SELECTION OF REFURBISHMENT ACTIONS FOR RESIDENTIAL BUILDINGS BY MULTI CRITERIA DECISION METHOD

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The majority of building stock in Europe is older than 30 years and in need of refurbishment. Funding for such actions is always limited, therefore rational methods have to be employed to determine the extent of refurbishment. The paper presents a computer supported multi-criteria decision model for the selection of a set of actions with highest cumulative utility score. A financial constraint can be imposed upon the solution. Mathematically, the model is based on the knapsack problem. The results of a case study show that the total utility score depends strongly upon the selected relative importance of criteria employed.

Keywords: building performance, decision theory, housing, operational research, refurbishment

INTRODUCTION

A large proportion of today's residential building stock in Europe stems from the period following the World War 2. Often, it can be observed that the maintenance of these buildings has been kept to a minimum. Further, new standards and codes introduced over the past decade have imposed additional requirements to the existing building in terms of thermal, acoustic insulation and, in some European countries, structural safety. Dwellings constructed during the post-war period often fail to comply to the contemporary living standards also in terms of the size and human comfort. As a consequence, increased migration of the tenants was observed in large neighbourhoods from this time period over the past two decades (Žarnić 2004).

Two options are options are available for the management of these buildings: demolition and construction of new buildings complying to contemporary requirements, or refurbishment of existing buildings. In this paper, the standard definition of refurbishement as »modification and improvements to an existing buildings or its parts to bring it up to an acceptable condition« (ISO 15686-1 2000) is employed. Following the sustainability principles applied to the built environment (Agenda 21 1999), and considering the number of multi-dwelling buildings from the discussed period, refurbishment is preferred to demolition.

After has established that a building is obsolete in environmental, functional or aesthetic aspect, and a decision initiating the rehabilitation process was made, design of the rehabilitation has to be laid down. These decisions are mainly made by a design team that consists of a design group, a client and, depending on the type of the

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building contract, a representative of the contractor. The design group typically includes an architect, a structural engineer, a HVAC engineer and an electricity engineer. A consensus between the members of the design team in as many as possible points of view has to be achieved if an optimum solution is to be selected. New building design as well as design of refurbishment of existing buildings is therefore an iterative process (Alanne 2004).

The number of available rehabilitation technologies and materials is increasing rapidly today, and identifying the best combination poses a real challenge for the design team. Both functional and aesthetic aspects have to be accounted for. In addition, as the awareness of the importance of sustainable development is increasing, the environmental performance of a new building is becoming a necessary criterion used in the selection of a set of refurbishment actions to be employed as well.

The purpose of this paper is to present a multi-criteria decision model to be used in selection of the most valuable set of rehabilitation actions from a comprehensive range of available actions. By using the model, the design team can quantify different options/refurbishment actions and make a rational base for their decision. The model is able to take into account financial constraints as it occurs in reality. Three aspects of each rehabilitation action are considered, namely functional, environmental and aesthetical. Mathematically, the model is based on the knapsack problem solution.

METHODOLOGY

Conventionally, once it is decided that the refurbishment will take place, the designers generate a few design alternatives, which are then evaluated by the design team. A limited number of alternatives can be assessed if evaluation is based solely upon the experience of the members. An automated decision support model has to be used if a larger number of alternatives is to be evaluated.

In this paper, refurbishment of a building is considered as a set of single actions that are expected to increase the sustainability, functionality and aesthetic value of the building. The single actions are members of a comprehensive list of all feasible actions.

The possible refurbishment actions, or decision variables, are labelled as

$a_1, a_2, \ldots, a_i, \ldots, a_n$

where $a_i \in \{0, 1\}$. $a_i = 1$ if the action is carried out, else $a_i = 0$.

Objective function, or total utility score, is defined by the expression

$$\max \sum_{i=1}^{n} (a_i S_i) \quad (1)$$

where S_i is the utility score achieved by selecting the renovation action a_i. The problem will be subject to constraints

$$\sum_{i=1}^{n} a_i C_i \leq C_{\max} \quad (2)$$

Where C_i is the cost of the action a_i, and C_{max} is the maximum allowable cost of the project.

In addition, the problem may be subject to other constraints that define compatibility of the actions, i.e. define, which actions can or have to be carried out together; necessary actions for the building (case-based constraints); minimum required performance (user-defined constraints); and other constraints, such as constraints dictated by laws or regulations. The mathematical form of above listed constraints depends on the case under consideration and can not be written in general terms.

The importance of different criteria used in the selection of actions can be captured by assigning criteria weights to indicate their relative importance. The sum of criteria weights equals to 1.

Utility can be seen as a value that can be expected by a decision-maker when selecting an option. Each action is assigned a utility value related to the individual criteria used in the analysis. Total utility score of a set of actions is a sum of utility values of all actions selected. The objective of the decision process is to select a set of actions that results in maximum total utility score (Eq.1) according to the criteria and their relative importance by taking into the account the financial constraint (Eq.2) and compatibility constraints defined for each individual case. The problem can be solved numerically by using the SOLVER function of MS Excel.

CASE STUDY

General data

Refurbishment of a residential multi-apartment building was selected to demonstrate the presented optimization method for selection of renovation actions. The building was built in 1960, and central heating system was added in 1980. Total heated area of the building is 1860 m^2, and the total envelope area (in contact with environment) is 1191 m^2. The windows' area is 189 m^2. Existing envelope consists of prefabricated concrete plates with the thermal insulation core 8 cm thick. Total thickness of the plate is 16 cm. The building dates from the period where no energy efficiency codes existed. An assessment showing that 40% of the energy could be saved by improving the thermal envelope was carried out in 2003. The recommendations made at the same time conform to the new thermal efficiency code from 2002. The energy loss could be reduced by adding insulation to the exterior walls or to the roof. The appearance of the building was visibly degraded, and there was a clear need for a new façade.

A comprehensive list of possible actions, their prices and assigned utility values $F_{i,j}$ for 3 criteria (environmental, functional and aesthetical) are presented in Table 1. The listed refurbishment actions can be divided into the following 7 groups according to their effects:

- Additional thermal insulation of exterior walls (actions 1, 2, 3)
- Façade change (actions 4, 5, 6)
- Additional roof insulation (actions 7, 8, 9)
- Roof change (flat/pitched) (actions 10, 11, 12, 13, 14)
- Window change (actions 15, 16, 17, 18, 19, 20)
- Addition of exterior/interior shading devices (actions 21, 22, 23, 24, 25)
- Balcony alternation (actions 26, 27, 28, 29, 30)

The scale for the three utility indexes used in Table 1 ranges from -10 to 10 for the aesthetical and functional criterion, and from 0 to 10 for the environmental criterion. Only one action can be chosen out of each group. For the first group, this constraint can be mathematically expressed as

Table 1: List of possible refurbishment actions, their costs and selected values for environmental, functional and aesthetic utiliy values.

i	Description of refurbishment action	Cost (EUR)	$F_{i,env}$ [0,10]	$F_{i,funct}$ [-10,10]	$F_{i,east}$ [-10,10]
1	Thermal insulation on outside wall (d=4 cm)	7.5/m²	2,00	-1,00	0,00
2	Thermal insulation on outside wall (d=6 cm)	8.3/m²	5,00	-3,00	0,00
3	Thermal insulation on outside wall (d=8 cm)	9.6/m²	7,00	-5,00	0,00
4	Façade – type A composite system	17.5/m²	0,00	-1,00	2,00
5	Façade – type B	121.7/m²	0,00	-2,50	4,00
6	Façade – type C	32/m²	0,00	-4,00	6,00
7	Thermal insulation under the roof (d=4 cm)	3.7/m²	1,00	-0,50	0,00
8	Thermal insulation under the roof (d=6 cm)	5.4/m²	3,00	-2,00	0,00
9	Thermal insulation under the roof (d=8 cm)	6/m²	6,00	-3,00	0,00
10	Pitched roof - type A	31.7/m²	0,00	1,50	4,00
11	Pitched roof - type B	36.7/m²	0,00	1,50	6,00
12	Pitched roof - type C	32.5/m²	0,00	2,00	5,00
13	Flat roof type A (RC concrete, mineral wool (6 cm), waterproof layer, gravel)	138/m²	1,50	3,00	1,50
14	Flat roof type B (RC concrete, mineral wool (6 cm), waterproof layer, concrete plates)	150/m²	1,50	5,00	3,00
15	Wooden window (140 x140), standard double glass	167/piece	0,80	1,00	4,00
16	PVC window- discont. thermal bridge, double sealing (140 x 140 cm), standard double glass (U=1.5 W/m²K)	208/piece	0,50	2,00	2,00
17	Alum. window – discont. thermal bridge, double sealing (140 x140 cm), standard double glass (U=1.5 W/m²K)	250/piece	0,50	2,00	1,20
18	Wooden window (140 x140 cm), standard double glass with pattern	183/piece	0,80	1,00	3,75
19	PVC window- discont. thermal bridge, double sealing (140 x140), standard double glass with pattern (U=1.5 W/m²K)	55000/piece	0,50	2,00	2,00
20	Alum. window – discont. thermal bridge, double sealing (140 x140 cm), standard double glass with pattern (U=1.5 W/m²K)	275/piece	0,50	2,00	1,50
21	Exterior shading device - wood shutters	146/piece	0,20	0,50	6,00
22	Exterior shading device – PVC shutters	187/piece	0,20	1,00	3,00
23	Exterior shading device - Aluminium shutters	229/piece	0,20	1,00	3,00
24	Interior shading device - Venetian blinds	20.8/m²	0,00	3,00	2,00
25	Exterior shading device - roller shutters	146/window	0,10	2,00	1,50
26	Standard iron balcony fence	125/r.m.	0,00	1,00	2,00
27	Forged iron balcony fence	250/r.m.	0,00	1,00	6,00
28	Brick wall fence of 90 cm height, marble shelf	83/r.m.	0,00	2,00	4,00
29	Closed balcony, brick wall, 90 cm high, marble shelf, upper part closed with glass (aluminium frame)	83/r.m.+ 1875 EUR	1,20	6,00	2,00
30	Closed balcony, brick wall, 90 cm high, marble shelf, upper part closed with glass (PVC frame)	83/r.m.+ 1500 EUR	1,20	6,00	2,00

$$\sum_{i=1}^{3} a_i \leq 1 \qquad (3)$$

Equivalent expressions can be written for other groups of actions.

Theoretically, if no constraints were imposed to the selection problem and there would be no dependences among the activities, there would be 2^{30} alternative sets of selected actions for the case presented. The use of decision tool presented leads to selection of the activity set with maximum total utility score with respect to the chosen combination of criteria.

Utility values for individual actions

Several goals should be attained by the selected refurbishment actions. Thermal efficiency of the building should be improved in order to reduce the energy required for the heating and the associated CO_2 release. Therefore, the largest environmental utility values are assigned to actions where thermal insulation is added to the building envelope, change of windows and to the closing of the balcony. Values presented in Table 1 are a first judgement that can be quantified more precisely by a detailed energy losses calculation for each action.

Functionality is a subjective issue, depending on the preference of the evaluator. In this paper, utility values for functionality are determined by answering the following list of questions (Alanne 2004):

- How easily can this action be carried out?
- Does it require any other actions to be feasible to carry out?
- Does it require any new methods or ways of implementation which do not exist yet?
- What is the effect on comfortability?
- What is the effect on reliability?
- What is the space requirement?
- What is its adaptability to existing structures?
- What is its impact on physical characteristics of the building?
- What is its impact on usability?
- What is its impact on serviceability?

Aesthetic utility values, again, depend strongly on the evaluator. Nevertheless, the improved appearance is an important outcome of any building refurbishment, therefore this criterion was added to the case study presented.

RESULTS AND DISCUSSION

Various weighting combinations of the criteria employed were taken into the account in the analysis. First, selection of rehabilitation actions was carried out by taking into the account each single criterion (Table 2, options 100/0/0, 0/100/0, 0/0/100). Secondly, one criterion was taken as not important at all, while the other two were assigned equal importance (Table 2, options 0/50/50, 50/0/50, 50/50/0). Thirdly, all three criteria were taken as equally important (Table 2, option 33/33/33). Financial constraint employed in the analysis was taken as 125000 EUR, which, when divided by the number of apartments, results in a viable financial contribution of the each resident.

Table 2: Overview of actions selected by using different weighting combinations (environmental/functional/aesthetical) at financial constraint of 125 kEUR (1=selected action)

Action	100/0/0	0/100/0	0/0/100	0/50/50	50/0/50	50/50/0	33/33/33
1	0	0	0	0	0	0	0
2	0	0	0	0	0	0	**1**
3	**1**	0	0	0	**1**	**1**	0
4	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0
6	0	0	**1**	**1**	**1**	0	**1**
7	0	0	0	0	0	0	0
8	0	0	**1**	0	0	0	0
9	**1**	0	0	0	**1**	**1**	**1**
10	0	0	0	0	0	0	0
11	0	0	**1**	**1**	**1**	0	**1**
12	0	**1**	0	0	0	**1**	0
13	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0
15	0	0	**1**	**1**	**1**	0	**1**
16	**1**	0	0	0	0	**1**	0
17	0	**1**	0	0	0	0	0
18	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0
21	**1**	0	**1**	**1**	**1**	0	**1**
22	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0
24	0	**1**	0	0	0	**1**	0
25	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0
28	0	0	**1**	**1**	**1**	0	**1**
29	0	0	0	0	0	0	0
30	**1**	**1**	0	0	0	**1**	0
Total utility score	15.40	13.00	26.00	13.50	20.00	10.10	10.99
Total cost (kEUR)	120.24	113.60	97.11	95.09	108.75	123.93	107.27

The results for the decision variables a_i (1 if action is selected, 0 is not selected) obtained by the SOLVER procedure are summarized in Table 2 for the weighing combinations described in the previous paragraph. It can be seen that total utility score (Eq.1) is significantly influenced by the combination of criteria weights employed. The score also depends upon assigned values for utilities of each individual action, which are a first approximation. An objective selection process can be based only on utility values that are either obtained quantitatively, or as a combination of opinions of several experts from relevant fields.

Table 3: Costs and contributions to total utility score of individual selected actions at criterion weighting combination 33/33/33 and 100/0/0; financial constraint equals to 125 kEUR

Weighting combination	**33/33/33**			**100/0/0**		
Action	a_i	**cost (EUR)**	**contr. to total utility score**	a_i	**cost (EUR)**	**contr. to total utility score**
1	0			0		
2	**1**	9925	0.67	0		
3	0			**1**	11414	7.00
4	0			0		
5	0			0		
6	**1**	38211	0.67	0		
7	0			0		
8	0			0		
9	**1**	2248	1.00	**1**	2248	6.00
10	0			0		
11	**1**	13640	2,50	0		
12	0			0		
13	0			0		
14	0			0		
15	**1**	13333	1.93	**0**		
16	0			**1**	16667	1.00
17	0			0		
18	0			0		
19	0			0		
20	0			0		
21	**1**	11667	2.23	**1**	11667	0.20
22	0			0		
23	0			0		
24	0			0		
25	0			0		
26	0			0		
27	0			0		
28	**1**	18242	2,00	0		
29	0			0		
30	0			**1**	78242	1.20
Σ		107265	10.99		120236	15.40

If environmental criterion is taken into the account only (option 100/0/0 of Table 2), the optimizing procedure results in the following selection: the thickest thermal insulation both on walls and under the roof (actions 3 and 9), PVC windows with double sealing (action 16 that has the same utility value as the aluminium window but its price is lower), wood shutters (action 21) and closing of the balcony (action 30), where the frame is made of PVC (again, this is the option with the same utility value as the alternative option with aluminium frame that is less expensive). No façade and roof change is proposed. Actual costs associated with the execution of selected set of actions are smaller than the allowable sum of 125 kEUR for all weighting combinations.

When all criteria are taken as equally important (option 33/33/33 of Table 2), the following combination is obtained as the result: addition of thermal insulation both on wall and roof (6 and 8 cm thick, respectively), façade type with largest aesthetical utility (action 6), roof change with largest functional utility value (action 11), wood window with standard glass and wood shutters (actions 15 and 21, both with high aesthetical utility values) and brick fence on the balcony (action 28).

Analysis of separate contributions to total utility score and cumulative cost is presented in Table 3 for the criteria weights combinations already discussed (i.e. option 33/33/33, equal importance of all criteria and option 100/0/0, environmental criterion only). It should be noted that contributions to total utility score for a particular action (e.g. action 21, Table 3) differ when different criterion weighting combinations are taken into the account.

Analysis was conducted also for variable financial constraint ranging from 20000 to 190000 EUR. The dependence between financial constraint and total utility score for different combinations of criteria weights is presented in Fig.1. It can be seen that total utility score increases as the financial constraint imposed upon the refurbishment increases and is limited by the total utility score that would be obtained without a financial constraint. Limiting values for total utility score are strongly dependent upon the combination of criteria employed. The highest utility values are assigned to aesthetical criterion, therefore the total utility value obtained is the highest for the case when the selection is takes into the account aesthetical criterion only (option 0/0/100).

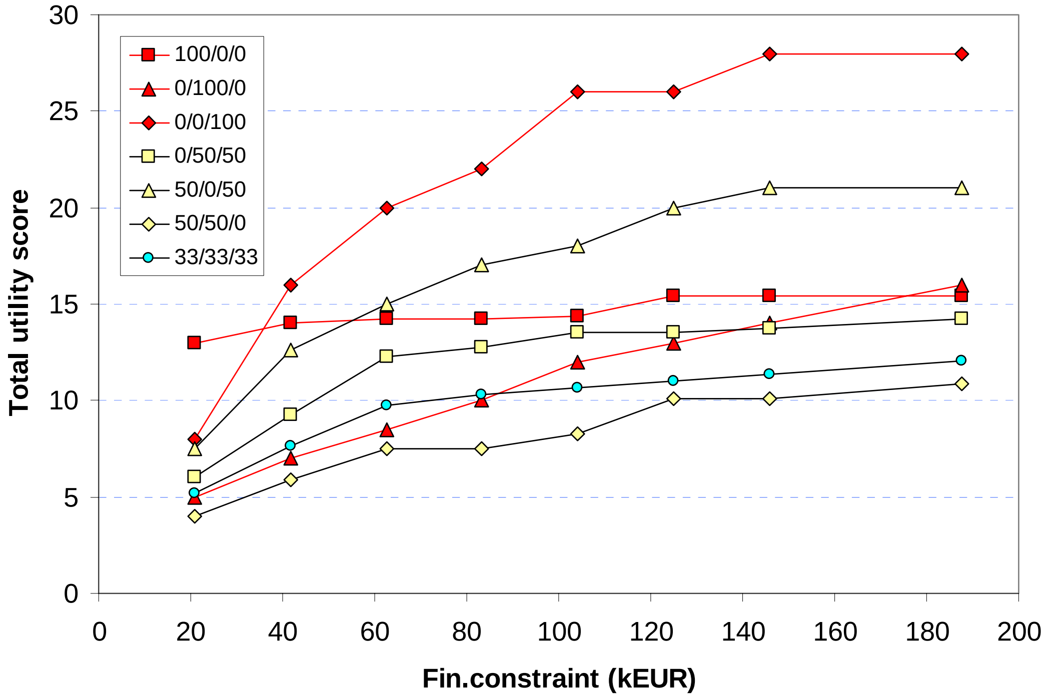

Figure 1: Influence of the financial constraint upon total utility score.

CONCLUSIONS

Aging of the residential stock dictates a rational approach to refurbishment and retrofit of existing residential buildings. In selecting the most appropriate set of actions for a particular case, several criteria or their combinations can be employed. Due to increasing number of products available at the market to be used in refurbishment, the decision maker is facing a large number of possible combinations, several compatibility constraints and a financial constraint imposed by the funds available. The paper is proposing a simple and effective approach in selecting the refurbishment actions. The automated decision tool allows the user to assign variable level of importance to each criterion employed. Mathematically, the tool is based on the knapsack problem formulation and solved by the SOLVER (MS Excel) function.

To ensure objectivity of the decision process, utility values assigned to the individual actions should be based on a quantifiable basis or obtained by a group of independent experts. The selection of criteria weights employed in the analysis, on the other hand, should be selected by the decision maker.

The main challenge for the practitioner who wants to employ the proposed model is first to identify all possible refurbishment options. This can only be done if analysis of the current state is carried out thoroughly, so that the full list of existing problems can be compiled. Problems that pose a threat to safety and health of the residents, such as insufficient structural integrity, have to be clearly indicated as actions for their mitigation have to be taken regardless of the associated cost. Next, the compatibility of remaining actions has to be analysed carefully in terms of materials, ease of execution, visual appearance and other aspects. This analysis results in additional set of constraints that has to be used in the optimization process. As already mentioned, one of the challenges is also the assignment of the utility values for separate refurbishment actions that needs to be established on rational background. Finally, once the solution is obtained, it should be evaluated in terms of the potential incompatibility of the selected actions in an integral fashion.

An analysis of a case study of a multi dwelling residential building is presented. The results clearly show that the combination of criteria weights employed plays a major role in obtaining the solution by using the proposed optimization procedure. The presented tool is more efficient if a large number of options is available where one can not arrive to the best solution only by personal judgement.

Further, the obtained results show that the dependence of the total utility score (that is being maximized by the selected set of actions) upon the maximum allowable cost is not linear. It may therefore be useful to study these relationships in advance, so that the maximum overall performance of the planned refurbishment is obtained.

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