coefficient λ of profile, parameter Rw of air sound isolation, air leakage, when pressure difference D_p = 50 Pa, waterproof-ness, guarantee period, light transmission of double glazing unit, pay-back period, etc.).

As can be seen from Table 8, each criterion goes together with its measurement unit and weight. The magnitude of weight indicates how many times one criterion is more significant than the other one in a multiple criteria evaluation of windows refurbishment. For example, in the evaluation of guarantee period significance by computer-aided calculations, it was obtained that q_{10} = 0.0302, what is 1.37 (q_{10}:g_{12} = 0.0302:0.022 = 1.37) times more significant for client than the light transmission of double glazing unit (significance, q_{12} = 0.022). The calculations revealed that the key factors that have affected the efficiency of windows refurbishment are (see Table 8): cost (weight, q_1 = 0.60), thermal transmission of double glazing unit (q_5 = 0.0322), longevity (q_{11} = 0.0309), waterproof-ness (q_9 = 0.0302), etc.

The determination of significance, priority and utility degree of alternatives is carried out in five stages.

Stage 1: The weighted normalized decision-making matrix D is formed (see formula 2 and Table 9). First formula is used for this purpose:

$$d_{11} = 0.6 \times 72116 : (72116 + 101896 + 84176 + 115072 + 92166) = 0.93,$$
$$d_{12} = 0.1314, \quad d_{13} = 0.1085, \quad d_{14} = 0.1483,$$
$$d_{15} = 0.1188, \text{etc.}$$

The value of significance q_i of the investigated criterion is proportionally distributed among all windows versions a_j according to their values x_{ij} (see Table 9). For example:

$$q_4 = 0.0048 + 0.0057 + 0.0057 + 0.0057 + 0.0066 = 0.0284.$$

Stage 2: The sums of weighted normalized indexes describing the jth version are calculated. The sums are calculated according to third formula:

$$S_{+1} = 0.0055 + 0.0127 + 0.0053 + 0.0098 + 0.0101 + 0.0058 + 0.0045 + 0.0049 + 0.0059 = 0.0645$$

$$S_{-1} = 0.093 + 0.0048 + 0.0063 + 0.0038 + 0.004 + 0.0022 + 0.0047 = 0.1188, \text{etc.}$$

Table 11
Development of building refurbishment alternatives based on codes of solution alternatives

The solutions considered	The formation of versions of building refurbishment																
	1	2	3	4	5	6	7	8	9	10	...	123	...	528	529	...	1023	1024
Renovation of																		
1. Walls	4	4	4	4	4	4	4	4	4	4	...	4	...	2	2	...	1	1
2. Windows	5	5	5	5	5	5	5	5	5	3	...	3	...	5	5	...	2	2
3. Roof	4	4	4	4	4	4	4	4	4	3	...	3	...	4	1	...	3	3
4. Entrance door	4	4	4	4	3	3	3	3	2	2	...	2	...	1	4	...	1	1
5. Thermal unit	3	1	4	2	3	1	4	2	3	4	...	4	...	2	3	...	4	2

Table 12
Formation of complex main building of VGTU refurbishment versions

The criteria considered	*	Measuring units	Significance	Numerical values of criteria of the compared building refurbishment versions						
				1	...	277	...	857	...	1024
Windows										
1. Price	–	US$	0.2514	92166	...	92166	...	84176	...	101897
2. Mechanical strength and stiffness	+	**	0.01152	1	...	1	...	1	...	1
3. Reliability	+	Cycles	0.01219	1000	...	1000	...	10000	...	1000
4. Thermal transmission coefficient λ of profile	–	W/m² K	0.01189	1.63	...	1.63	...	1,4	...	1,4
5. Thermal transmission coefficient λ of double glazing unit	–	W/m² K	0.01349	1.14	...	1.14	...	1,1	...	1,2
6. Emission ability of low emissive glass coating, ε	–	***	0.009637	0.05	...	0.05	...	0,05	...	0,1
7. Parameter of air sound isolation, Rw	+	Db	0.01085	32	...	32	...	34	...	33
8. Air leakage, when pressure difference Δp = 50 Pa	–	(m³/m² h)	0.00103	0.31	...	0.31	...	0,18	...	0,15
9. Waterproof-ness	+	Pa	0.01265	100	...	100	...	600	...	300
10. Guarantee period	+	Years	0.01265	5	...	5	...	5	...	5
11. Durability	+	Years	0.012947	30	...	30	...	50	...	30
12. Light transmission of double glazing unit	+	%	0.009218	78	...	78	...	81	...	78
13. Pay-back period	–	Years	0.010998	25.9	...	25.9	...	30	...	40
14. Duration of works	–	Days	0.00942	60	...	60	...	60	...	50
15. Quantity of windows with two opening positions (horizontal and vertical) (in percent of the area of all windows)	+	%	0.009	27.43	...	27.43	...	37	...	100
16. Quantity of windows with closing infiltration air vent or the third opening position (in percent of the area of all windows)	+	%	0.0108	27.43	...	27.43	...	37	...	100
Roof										
17. Price	–	US$	0.087	42862	...	30330	...	30330	...	33363
18. Labor expenditures	–	Hours	0.00145	519.93	...	371.38	...	371.38	...	408.52
19. Durability	+	Years	0.02175	30	...	30	...	30	...	30
20. Reliability	+	Points	0.0116	8	...	7.5	...	7,5	...	7
21. Workability	+	Points	0.0029	1	...	1	...	1	...	1
22. Guarantee period	+	Years	0.007252	15	...	15	...	15	...	15
23. Pay-back period	–	Years	0.0087	6.1	...	4.3	...	4,3	...	4,8
24. Duration of works	–	Days	0.00435	13	...	9	...	9	...	10
Entrance door										
25. Price	–	US$	0.0288	7581	...	6317	...	6883	...	6592
26. Mechanical strength and stiffness	+		0.00384	1	...	1	...	1	...	1
27. Reliability	+	Cycles	0.0036	12500	...	10000	...	10000	...	10000
28. Thermal transmission coefficient λ	–	W/m² K	0.003264	1.6	...	1.4	...	1,5	...	1,5
29. Guarantee period	+	Years	0.003744	10	...	5	...	5	...	5
30. Durability	+	Years	0.0036	50	...	30	...	35	...	40
31. Pay-back period	–	Years	0.000672	28.3	...	23.6	...	25,7	...	24,6
32. Duration of works	–	Days	0.00048	3	...	2	...	4	...	4
Thermal unit										
33. Price	–	US$	0.0516	5190	...	5190	...	5190	...	6000
34. Guarantee period	+	Years	0.008688	5	...	5	...	5	...	3
35. Durability	+	Years	0.00774	25	...	25	...	25	...	25
36. Pay-back period	–	Years	0.0086	2.7	...	2.7	...	2.7	...	3.1
37. Duration of works	–	Days	0.0043	10	...	10	...	10	...	12
38. Reliability	+	Category	0.00688	1	...	1	...	1	...	1
Walls										
39. Price	–	US$	0.181	128032	...	126302	...	140143	...	140143
...										
58. Guarantee period	+	Years	0.009362	5	...	7	...	5	...	5
59. Service life (longevity)	+	Years	0.011778	40	...	30	...	30	...	30

*The sign (+/–) indicates that a greater/lesser criterion value satisfies a client.

In any case, the sums of "pluses" S_{+j} and "minuses" S_{-j} of all alternative projects are always, respectively, equal to all sums of the weights of maximizing and minimizing criteria (see formula 4):

$$S_{+} = 0.0645 + 0.0449 + 0.0563 + 0.0459 + 0.0315 = 0.243,$$

$$S_{-} = 0.1188 + 0.1657 + 0.1381 + 0.1831 + 0.1516 = 0.757.$$

Stage 3: Relative significance Q_j of each project a_j is found according to fifth formula (see Table 9):

$$Q_1 = 0.0645 + \frac{0.1188(0.1188 + 0.1657 + 0.1381 + 0.1831 + 0.1516)}{0.1188((0.1188/0.1188) + (0.1188/0.1657) + (0.1188/0.1831) + (0.1188/0.1516))} = 0.2534$$

Stage 4: The greater the Q_j, the higher is the efficiency (priority) of the windows alternatives. $Q_1 > Q_3 > Q_2 > Q_5 > Q_4$ ($0.2534 > 0.2188 > 0.1803 > 0.1795 > 0.1684$). Table 9 shows that the first version is the best in the utility degree equaling 100%. The third version was second according to priority and its utility degree was equal to 86.35%.

Stage 5: Sixth formula is used for the calculation utility degree N_j:

$$N_1 = (0.2534 : 0.2534) \times 100\% = 100\%,$$
$$N_2 = 71.15\%, \quad N_3 = 86.35\%,$$
$$N_4 = 66.46\%, \quad N_5 = 70.84\%.$$

The results of a multiple criteria evaluation of five window refurbishment versions are presented in Table 9. From Table 9, it is seen that the first version is the best in the utility degree that equals 100%.

Stage 6: Multiple criteria analysis of solutions dealing with renovation of a thermal unit, roof, walls, entrance door, etc. was carried out in a similar way as that of the windows. Further on, we repeated the first five stages till the significance, utility degree and priority of all the renovation elements of a building were estimated.

5.3. Multivariant design and multiple criteria analysis of the whole building refurbishment

After the multiple criteria analysis of the refurbishment project's components (walls, windows, roof, thermal unit, etc.) and a selection the most efficient versions, the received compatible and rational components of a refurbishment are joined into the alternatives. Having performed a multivariant design and multiple criteria analysis of the building refurbishment in this way, one can select the most efficient alternatives. Multivariant design and multiple criteria analysis of the whole building refurbishment are carried out in next six stages.

Stage 7: Rejection of potentially inefficient versions. Further complex multiple criteria analysis of building refurbishments was based on the four best solution versions (see Table 10) that were chosen separately for various components. For example, wall renovation top priority versions are correspondingly 3, 4, 1 and 2; while those dealing with the renovation of windows are 1, 3, 2 and 5.

Stage 8: The codes of building refurbishment alternative solutions with conceptual and quantitative information (see Table 4) have been developed.

Stage 9: Development of building refurbishment alternatives based on codes of solution alternatives. An example formation of the variants (according to their codes) making a complex building refurbishment scheme is given in Table 11. In the process of forming possible versions the compatibility of separate variants of complex renovation is taken into account.

Stages 10 and 11: Development of a summarized decision-making table of all building refurbishment versions are obtained. An example of the formation of complex building refurbishment versions and pertinent characteristics (e.g. the system of criteria, units of measure, values and weights) is shown in Table 12. The prepared building refurbishment versions are assessed according to different requirements. A version not corresponding to these requirements is stricken out and no longer considered.

Stage 12: Determination of building refurbishment significances, priorities and utility degree.

The results of the multiple criteria evaluation of the 1024 building refurbishment versions are given in Table 13. From the numeric values it can be seen that the 915th version is the best among all the versions that were evaluated. The utility degree of it $N_{915} = 100\%$. The 925th version according to its priority was recognized as the second best. The utility degree of it $N_{925} = 99.94\%$ (see Table 13).

Table 13
Determination of building refurbishment significances, priorities and utility degree

Priority	Renovation alternative number	Total significance, Q_j	Total utility degree, N_j
1	915	96.93	100.00
2	925	97.43	99.94
3	948	96.44	99.76
4	959	96.93	99.69
5	932	95.95	99.53
6	943	96.44	99.46
7	954	96.93	99.39
8	934	96.44	99.15
9	900	95	99.06
10	905	95.47	98.99

6. Conclusion

Multiple criteria analysis of the building's refurbishment allows for the evaluation of economic, technical, and qualitative architectural, aesthetic and comfort aspects. In addition, technological, social, legislative, infrastructure, technical and other decisions are made in conformity with needs and opportunities of clients, designers, contractors, users, and other participants. These needs are expressed through the systems, values and weights of quantitative and qualitative criteria.

The presented methodology of multivariant design and multiple criteria analysis of a building refurbishment enabled one to form up to 100,000 alternative versions. This methodology allows one to determine the strongest and weakest points of each building's refurbishment project and its constituent parts. Calculations are made to find out by what degree one version is better than another and the reasons as to why this is so are disclosed. In order to demonstrate the developed method, a practical example is presented in this paper.

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