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Selection of renovation actions using multi-criteria “knapsack” model

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Abstract

In recent years, many new technological solutions have been introduced, aiming to improve the ability of buildings to satisfy a variety of needs of human beings and the environment. As a consequence, designing an optimal building has become more challenging than it has been before.

In this article, a multi-criteria “knapsack” model is proposed to help designers to select the most feasible renovation actions in the conceptual phase of a renovation project. Firstly, the methodology is described. Then, a case study is presented. Finally, advantages and disadvantages of the methodology are considered and needs for future research are suggested.

Keywords: Building renovation; Decision support systems; Multi-criteria decision-making; Expert systems

1. Introduction

Designing an optimal building has become more challenging than it has been before. Three typical challenges can be seen. The first challenge is associated with the fact, that decisions concerning building design are mainly made by a design team consisting of a design group (including at least an architect, an HVAC engineer, an electricity engineer and a structural engineer), a real estate owner (a client) and a contractor. The question is how to find a consensus between the members of a design team taking into account as many points of view as possible [1]. A practical solution of this problem is presented for example by Tanimoto et al. [2], who consider the design process of a building as an iterative process with several actors linked to their opinions.

The second challenge is associated with sustainable development [3]. According to the definition by the World Commission on Environment and Development, sustainable development is regarded as “Development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [4]. Sustainable development in the context of construction industry simply means making buildings better satisfy the needs of human beings and the environment [5]. In practice, sustainability is usually illustrated using numerical indicators providing information about the status of a phenom-

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enon, environment or area. An example of a list of indicators describing sustainability of buildings and their technological systems, called VTTProP, is presented by Häkkinen et al. [6]. The sustainability of buildings and their systems is usually defined by means of conflicting criteria. The challenge is to make an optimal decision on the basis of these criteria. Multi-criteria decision-making (MCDM) methods are usually presented as a solution of this kind of problems, like has been done for example by Andresen [7].

The third challenge is an increasing amount of technological solutions on the market. In order to design a building with maximum sustainability, designers have to consider effects of more and more technological options. Dealing with this problem has not been such a popular subject in earlier studies, although it has been handled for example by Flourentzou et al. [8], and Rosenfeld and Shohet [9]. The introduction of new, fast personal computers on everyone's desk makes it possible to handle the problem in the form of a combinatorial optimization problem. This approach seems to be new in the field of building design. In Linköping, Sweden, some studies have been carried out concerning this issue. In these studies, however, the multi-criteria and multi-perspective nature of the problem have not been dealt with [10].

A great potential exists for the introduction of new technologies through renovation projects, because almost half of construction industry in developed countries is directed to the existing building stock [11]. The concept "renovation" is usually divided under two categories: retrofit and refurbishment. The concept "retrofit" is generally used to identify actions that are required to bring a building into the framework of new requirements. The purpose of "refurbishment", instead, is to bring a building back to its original state [8].

In this paper, a multi-criteria "knapsack" model is proposed to help designers select the most feasible renovation actions in the conceptual phase of a renovation project. Firstly, the methodology is described. Then, a case study is presented dealing with the retrofit project of a residential building in Finland. Finally, some needs for future research are suggested as well as advantages and disadvantages of this decision-support method are concerned.

2. Theory and methodology

2.1. General review

In this study, the renovation of a building is regarded as a set of single actions that are expected to improve the sustainability of a building. Substituting a traditional oil heating system by a fuel-cell-based combined heat and power system is a good example of a modern renovation action hypothetically improving the sustainability of a building.

Decision-making concerning selection of renovation actions as far has been studied for example by Rosenfeld et al. [9]. In that study, the deterioration state of building parts has been assumed to determine the need for renovation. The method is rational and reasonable in the context of cases that are refurbishment projects by nature. Related to the challenges concerning an optimal building design also in the case of retrofit projects, the following improvements can be proposed. Firstly, conflicting preferences inside the group of decision-makers should be taken into account. Secondly, the additional utility that can be achieved in the context of sustainability by selecting certain renovation actions should be better illustrated. Thirdly, the automation could be improved from 'semi-automated' level to 'fully automated' level by applying a suitable optimization model and a modern personal computer.

In this chapter, a new approach is presented how to help a design team to find the most sustainable reno-

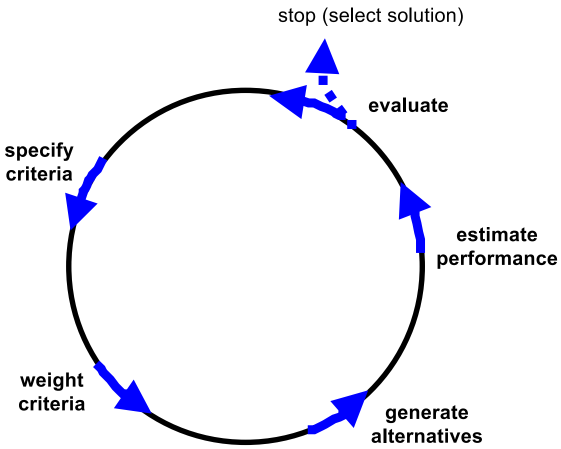


Fig. 1. An iterative, cyclical decision-making process at conceptual phase of design [2].

vation actions in a renovation project. The decision-making process, particularly during the conceptual phase of design, can be seen as an iterative and cyclical process (see Fig. 1). Typically, designers manually generate two or more design alternatives (alternative sets of renovation actions in this context) to be evaluated by the design team [2]. This paper argues that generating the design alternatives as well as evaluating them can be automated by applying the knapsack model. Generally speaking, this is a case of portfolio optimization. The model presented in the article is applicable to various decision-making tools as well as expert systems.

2.2. Description of the problem

2.2.1. Mathematical expression

The methodology presented in this paper can be described using a mathematical expression that follows the traditional "knapsack problem": which renovation actions should be selected in order to achieve the best possible improvement in the sustainability of the building that is to be renovated? If an additive "knapsack" approach is applied in the context of the utility theory, the mathematical form will be as follows.

Assume we have:

- decision variables (possible renovation actions) $a_1,\ldots a_i,\ldots a_n$
- $a_i = 1$, if action a_i is carried out, else $a_i = 0$

Objective function will be then

$$\mathrm{MAX} \sum_{i=1}^{n} a_i S_i, \tag{1}$$

where S_i = utility score achieved by selecting the renovation action a_i.

The problem will be at least subject to constraints $a_i \in \{0,1\}$

$$\sum_{i=1}^{n} a_i C_i \leq C_{\mathrm{MAX}}, \tag{2}$$

where C_i = cost of action a_i; C_{MAX} = maximum allowable costs of the project.

In addition, the problem may be subject to

- constraints for compatibility (which actions technically can be carried out together?)
- case-based constraints (e.g. necessary actions for the building)
- possible user-defined constraints (e.g. minimum required performance)
- possible other constraints (e.g. constraints dictated by laws or regulations)

The mathematical form and the number of these additional constraints varies depending on the case. Thus, a single general mathematical expression cannot be presented.

2.2.2. Expression of the utility

In order to make the concept "utility" more understandable, the concept "criteria" firstly needs some explanation. The definition of the concept "criteria" by Andresen is "standards of judgement or rules to test acceptability" [7]. In other words, they say something about what is expected by a decision-maker when selecting an option. As well, the utility can be seen as a value that can be expected by a decision-maker when paying a certain amount of money. Thus, it is usually regarded as the opposite of costs. This section illustrates how the utility value can be defined on the basis of evaluation criteria.

In the context of MCDM, a set of criteria is used, that is usually put into the form of a tree-structured model in which a single node represents a criterion. This idea is illustrated in Fig. 2. Main criteria indicate general, strategic objectives (e.g. minimum resource use), whereas sub-criteria deal with more detailed issues. The lowest level in the tree represents criteria that are indicatable by means of numerical or otherwise unambiguous factors, like sustainability indicators [2]. In practice, sub-criteria may be either quantifiable, such as annual energy use, or qualitative, such as aesthetics.

It is obvious that the number of criteria depends on the case. In the context of building renovation projects, criteria usually are selected by a design team. According to Huovila et al. [1] and Tanimoto et al. [2], a consensus among team members only can be achieved through a sufficient number of meetings. There is not a theoretical maximum number of criteria

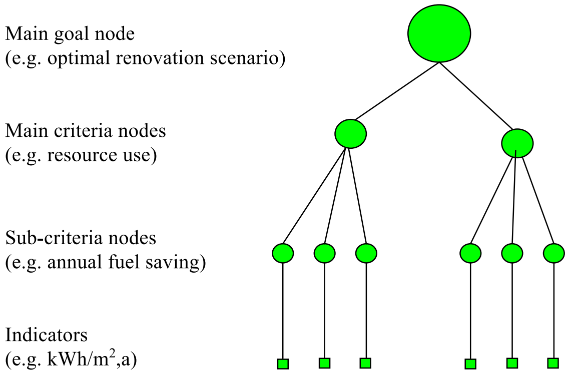


Fig. 2. A tree-structured criteria model [2].

for a single evaluation, but Tanimoto et al. [2] recommend, that in order to avoid overlapping evaluations, the number of main-criteria should not be more than 8 and the number of sub-criteria should not be more than 8 under each main-criterion.

The need for capturing the importance of *different criteria* related to each other arises from the nature of multi-criteria problems. In the context of practical sustainable building design, for example, a question can be asked: What if human requirements do not agree with energy saving options? One widespread way to handle this problem is to assign criteria weights to indicate their relative importance. Vice versa, the criteria weights are indicators of the influence of individual criteria on the decision [7].

There are various methods for assigning weights. So-called "Grading Method" is recommended by Tanimoto et al. [2], because of its simplicity to use. In that case, weights are determined by using a 10-grade scale. Firstly, the most important criterion on a certain level in the tree (see Fig. 2) receives a grade of 10. All the other criteria (on the same level) are compared to the most important criterion. For example, if a criterion is felt to be somewhat less important than the most important one, it receives a grade of 7. This idea is presented in Table 1. The weights are then normalized to range between 0 and 1, so that the sum of the weights (on a certain level) is unity. The procedure will be repeated for each level in the criteria tree. There are also other methods for assigning weights. The Analytical Hierarchy Process (AHP) is mentioned as an example by Mustajoki et al. [12].

In order to completely understand the link between a set of criteria, weight factors and a utility value, the concept "attributes" also needs some explanation. Attributes can be regarded as a characteristic of an option being evaluated, which is measurable against some objective or subjective yardstick. Thus, attributes say something about what an option actually is, in respect to the criteria. Although in the literature, the concepts criteria and attributes often are mixed with each other, one should remember that their information in general case is entirely different [7]. When talking about attributes in the context of this study, we always mean features of an option in respect to the lowest level of sub-criteria in a criteria tree (see Fig. 2).

To indicate the utility in the numerical form in the context of MCDM, a commensurate value scale between each sub-criterion on the lowest level of a criteria tree as well as that between each attribute is necessary [7]. An attribute can then be indicated in respect to a corresponding sub-criterion by means of a score number. In this study, we try to illustrate the importance of a renovation on the basis of a building's original status, and thus, we recommend that the score number should vary between -10 and $+10$, as is presented in Table 2.

The next step is to aggregate the score values over the entire set of criteria into a single score number S_i indicating the *total utility* caused by the renovation action i. Assume we have m sub-criteria under an arbitrary node l in the criteria tree, j representing an arbitrary sub-criterion between 1 and m. Following the idea represented by Tanimoto

Table 1
Eliciting the weights using the Grading Method

Grade	Relative importance compared with the most important criterion
10	Equal importance
9	
8	
7	Somewhat less important
6	
5	
4	
3	Significantly less important
2	
1	
0	Not important at all

Table 2
Relation between a utility definition and score value

Score	Utility definition
10	huge improvement compared with situation before renovation
8	great...
6	fair...
4	moderate...
2	slight...
0	no improvement compared with situation before renovation or no effect on this criterion
− 2	slight...
− 4	moderate...
− 6	fair...
− 8	great...
− 10	huge drawback compared with situation before renovation (example from the practice: work always has to be done, when an action is carried out)

et al. [2] and Andresen et al. [7], a simple additive weighting model is applied to aggregate scores to get a single score number representing the score in the node l. Thus, an equation

$$S_l = \sum_{j=1}^{m} w_j s_j \tag{3}$$

can be established, where S_l represents the score number in the node l, m is the number of sub-criteria under that node, is the normalised weight (between 0 and 1) of the sub-criterion j, and is the score number corresponding sub-criterion j. Before the aggregation, the weights are normalised by dividing an individual weight by the total sum of weights.

The procedure is repeated for each node in the criteria tree (see Fig. 2), beginning from the lowest level. The process is continued until a single total score corresponding the node "main goal" has been achieved. This results in the total score S_i, which is then calculated for each alternative renovation action i and finally is applied in Eq. (1).

2.2.3. A practical example

The following example illustrates the process described in Section 2.2.2 applied to an arbitrary renovation action. In order to illustrate "drawbacks" that sometimes are assumed to be as a consequence of a renovation action, costs are regarded as a "negative utility". This example has nothing to do with any existing renovation project.

Assume a renovation action with investment costs of 600€, energy savings of 1000 kW h/a, and maintenance savings of 100€/a. Let the maximum allowable cost be 2400€, which is regarded as a "huge drawback" by the design team. Using the scale presented in Table 2, the score then is

$$\frac{600}{2400}(-10) = -2.5$$

If the design group decides that energy savings of 2000 kW h/a is a "huge improvement" compared with the situation before the renovation (savings 0 kW h/a), this action is worth the score number

$$\frac{1000}{2000}10 = +5$$

If 500€/a is regarded as a "huge improvement" in maintenance costs, compared with the situation before this renovation (0€/a), the score is

$$\frac{100}{500}10 = +2$$

Finally, let the criteria weights be as follows: investment (0.6), energy savings (0.3), and maintenance savings (0.1). The total score for this renovation action then is

$$S = 0.6(-2.5) + 0.3 \cdot 5 + 0.1 \cdot 2 = \underline{0.2}$$

A "utility profile" (see Fig. 3) illustrates, on the basis of which sub-criteria this alternative is "good" or "bad".

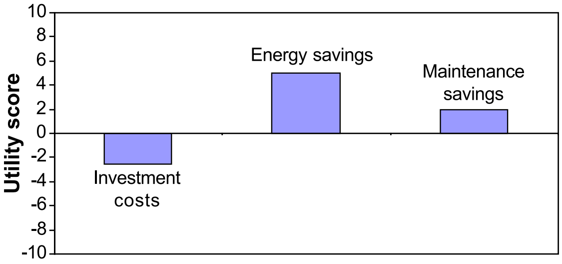


Fig. 3. An example of a utility profile.

3. A case study

In this chapter, a simple practical case study is presented, concerning a retrofit project of a residential building in Finland. In the case study, the acceptability of a retrofit scenario was simply defined on the basis of two criteria: environmental value and functionality. The criteria tree (see Fig. 2) therefore only consists of three nodes: main goal and two criteria with their indicators. The objective function was maximised subject to an investment cost constraint and eight other constraints. The aim of this case study was actually not so much to search optimal retrofit actions for a practical real-life case, as to test the applicability and functionality of the "knapsack" model in the context of this type of problems and just to demonstrate a new model. For these reasons and in order to avoid confusion, a simplified approach was considered powerful enough to be applied.

3.1. Introduction of the target building

The case study handles an apartment building owned by VVO (see Fig. 4), which is one of the biggest social housing owners in Finland. The building was constructed in 1983. The total building volume is 7080 m^3 and the floor-area is 2045.10 m^2. The building has 29 dwellings in 3 stairways and 3 floors. The average amount of inhabitants is 55.

Fig. 4. The Finnish target building in Eerikinkallio 4 in Kirkkonummi.

The theoretical annual heating energy and electricity consumptions of the building are 313 MW h (44.2 kW h/m^3) and 103 MW h (14.5 kW h/m^3), respectively. These values are based on calculations made using WinEtana simulation program. According to Kosonen et al. [13], the electricity consumption of electrified car parking spaces can be assumed to be 5% of total electricity consumption.

The building is equipped with a district heating system and exhaust air fans (without any heat recovery system). It has double-glazed windows ($U = 2.2$ W/m^2 K). The U-values of walls and roof structures are 0.28 W/m^2 K and 0.22 W/m^2 K, respectively. The initial room temperature 21 °C is used for calculations.

3.2. Alternative retrofit actions

A list of alternative retrofit actions applied in this study is based on a Finnish report edited by innominated authors and published by Finnish Ministry of Environment [14]. Typical retrofit actions have been introduced on the list aiming at improving the building energy economy by decreasing energy consumption. The list is presented in Table 3.

3.3. The utility of alternative retrofit actions

In the case study, the acceptability of a retrofit scenario was simply defined by means of two criteria: environmental value and functionality. For the reasons mentioned at the beginning of Section 3, simplifications were made ignoring some criteria that should be taken into account in practice.

The environmental value of a retrofit project usually is associated with reduction potentials of NO_x-, SO_x-, and CO_2-emissions. In the simplified approach, the reduction potential of CO_2-emissions has been regarded as a criterion descriptive enough for the environmental value of a retrofit action. This is justifiable, because carbon dioxide is one of the most problematic greenhouse gases and it has been attacked by several climate strategies in national and international level. According to the National Climate Strategy, Finland should cut its CO_2-emission rates to the level of year 1990 during years 2008–2012 [15]. Taking into account statistical biases, Finland should cut its emissions about 15%. As-

Table 3
A list of retrofit actions [14]

N	Name of the retrofit action
1	Decrease and adjustment of indoor temperatures: −1 °C
2	Decrease and adjustment of indoor temperatures: −2 °C
3	Decrease and adjustment of indoor temperatures: −3 °C
4	Decrease and adjustment of indoor temperatures: −4 °C
5	Adding heat recovery to ventilation
6	Installation of new windows: 3 × glass
7	Installation of new windows: 3 × glass selective
8	Installation of new windows: 3 × glass selective + argon
9	Additional insulation to roof: 50 mm
10	Additional insulation to roof: 100 mm
11	Additional insulation to roof: 150 mm
12	Additional insulation to roof: 200 mm
13	Additional insulation to walls: 50 mm
14	Additional insulation to walls: 100 mm
15	Additional insulation to walls: 150 mm
16	Additional insulation to walls: 200 mm
17	Flow rate adjustment of water fittings
18	Installation of economizer jets into water fittings
19	Installation of new water fittings
20	Installation of pressure reducer into water distribution system
21	Water consumption measurement into apartment level
22	Energy consumption measurement into apartment level
23	Radiator network adjustment, installation of thermostatic valves
24	Installation of new light fittings
25	Improvement of lighting control
26	Improvement of control of electrified parking space
27	Installation of peak power limit

suming a linear value function and regarding the decrease of 20% in CO_2-emissions as a "huge improvement", the following presentation (see Fig. 5) can be derived for the environmental value. According to the National Climate Program-Sectoral Statement, specific emission factors for district heat production (337 kg/MW h) and electricity production (160 kg/MW h) are presented, which were used when calculating the reduction potential in CO_2-emissions for each retrofit action [16].

CO_2-emissions can be defined in quite an easy way, but instead there is not a straightforward and exact way to calculate functionality. This is for the following reasons. Firstly, functionality is more or less a qualitative issue, which makes it immeasurable. Secondly, functionality is more or less a subjective issue depending on the preferences of an evaluator. In this study, the following 10 aspects were taken into account, when evaluating the utility value of a retrofit action in a retrofit scenario in the context of functionality [14].

- How easily this retrofit action can 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 its effect on comfortability?
- What is its 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?

When defining the utility for each retrofit action in the context of the concept "functionality", a criteria tree (see Fig. 2) normally should be constructed using reasonable amount of sub-criteria levels (nodes) based on the aspects listed previously. Then, the scores should be calculated for each node like was presented in Section 2. In the simplified approach, this phase was ignored because of briefness and simplicity and functionality directly was evaluated for each retrofit

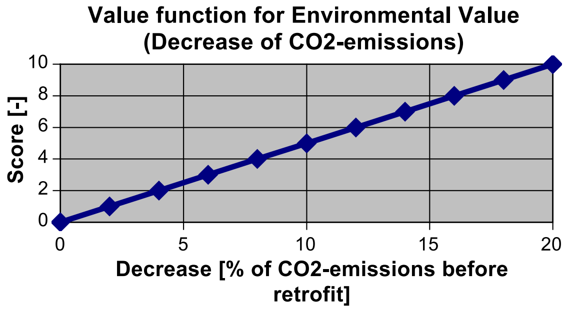


Fig. 5. Value function for criterion "Environmental Value".

Table 4
Features of different retrofit actions

N	Saving potential	Costs*** [•/m^2]	Decr. CO$_2$ [%]	Advantages and disadvantages
1	4% heat	0.2	3.81	Decrease and adjustment of indoor temperatures: • easy to carry out • decreases comfortability (+21 C original state) • reliable way to carry out energy savings • may require additional actions (radiator network adjustment, etc.)
2	8% heat	0.2	7.61	
3	12% heat	0.2	11.42	
4	16% heat	0.2	15.23	
5	15–20% heat	10	14.27	Adding heat recovery to ventilation: • positive effect on indoor air quality • may require additional actions • requires use instructions
6	4% heat*	11.58	3.81	Installation of new windows: • draught, radiation and noise reduction • lack of instructions
7	6% heat*	12.41	5.71	
8	9% heat*	14.06	8.56	
9	1% heat*	0.15	0.95	Additional insulation to roof or walls: • space requirement • adaptability to existing structures • physical characteristics may not change
10	2% heat*	0.3	1.90	
11	3% heat*	0.45	2.85	
12	3% heat*	0.6	2.85	
13	1% heat*	0.15	0.95	
14	2% heat*	0.3	1.90	
15	3% heat*	0.45	2.85	
16	5% heat*	0.6	4.76	
17	5–7% heat	0.3	4.76	Flow rate adjustment of water fittings: • demands control possibility in an existing fitting
18	5% heat	5	4.76	Installation of economizer jets into water fittings: • easy to carry out • comfortable when having a shower
19	5–10% heat	15	4.76	Installation of new water fittings: • vulnerability to pollution • vulnerability to breakages • may improve usability
20	0–10% heat	1	4.76	
21	0–10% heat	15	4.76	Water consumption measurement apartment level: • measuring errors • serviceability
22	10–15% heat	15	9.52	Energy consumption measurement apartment level: • not usual action • unreliable • unfair
23	5–10% heat	0.3	9.52	Radiator network adj., inst. of therm.valves: • quite easy to carry out • instructions and methods exist

Table 4 (*continued*)

N	Saving potential	Costs*** [•/m^2]	Decr. CO$_2$ [%]	Advantages and disadvantages
24	5–10% electricity	8	0.48	Installation of new light fittings and impr. of lighting control: • safety • comfortability • easy to carry out
25	5–10% electricity	5	0.48	
26	2% of electricity*	5	0.10	Improvement of control of electrified parking space: • comfortability • environmental factors • decrease of property risk
27	1% of electricity**	1	0.05	Installation of peak power limit: • indirect effect on optimization of power plant capacity

* Achieved through calculations by WinEtana.

** Approximated value.

*** Based on VTT's cost database for residential buildings.

action by judging them against the listed aspects. The results of these judgements are presented in Table 4 by "advantages and disadvantages". Features of alternative retrofit actions (to shorten the representation, *N* refers to the actions listed in Table 3) as well as their score values using a scale from −10 to +10 for functionality and environmental value, are presented in Tables 4 and 5.

3.4. Implementation of the method

Using a linear model and following the expression described in Section 2, we now have 27 decision variables (alternative retrofit actions, see Table 3) $a_1,\ldots a_i,\ldots a_{27}$. The objective function is

$$\mathrm{MAX}\sum_{i=1}^{27} a_i S_i, \tag{4}$$

where S_i = utility score achieved by selecting the renovation action a_i.

Let the criterion "environmental value" be marked by index number 1 and the criterion "functionality" by index number 2. In this simple case, the utility for an arbitrary retrofit action i is

$$S_i = w_1 s_{1,i} + w_2 s_{2,i} \tag{5}$$

where w_1 and w_2 are normalised weights (between 0 and 1) for criteria 1 and 2, respectively. As well, $s_{1,i}$ and $s_{2,i}$ are utility score numbers for an arbitrary retrofit action i, in respect to the score values for criteria 1 and 2, respectively.

Table 5
Functionality and environmental index value of alternative retrofit actions

N	Environmental value	Functionality
1	1.90	0
2	3.81	−4
3	5.71	−6
4	7.61	−8
5	7.14	2
6	1.90	2
7	2.85	4
8	4.28	5
9	0.48	−4
10	0.95	−5
11	1.43	−7
12	1.43	−8
13	0.48	−4
14	0.95	−5
15	1.43	−7
16	2.38	−8
17	2.38	−4
18	2.38	2
19	2.38	3
20	2.38	−4
21	2.38	−2
22	4.76	−4
23	4.76	1
24	0.24	4
25	0.24	4
26	0.05	5
27	0.02	2

Because there are 27 alternative retrofit actions, there would be 227 possible portfolios if no constraints were defined. On the other hand, an unconstrained problem definition might lead to a trivial solution, in which all the options with a non-negative total utility value would be recommended.

In a "knapsack model", $a_i = 1$ if action a_i is carried out, else $a_i = 0$. Thus, it is required that $a_i \in \{0,1\}$. The first constraint limiting number of portfolios is maximum allowable costs of the project

$$\sum_{i=1}^{27} a_i C_i \leq C_{\mathrm{MAX}} \tag{6}$$

where C_i = cost of action a_i and C_{MAX} = maximum allowable costs of the project.

The following constraints usually limit the compatibility between the listed retrofit actions [16]. In the mathematical form, they can be presented as follows. A rational assumption is that only one temperature drop is selected at a time, which means that

$$\sum_{i=1}^{4} a_i \leq 1 \tag{7}$$

Usually, only one window type is selected into a retrofit scenario, which can be expressed by means of the following constraint equation.

$$\sum_{i=6}^{8} a_i \leq 1 \tag{8}$$

It is also obvious that only one thickness of roof insulation is selected, which is expressed by constraint Eq. (9),

$$\sum_{i=9}^{12} a_i \leq 1 \tag{9}$$

as well as one thickness of wall insulation, like is expressed by Eq. (10).

$$\sum_{i=13}^{16} a_i \leq 1 \tag{10}$$

Flow rate adjustment and economizer jets are alternative ways of adjustment, which requires that

$$\sum_{i=17}^{18} a_i \leq 1 \tag{11}$$

The flow rate adjustment is necessary, if new water fittings are installed. This is expressed by Eq. (12).

$$a_{17} \geq a_{19} \tag{12}$$

The same requirement is valid, if pressure reduce are installed, requiring

$$a_{17} \geq a_{20} \tag{13}$$

Improvement of the lighting control system urges on the installation of new light fittings, requiring

$$a_{24} \geq a_{25} \tag{14}$$

In this study, the model was solved by using Solver function of MS Excel. The approach was based on incomplete preference information, which means that the study was a sensitivity analysis by nature. The maximum allowable investment costs were let to vary from 10 000€ to 100 000€, at 10 000€ intervals. For each investment cost level, five combinations of weight factors were analyzed. The cases were:

1. Completely environment oriented case: weight of environmental value 100/weight of functionality 0 (Corresponding normalized weight factors 1.0/0.0)
2. Slightly environment oriented case: weight of environmental value 100/weight of functionality 50 (Corresponding normalized weight factors 0.67/0.33)
3. Equal importance-case: weight of environmental value 100/weight of functionality 100 (Corresponding normalized weight factors 0.5/0.5)
4. Slightly functionality oriented case: weight of environmental value 50/weight of functionality 100 (Corresponding normalized weight factors 0.33/0.66)
5. Completely functionality oriented case: weight of environmental value 0/weight of functionality 100 (Corresponding normalized weight factors 0.1/1.0)

In addition, the model was calculated in the case of the best possible environmental value and the best possible functionality without the cost constraint, to verify its rationality. The total number of analyzed cases was thus 52.

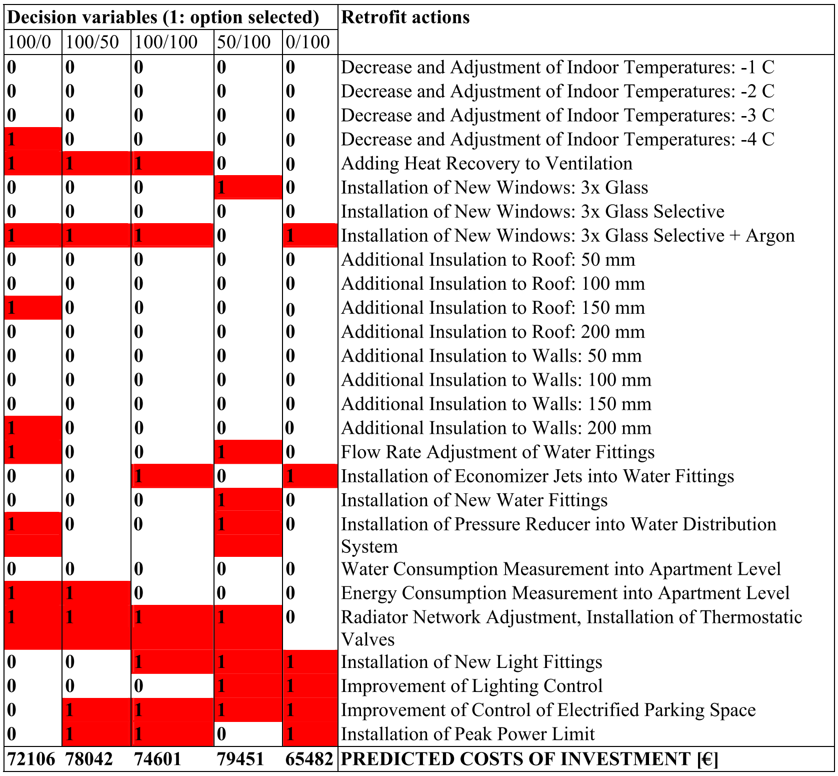
3.5. Results of the study

As a result of the optimization, retrofit scenarios were achieved that can be recommended in the case of given constraints and criteria weights. Because of the large amount of cases, all the optimal scenarios are not presented in this section, but some conclusions are made concerning the applicability of the methodology as well as recommendable retrofit actions.

The theoretical annual heat consumption of the target building compared to that of electricity is large. Similarly, the specific emission factor for district heat production compared to that for electricity production is significant. In addition, the most significant energy saving potential is associated with retrofit actions saving heating energy. As a consequence, it is obvious that retrofit actions decreasing heat consumption cause the largest additional value on environmental value. A retrofit project of an electricity system probably improves functionality, which is a conclusion from the information presented in Table 4.

These arguments were clearly verified by the analysis. The case with maximum allowable costs of 80 000 is presented in Fig. 6, as an example of the output data. The results indicate that the more weight is put on functionality, the more electricity saving options are recommended by the model. (Note in Fig. 6: decision variable 0 = an option should not be selected, 1 = an option should be selected.)

Infeasible retrofit actions were taken into account by the model, like was expected. For example, room temperature drop of 3° or 4° is usually out of optimality, if the initial room temperature is already optimal: 21 °C. This kind of retrofit actions was automatically excluded by the model, if any weight was put on functionality (and thus comfortability). On



Decision variables (1: option selected)					**Retrofit actions**
100/0	100/50	100/100	50/100	0/100	
0	**0**	**0**	**0**	**0**	Decrease and Adjustment of Indoor Temperatures: -1 C
0	**0**	**0**	**0**	**0**	Decrease and Adjustment of Indoor Temperatures: -2 C
0	**0**	**0**	**0**	**0**	Decrease and Adjustment of Indoor Temperatures: -3 C
1	**0**	**0**	**0**	**0**	Decrease and Adjustment of Indoor Temperatures: -4 C
1	1	1	**0**	**0**	Adding Heat Recovery to Ventilation
0	**0**	**0**	1	**0**	Installation of New Windows: 3x Glass
0	**0**	**0**	**0**	**0**	Installation of New Windows: 3x Glass Selective
1	1	1	**0**	1	Installation of New Windows: 3x Glass Selective + Argon
0	**0**	**0**	**0**	**0**	Additional Insulation to Roof: 50 mm
0	**0**	**0**	**0**	**0**	Additional Insulation to Roof: 100 mm
1	**0**	**0**	**0**	**0**	Additional Insulation to Roof: 150 mm
0	**0**	**0**	**0**	**0**	Additional Insulation to Roof: 200 mm
0	**0**	**0**	**0**	**0**	Additional Insulation to Walls: 50 mm
0	**0**	**0**	**0**	**0**	Additional Insulation to Walls: 100 mm
0	**0**	**0**	**0**	**0**	Additional Insulation to Walls: 150 mm
1	**0**	**0**	**0**	**0**	Additional Insulation to Walls: 200 mm
1	**0**	**0**	1	**0**	Flow Rate Adjustment of Water Fittings
0	**0**	1	**0**	1	Installation of Economizer Jets into Water Fittings
0	**0**	**0**	1	**0**	Installation of New Water Fittings
1	**0**	**0**	1	**0**	Installation of Pressure Reducer into Water Distribution System
0	**0**	**0**	**0**	**0**	Water Consumption Measurement into Apartment Level
1	1	**0**	**0**	**0**	Energy Consumption Measurement into Apartment Level
1	1	1	1	**0**	Radiator Network Adjustment, Installation of Thermostatic Valves
0	**0**	1	1	1	Installation of New Light Fittings
0	**0**	**0**	1	1	Improvement of Lighting Control
0	1	1	1	1	Improvement of Control of Electrified Parking Space
0	1	1	**0**	1	Installation of Peak Power Limit
72106	**78042**	**74601**	**79451**	**65482**	**PREDICTED COSTS OF INVESTMENT [€]**

Fig. 6. Example of output data for the case analysis.

the other hand, the model took into account that decreasing room temperatures is a cheap way to save energy and thus to improve the environmental value.

In general, radiator network adjustment together with installation of thermostatic valves clearly were the most recommendable retrofit actions in the majority of analyzed cases. They were recommended in 90% of cases. This can be explained by a good price–quality ratio of this retrofit action, as well as by its ability to improve both comfortability and energy economy. Traditional energy saving actions, such like additional insulation and some new solutions like energy and water consumption measurement in the apartment level, were not recommended. Instead, some new solutions like installation of peak power limit and selective-argon windows were almost surprisingly recommendable. Analysis without the cost constraint showed that by allowing more than 70 000 to the investment, no additional functionality was achieved. In the case of additional environmental value, this limit was 158 000. The percentage of cases in which an alternative action was recommended, is presented in Table 6.

Table 6
Percentage of recommended cases for each retrofit option

Retrofit action	Recommended in % of cases
Radiator network adjustment, installation of thermostatic valves	90
Flow rate adjustment of water fittings	64
Improvement of control of electrified parking space	60
Installation of peak power limit	58
Adding heat recovery to ventilation	50
Installation of new light fittings	46
Installation of new windows: 3 × glass selective + argon	44
Installation of pressure reducer into water distribution system	38
Improvement of lighting control	30
Decrease and adjustment of indoor temperatures: − 4 °C	30
Additional insulation to walls: 200 mm	20
Additional insulation to roof: 150 mm	18
Installation of economizer jets into water fittings	16
Installation of new water fittings	14
Energy consumption measurement into apartment level	14
Decrease and adjustment of indoor temperatures: − 1 °C	12
Installation of new windows: 3 × glass selective	6
Water consumption measurement into apartment level	4
Installation of new windows: 3 × glass	2
Additional insulation to roof: 50 mm	2
Decrease and adjustment of indoor temperatures: − 2 °C	0
Decrease and adjustment of indoor temperatures: − 3 °C	0
Additional insulation to roof: 100 mm	0
Additional insulation to roof: 200 mm	0
Additional insulation to walls: 50 mm	0
Additional insulation to walls: 100 mm	0
Additional insulation to walls: 150 mm	0

4. Evaluation of the model

Three typical challenges were presented in Section 1 in the context of decision-making of today's construction. The novelty of the approach presented in this paper is especially to give an answer to the challenge: how to find an optimal technology portfolio by evaluating a lot of technological options. The other challenges—the large amount of conflicting preferences and conflicting evaluation criteria—also have an important role in this analysis.

Traditionally, building designers produce not more than a few alternative design scenarios which then will be evaluated for the final choice. The most important strength of the knapsack model in the context of renovation project planning is its ability to automatically evaluate a large amount of mutually compatible or non-compatible renovation actions in order to find an optimal portfolio. This is a great improvement compared with the present situation. Although the human reasoning hardly never can be substituted by a mathematical model, this kind of approach may help designers to achieve solutions that otherwise would not come to their mind, especially in a case of many, conflicting criteria and constraints.

The knapsack model is at its best, when the amount of options is large and there are conflicting constraints. For example, if there are 27 options, the total amount of possible portfolios in an unconstrained case is $2^{27} = 134\ 217\ 728$. Despite the constraints, the number of portfolios can easily rise up to hundreds of thousands. Evaluating this amount of portfolios manually is practically impossible.

In the approach presented in this paper, multi-criteria decision-making and a knapsack model are combined by first evaluating individually each option using a multi-criteria approach in order to achieve the utility caused by this option. Then the results are used as an input for the knapsack model which maximises the sum of utilities brought by single options into a portfolio subject to given maximum allowable costs.

Any multi-criteria evaluation principally has following challenges. Firstly, criteria can be both quantitative and qualitative by nature. If a criterion is qualitative, there is not a straightforward and exact way to calculate a numerical value to indicate it. In order to indicate the utility of an option by means of a single numerical value, all the criteria must be indicatable in a commensurate scale. This leads to the second challenge: defining the scale may depend on the preferences of an evaluator, being actually a subjective choice. Because the "goodness" of different options usually is evaluated by a single expert or a group of experts, subjectivity also is a part of the evaluation itself. Misleading results may be achieved, if the results of the audits, operational experiences and opinions are combined in a careless way. To avoid misleading results, as many quantitative criteria should be used as possible and as many expert opinions should be taken into account as possible.

The model presented in this paper is completely additive. Firstly, the simple additive weighting model is applied to aggregate the scores to get a single score number representing the utility of an option. The additive model is at its best, when the characteristics (attributes) of an option can be considered separately, without overlaps. This method is very popular, probably because it allows a decision-maker to combine the scores of all the nodes in a criteria tree into a single number making it easier to compare the options. The problem occurs, however, if the set of criteria has been defined so that overlapping evaluations become possible. Then, this approach may give misleading results. The additive model also is compensatory, which means that strengths of an option in respect to that criterion compensate its weaknesses in respect to another criterion. Whether this is an advantage or a disadvantage probably depends on the perspective.

Secondly, the knapsack model is additive by nature. The model assumes that each option will bring some utility, i.e. additional value (either improvement or drawback) into the portfolio. Before an evaluation, one has to be sure that the additional value for the portfolio can be indicated in the form of improvement or drawback for each criterion. Referring to the retrofit case study presented in Section 3, reduction potential in CO_2-emissions in a whole retrofit scenario maybe can be approximated as a sum of reduction potentials of single retrofit actions, which makes it reasonable to use an additive approach. On the other hand, the additivity is much more controversial in the case of functionality. Some aspects like "space requirement" can be additive, whereas other aspects like "adaptability to existing structures" maybe not. Additional studies are needed to find out the applicability of additive models in the context of building energy technology.

The additive knapsack model presented in this study is based on linear programming. Methods like Branch and Bound make it possible to solve this kind of problems in minutes or even in seconds (for example: Solver function of MS Excel). According to Gustafsson [10], the models in the context of building design, however, often are nonlinear. Because of the complex solution of nonlinear knapsack problems, and because of increased computing power of computers, a nonlinear problem can be solved simply by computing the value of the objective function for all the portfolios [17]. Applying computers and data structures in this context has been handled for example by Alanne [18].

The knapsack model is at its best, when there really is a large amount of options and a lot of constraints. The knapsack model is expected to be the most applicable in the future, when there are so many technologies on the market, that a comprehensive evaluation of portfolios is not feasible by means of traditional methods. At this moment, however, the best way to search for the optimal solution still probably is the traditional way to manually generate a few portfolios and then evaluate them. There are many multi-criteria evaluation tools for that kind of analysis, for example, PRIME, HIPRE and MCDM-23. More about these tools has been written for example by Huovila [1], Tanimoto [2], Mustajoki [12], and Gustafsson [19].

5. Conclusions

In recent years, many new technological solutions have been introduced, aiming to improve the ability of buildings to satisfy a variety of needs of human beings and the environment. As a consequence, designing an optimal building has become more challenging than it has been before. The novelty of the approach presented in this paper is especially to give an answer to the challenge: how to find an optimal technology portfolio by evaluating a lot of technological options. The other challenges—a large amount of conflicting preferences and conflicting evaluation criteria—also have an important role in this study. A great potential exists for the introduction of new technologies through renovation projects, because almost half of construction industry in developed countries is directed to the existing building stock. Thus, selection of building renovation actions is handled as a main practical application in this study.

In this paper, a multi-criteria “knapsack” model has been proposed to help designers to select the most feasible renovation actions in the conceptual phase of a renovation project. Generally speaking, this is a specified case of portfolio optimization. A case analysis concerning a real, Finnish apartment building also has been presented. The aim of this case study has been primarily to test the applicability and functionality of the “knapsack” model in the context of this type of problems and to demonstrate a new model. For these reasons and in order to avoid confusion, the simplified approach has been applied. In conclusion of the results, the method worked as had been expected. The radiator network adjustment with installation of thermostatic valves was recommended by the analysis, concerning the case building. Subjectivity as a feature of multi-criteria evaluation as well as additivity of the model was regarded as the most controversial factors when evaluating the model.

For the future, the following additional studies concerning the methodology can be recommended. Studies will be needed in order to find out the applicability of additive models in the context of previously mentioned problems. The sensitivity analysis presented in this study can be expanded, also to include incomplete information concerning attributes of different renovation actions. The discrete knapsack model could be extended to continuous variables. Thus, conventional sizing parameters like thickness of insulation or size of heat exchanger could be regarded as decision variables. In general, many extensive case studies should be carried out applying the knapsack model, in order to get operational experiences in a larger context than has been presented in this paper.

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References

[1] P. Huovila, M. Sunikka, J. Leinonen, J. Nieminen, MCDM using EcoProP, QFD and MCDM-23, IEA Task 23 Report, VTT Building Technology, 1999.

[2] J. Tanimoto, P. Chimklai, D. Balcomb, I. Andresen, S. Aggerholm, Multi-criteria Decision-making MCDM-23, a method for specifying and prioritising criteria and goals in design (Draft), International Energy Agency Solar Heating and Cooling (2001) 4–11.

[3] N.H. Afgan, M.G. Carvalho, D.A. Gobaisi, M. Cumo, Sustainable energy development, Renewable and Sustainable Energy Reviews 2 (1998) 235–286.

[4] Our common future, World Commission on Environment and Development (WCED), Oxford, 1987.

[5] H. Matala, Decision making and economy in Refurbishment (Only in Finnish), Suomen Kunnat 21 (1985) 26–28.

[6] T. Häkkinen, P. Huovila, K. Tattari, S. Vares, J. Seppälä, S. Koskela, J. Leivonen, T. Pylkkö, Eco-efficiency of buildings (only in Finnish), Ministry of the Environment (2002) 74–82.

[7] I. Andresen, Multiple Criteria Decision Analysis (MCDA), A Survey of methods (1st draft), Department of building technology, Faculty of Architecture, Norwegian University of Science and Technology, Trondheim, Norway, 1998.

[8] F. Flourentzou, C.A. Roulet, Elaboration of retrofit scenarios, Energy and Buildings 34 (2002) 185–192.

[9] Y. Rosenfeld, I.M. Shohet, Decision support model for semi-automated selection of renovation alternatives, Automation in Construction 8 (1999) 503–510.

[10] S.-I. Gustafsson, Mixed integer linear programming and building retrofits, Energy and Buildings 28 (1998) 191–196.

[11] T. Vainio, Rakentamalla Hyvinvointia 1999 (only in Finnish), VTT Building Technology, Tampere, 1999.

[12] J. Mustajoki, R.P. Hämäläinen, Web-HIPRE: global decision support by value tree and AHP analysis, Infor 38 (2000) 208–220.

[13] R. Kosonen, J. Shemeikka, The use of a simple simulation tool for energy analysis, VTT Building Technology.

[14] Energy saving potential in residential buildings-preliminary study, (only in Finnish), Ministry of the Environment (2000) 38–54.

[15] Energy Review 1/2002 (only in Finnish), Ministry of Trade and Industry, 2002.

[16] National Climate Program-Sectoral Statement (only in Finnish), Ministry of the Environment, 2001. Available at: http://www.vyh.fi/palvelut/julkaisu/elektro/sy473/sy473.htm.

[17] D.S. Hochbaum, A nonlinear Knapsack Problem, Operations Research Letters 17 (1995) 103–110.

[18] K. Alanne, A computer-applicable methodology for formulating system alternatives in the design of building energy systems (only in Finnish), Licentiate thesis, Department of Energy Technology, Lappeenranta University of Technology, 2000.

[19] J. Gustafsson, A. Salo, T. Gustafsson, PRIME Decisions—an interactive tool for value tree analysis, in: M. Köksalan, S. Zionts (Eds.), Proc. of the Fifteenth International Conference on Multiple Criteria Decision Making (MCDM) Ankara, Turkey, July 10–14, 2000, Lecture Notes in Economics and Mathematical Systems, vol. 507, 2001, pp. 165–176.