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DECISION-MAKING MODEL FOR CHOOSING RESIDENTIAL BUILDING REPAIR VARIANTS

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Abstract. During the use of buildings it becomes necessary to carry out repair works including modernisation. Deciding on the choice of repair solutions is a difficult and complex task. Building administrators have to consider both, the benefits of some repair works, and limitations due to the availability of funds. Selection of a repair solution, bearing in mind the above, requires a comprehensive approach that will allow assessment of the building condition and determining the repair scope required. The research conducted by the authors was aimed at developing a decision-making model and its computer-aided implementation, taking into account a number of operating demands. The system algorithm proposed comprises five stages including: building condition assessment, building use value evaluation, repair classification, multiple variants of repair and the choice of repair solutions. The article describes individual stages of the model in detail, giving numerical application examples of the method for repair solution choice for five multi-family houses.

Keywords: repair solution, operating requirements, building evaluation, repair, renovation.

Introduction

Residential building management requires to maintain the building in non-deteriorated condition and obliges the administrator to reasonably invest funds for repairs (art. 185 par. 1 of the Real estate management law). Difficulties involved in this process are the main reason why vast experience and skills are required from the administrator while making repair-related decisions. This involves multiple criteria evaluation of the building condition. Various factors are adopted to assess a building condition. One of them is so called use value (Niezabitowska *et al*. 2003; Orłowski, Szklennik 2011), defined as the building ability to satisfy its users' demands. This ability is assessed by a set of measurable features important for the use, i.e. technical, energy, visual and functional ones.

The building use value appraisal allows studying its condition and establish the relevant repair needs. However, the problem encountered by residential building administrators lies in the funds available for repairs, which are usually insufficient. This article presents the methods for choosing the repair solution meeting the above assumptions. It includes five steps in which various calculation tools were used. The first stage includes building condition assessment, also applying the methods proposed for that purpose, i.e. the technical, energy and functional assessment. The second and third steps evaluate the building use value, which determines the building quality and further repair activities performed based on that. The fourth step requires to determine the repair needs based on prior building condition assessment. Various repair technologies can be employed, i.e. different variants, requiring different expenditure. The last step of the model is to show an optimum repair solution for buildings, considering the limitations of the repair funds available.

1. Decision support methods and models for building maintenance

Building condition assessment, in addition to technical deterioration, includes also other building features, such as those related to its functionality, aesthetics, energy efficiency, etc. To this end, multiple criteria decision making (MCDM) methods are used. The multiple criteria (multiple factor) evaluation of a building has been the subject of numerous analyses and research projects in Poland and abroad, aimed at developing a comprehensive method for determining the condition of a residential building. The scholars' interest in this subject has been so

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far of scientific nature, however, presumably, the growing operational demands prescribed by law or from the users will contribute to more intense actions aimed at developing a suitable assessment method which would be useful in practice.

An example of a comprehensive approach to building assessment is the LEED (Leadership in Energy and Environmental Design) method created in 1990s, described in detail by Roderick *et al.* (2009). This method evaluates a building bearing in mind the sustainable development principles, such as building location, use of water resources, energy consumption, recycling of materials, internal environment, as well as material and technology innovation and regional environmental priorities. In the British BREEAM (Building Research Establishment Environmental Assessment Method) system described by Reed *et al.* (2011), while assessing a building, the environmental protection requirements (saving water, energy, eco-friendly and recyclable materials, pollution), residents' health requirements and building management methods are considered. Even more varied requirements are included in the German DGNB (German Sustainable Building Council) system, in which the evaluation scope refers to the environmental, economic, social and cultural, technical, design factors and building location (Alchimoviene, Raslanas 2011). The equivalents of the mentioned systems are the EU GreenBuilding, Australian Green Star and Japanese CASBEE (Comprehensive Assessment System for Built Environment Efficiency) systems (Reed *et al.* 2011).

A tool for diagnosing the condition of office buildings, allowing determination their modernisation cost is TOBUS (European diagnostics and decision-making Tool for Office Building Upgrading Solutions) (Caccavelli, Gugerli 2002). The system proposed encompasses the evaluation of physical condition of building components, functional ageing, energy consumption, the quality of the internal environment.

Another example of a multiple criteria building appraisal method is the POE (Post-Occupancy Evaluation), developed by Preiser (1995). This method allows the assessment of the technical, functional, behavioural, organisational and economic quality of building, while its extended BPE (Building Performance Evaluation) version, created by Preiser and Vischer (2005) is effective in assessing also the building design and construction quality.

Many useful tools for building appraisal are proposed by IDCOP (Innovation In Design, Construction & Operation of Buildings for People), including the system for assessing building façade, developed and presented by Chen (2006). A facade innovation factor is applied for this assessment, which depends on how a number of requirements are complied with, including the adaptive abilities, affordability, durability, energy consumption and aesthetic, sound, heat comfort requirements and others.

An application example of the FAHP method to determine the significance of the operating requirements is presented in the work of Pan (2008). He applied that method to determine the significance of factors used to evaluate a road bridge.

An interesting approach to the multiple criteria assessment of building operating conditions is presented by Kasprowicz (2005). He defines the operating condition and identifies the assessment criteria based on a set of requirements provided in the Construction Law. Selected factors are divided to measurable (quantitative) and immeasurable (qualitative) ones. He assumes that, depending on the type, properties and possibility to measure, determine or calculate operating properties of a building, the operating features can be identified which can be fixed, fuzzy or probabilistic values, which requires application of proper measuring methods.

Kaklauskas *et al.* (2005) developed a method of multiple criteria building assessment, aimed at determining the significance of repair and their completion degree. The methods comprise six steps: (1) building component evaluation criteria are selected, followed by determining the importance of criteria; (2) the indices of minimum and maximum objective are calculated for each alternative solution; (3) and (4), respectively, the value of each solution is determined and put in order; (5) the degree of compliance with the requirements for every solution is determined; (6) the repair priority is determined for all considered parts to be repaired.

Using, for building evaluation, multiple factors with different nature, with fixed, variable random and fuzzy and more or less interrelated values has led to the development of a model and systems supporting the decision making – DSS. Such systems including multiple criteria rankings of the MCDM phenomenon studied are based on expert systems and artificial intelligence methods, using fuzzy sets, neural networks, evolutionary algorithms, etc.

An example of a computer-aided repair decision support system is EPIQR (Energy Performance and Indoor Quality Retrofit). It is used for estimation of building renovation cost, taking into consideration the reasonable use of energy and improving the standard of living (Vilhena *et al.* 2011). It is an integrated system for diagnosing of building condition and computer-aided decision making as to the type and scope of repair projects, including thermal improvement projects, with various work scenarios, with continued control of the project cost.

Another example of a system supporting decisions as to the allocation of funds for the repair of building in Tainan is presented by Perng *et al.* (2007). To evaluate buildings the authors propose a solution based on the multiple criteria TOPSIS analysis. To this end, they identified ten factors which relate to the technical, political and economic requirements. The result of the evaluation is showing how much needed the repair is (with a four-grade scale). The repair solutions were selected with an evolutionary algorithm which defines the most cost-effective repair methods for individual building, considering the financial limitations.

Application of the evolutionary algorithms in complex DSS models, aimed at developing the repair policy for buildings, are presented in the work of Juan *et al.* (2009). To evaluate the building quality, the authors propose application of such criteria as the safety, usability, user health, comfort of use, usefulness. The effect of each of them is assessed with the AHP method. To show repair solutions, they suggest application of an evolutionary algorithm based on two various (priorities) objective functions. The aim of the first one is to determine the most cost-effective scope of repair, for which no assumed repair budged, is exceeded. The other is aimed at showing the most favourable repair options in terms of cost, assuming that the minimum threshold level of building quality and the target level identified by the decision-maker would be achieved.

In the literature other interesting decision making systems in building maintenance are presented, in which such tools as the Markov chains are applied to describe the risk occurrence of building elements failure or the optimalisation methods to the allocation of repair financial means, e.g. Lounis and Vanier (2000), Langevine *et al.* (2006).

Another example of the DSS and selection of alternative repair options is the Decision Support Model for Semi-Automated Selection of Renovation Alternatives proposed by Rosenfeld and Shohet (1999). Its structure comprises four modules: (1) building compliance with the legal and environmental requirements is initially analysed; (2) the physical and functional condition is assessed; (3) feasible actions are proposed to improve building condition, and alternative solutions are developed; (4) the qualitative and technical and economic comparison of the (feasible) alternatives is performed.

Identification and analysis of the methods and models applied in the above chosen DSS systems for building maintenance, taking into consideration multiple criteria of rankings, served as the grounds for the authors' work on the development of an original method for selection of an appropriate variant from multiple options possible, considering the multiple criteria building assessment and limited funds for the repair works.

2. Description of the method proposed

2.1. General concept

In the method proposed, the repair-related decisions depend on three building qualities, i.e. the technical conditions, energy and functional status, whereby each of them is affected by a number of factors. Therefore this is a complex calculation and decision-making problem. Based on the above ranks, a synthetic building use value is determined, which determines the choice of the repair solution that allows the highest increment of the building use value in relation to the funds invested.

The methods for creating a decision-making model included five main stages presented in the Figure 1.

It should be noted that the term "repair" used in the article indicates "performance of construction works in an existing building which not only concerns the restoration of building original state but also leads to its improvement according to requirements of changing regulations and requirements of building users or owners".

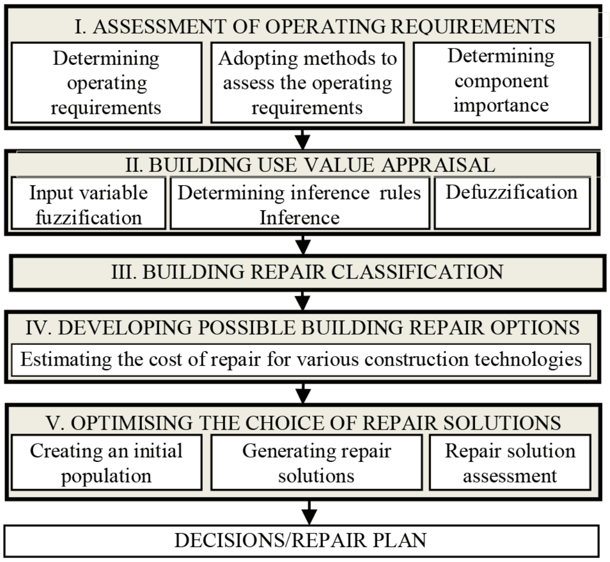

Fig. 1. Decision-making model flowchart

2.2. Operating (maintenance) requirement assessment

Three K_j criteria were assumed which are the basis for building use value (*WUB*) assessment: K_1 – technical condition; K_2 – functional status and K_3 – energy status.

Technical condition assessment. A set of building components was determined by $E = \{E_1, E_2, ..., E_n\}$, based on which the building deterioration is evaluated. While assessing the technical condition of a building, such components as walls, floors, roof, stairs, balconies, vestibules etc. were considered. The $E_i \in E$ components are assessed based on a set of factors $E_i = \{u_1, u_2, ..., u_p\}$ describing its damage, e.g. while assessing the walls: cracks, subsiding, vertical tilt and humidity.

To evaluate the technical condition O_{K_1}, the weighted average method was adopted (Bucoń, Sobotka 2012), in which the building wear index is expressed in a 0÷100% scale. Individual building components are assessed visually, hence the assessment represents also the visual condition:

$$O_{K_1} = \sum_{i=1}^{n} (w_{E_i} \cdot O_{E_i}^{K_1}) / 100, \tag{1}$$

where: w_{E_i}– significance of the condition component evaluated; $O_{E_i}^{K_1}$– technical deterioration of an i^{th} component of the building [%]; n – number of components assessed for the K_1 criterion.

Individual building components E_i are assessed according to the damage found u_i, based on which an expert determines the component deterioration $O_{E_i}^{K_1}$, using the linguistic rank scale: good – *G*; satisfactory – *S*; medium – *M*; poor – *P*; bad – *B*, to which the deterioration grades, expressed in %, are assigned respectively 0÷15, 16÷30, 31÷50, 51÷70, 71÷100.

Functional status assessment. A set of building features $C = \{C_1, C_2, ..., C_5\}$, was determined according to which its functional status will be assessed.

To assess the building functional status, the features considered were: functionality of balconies and entrances, communication inside the staircase, safety and security and ventilation. The rank assessment of all building features assumed $C_i \in C$ is affected by numerous factors $C_i = \{c_1, c_2, ..., c_o\}$, e.g. while assessing a balcony: the area, finishing, safety, furnishing, visual aspects etc.

To evaluate the functional status O_{K_2}, as above, the weighted average method was adopted which, in this case, consists in evaluating building features C_i based on the compliance with the requirements for each of the c_i factors:

$$O_{K_2} = \sum_{i=1}^{5} w_{C_i} \cdot O_{C_i}^{K_2}, \qquad (2)$$

where: w_{C_i}– significance of the feature assessed; $O_{C_i}^{K_2}$ – functional status feature rank [points].

Functional assessment of building feature is given in a 0÷5 points scale. Based on the building feature condition C_i, an expert grades it $O_{C_i}^{K_2}$ with the linguistic rank scale: good – *G*; satisfactory – *S*; medium – *M*; poor – *P*; bad – *B*; no component – *N*, to which the grades 5÷0 points are assigned.

Energy status assessment. A set of building components $E = \{E_1, E_2, ..., E_n\}$ was determined to assess its energy status. Some components $E_i \in E$, such as the walls, roof, basement floor, door and window joinery etc. correspond to those assessed against the K_1 criterion.

Assessment O_{K_3} should be carried out according to the methodology present in the standards of building thermal protection. It leads to the calculation of energy status assessment O_{K_3} expressed in kWh/m^2·year, determining on based seasonal building energy demand for heating purposes:

$$O_{K_3} = Q_h / A, \qquad (3)$$

where: Q_h – seasonal demand for heating, [kWh/m^2· – year]; A – area of external partitions [m^2].

Due to the fact that individual components considered while assessing the criteria adopted affect, to various degree, the building operation, i.e. its technical and functional status, their effects are varied by significance levels. The significance of components assessed are determined with the pseudo-fuzzy scaling method (Bucon, Sobotka 2012).

2.3. Assessing use value of buildings

The building use value *WUB* is calculated based on the assessment of three criteria K_j. Each of them is represented by a linguistic variable x_j expressed by fuzzy sets A_i^j in some space x_j:

$$A_i^j = \left\{ \left(x_j, \mu_{A_i^j}(x_j) \right) : x_j \in X_j, \mu_{A_i^j}(x_j) \in [0,1] \right\}, \qquad (4)$$

where: $\mu_{A_i^j}(x_j)$ – degree of belonging to A_i^j fuzzy set; i – the number of fuzzy sets for each of the j^{th} criteria: $x_1 = \{A_1^1, A_2^1, ..., A_5^1\}$, where: $A_1^1, A_2^1, ..., A_5^1$ denote fuzzy sets to be evaluated according to the K_1 criterion; $x_2 = \{A_1^2, A_2^2, A_3^2\}$, where: A_1^2, A_2^2, A_3^2 denote fuzzy sets to be evaluated according to the K_2 criterion; $x_3 = \{A_1^3, A_2^3, ..., A_6^3\}$, where: $A_1^3, A_2^3, ..., A_6^3$ denote fuzzy sets to be evaluated according to the K_3 criterion.

Each of the A_i^j fuzzy sets, except for the extreme ones, is expressed with a number of triangular membership functions, the peaks of which are located in the centre of each of the *n*-adopted ranges.

Fuzzification of the input variables required determining the number of fuzzy sets and establishing the characteristics and shape of membership functions describing them. The model assumes fuzzification of each input variable in such a manner that the division correspond to the categorisation method applied in practice.

Five grading categories were adopted for the input variable describing the technical condition, according to the division adopted in building periodic inspection reports. The categories were described with five fuzzy sets using linguistic descriptions: good – *G*; satisfactory – *S*; medium – *M*; poor – *P*; bad – *B*, for which the degree of deterioration expressed in %, is, respectively: 0÷15, 16÷30, 31÷50, 51÷70, 71÷100.

The other variable representing the functional status was divided to two ranges, which are described with three fuzzy sets with triangular belonging, representing the values: bad – *B*; medium – *M*; good – *G*, to which the following values [points] apply: 0÷2,5; 0÷5; 2,5÷5.

For a third input variable (energy status), the categorisation resulting from the proposed division to energy class (Pater, Magiera 2011) was adopted. Following the naming adopted, the variable was divided into six energy classes: low energy *LE*, energy-efficient *EE*, medium energy-efficient *MEE*, medium energy-consuming *MEC*, energy-consuming *EC*, high energy-consuming *HEC* buildings, for which energy status expressed in kWh/m^2·year is respectively: 20÷45, 45÷80, 81÷100, 101÷150, 151÷250, >251.

Relationships between the criteria grades are included in a set of rules R_k providing details of the relationships between the premises constituting the input variables x_j and conclusion representing the output variable y. The output variable (rule conclusion) in

Takagi-Sugeno-Kang (Takagi, Sugeno 1985) model adopted is expressed in a form of a functional dependency $y = f(x_1, x_2, x_3)$ between the inputs and output, and in the premise part, this rule is of fuzzy nature. For the model structure adopted, the set of rules can be presented as follows:

$$\text{if } \mu_{A_t^1}(x_1) \geq 0 \text{ and} \ldots \text{and } \mu_{A_v^3}(x_3) \text{ then} \mu_{WUB(n)}(y) \geq 0, \quad (5)$$

where: $\mu_{A_i^j}(x_j)$ – degree of belonging of the input variable x_1, x_2, x_3 to fuzzy sets t, u, v; $\mu_{WUB(n)}(y)$ – degree of belonging of the output variable y to *WUB*(*n*).

Linguistic variables appearing on the left side of fuzzy rules are the input variables and referred to as the premises (t, u, v) being the activated fuzzy sets. The rule is activated if the premises are met. The conclusion of every rule is provided on the right of the equation. In the model discussed, the output variable is expressed with singletons describing the building use value.

Rule base. In this paper an original algorithm for generating the base of system rules is presented (Bucoń, Sobotka 2012), which forms an integral part of the model developed. It is based on expert knowledge in assessing building use value, which requires the following activities:

Step 1. Expert research. It consists in assigning each of five values of the output variable of *WUB* expressed in points: very high *VH* (100), high *H* (70), medium *M* (50), average *A* (30), low *L* (10) of the input variables x_j.

Gathering information for every expert participating in the research involves filling in a form, in which the experts assign all the input variable values x_1 *(G, S, M, P, B)*, x_2 *(G, M, B)*, x_3 *(LE, EE, MEE, MEC, EC, HEC)* to one of five values of the output variable y describing *WUB (VH, H, M, A, L)*, e.g. if $x_1 = G$ and $x_2 = G$ and $x_3 = LE \div EE$ then $y = VH$.

Step 2. Calculating criteria significance. The fuzzy extension of the AHP method was adopted, described in detail in the work of Jaskowski *et al.* (2010). This method allows determination of criteria significance by aggregation of ranks of the *K* group of experts – each of them performs $m = n \cdot (n–1)/2$ comparisons with pairs of criteria on a given problem priority level (the relative exceeding, preference, significance levels are determined) with the scale 1/9, 1/7, 1/5, 1/3, 1, 3, 5, 7, 9 extended possibly by the intermediate ranks 1/8, 1/6, 1/4, 1/2, 2, 4, 6, 8. Aggregation of expert opinions is aimed at finding one common significance rank on the criteria adopted.

Step 3. Calculation is made of the degree of belonging $\mu_{A_i^j, WUB(n)}$ of the input variables x_j fuzzy sets to the output variable value *WUB(n)*, expressed in the *VH, H, M, A, L* singletons, based on the information received from experts (step 1):

$$\mu_{A_i^j, WUB(n)}(y) = \frac{O_{A_i^j, WUB(n)}}{N}, \quad n = 1, 2, 3, ..., 5, \quad (6)$$

where: $O_{A_i^j, WUB(n)}$ – the number of experts to confirm the rule: "if the grades of the j criterion belong to A_i^j term, then the input variable belongs to the *WUB*(*n*) singleton", N – number of all experts.

Step 4. Calculating the conclusion value for each generated rule R_k (the number of k rules equals the product of fuzzy sets of input variables x_j and equals 90). To this end, for every i^{th} fuzzy set of the j^{th} criterion, the membership function value and the number of fuzzy set s_i^j is selected, for which the membership function takes the maximum value, according to the formula:

$$\mu_{WUB(s_i^j)} = \max \{\mu_{A_i^j, WUB(L)}(y), ..., \mu_{A_i^j, WUB(VH)}(y)\}. \quad (7)$$

Further on, for every rule R_k generated, the following K_k conclusion is calculated:

$$K_k = \sum_{i=1}^{n} \sum_{j=1}^{m} w_j \cdot \mu_{WUB(S_i^j)} \cdot WUB(s_i^j), \quad (8)$$

where: s_i^j – premises of the j^{th} criterion respectively for $i = u, t, v$, whereas $u = 1, 2,.., 5$, $t = 1, 2, 6$, $v = 1, 2, 3$; w_j – significance of the input variable $j = 1, 2, 3$; $WUB(s_i^j)$ – *WUB* determined for the i^{th} set A_i^j of variable x_j.

Step 5. To every k^{th} rule R, a value of the output variable *WUB*(*n*) is assigned, based on the conclusion factor K_1 calculated for it. It is related, to a varied extent, to the degree of belonging to two different *WUB* values, which leads to a conflict and doubling the number of rules. As a solution to avoid such situation, the value *WUB*(*n*) is assumed, for which the level of belonging $\mu_{WUB(n)}$ is higher.

Concluding. At this stage, every rule, the premises of which are met, is activated. Generally, based on the premises (t, u, v), an appropriate output value *WUB*(*n*) is found, which is the conclusion from the fuzzy rules adopted.

Concluding with a rule base is performed in two steps:

Step 1. Calculating the level of belonging μA_i^j of the premises $i = t, u, v$ being the fuzzy sets of the three input variables x_j.

Step 2. Calculating the degree of meeting the entire condition (rule) as a membership function of the product of fuzzy sets being calculated with the *prod* operator:

$$\mu_{WUB(n)}^{R_k} = prod(\mu_{A_i^j}(x_1) \cdot \mu_{A_i^j}(x_2) \cdot \mu_{A_i^j}(x_3). \quad (9)$$

Sharpening. Calculation of the building use value is the result of activating the conclusion of individual system rules. The sharpening process requires an appropriate defuzzification method. For the Takagi-Sugeno-Kanga model, the "weighted sum" method was adopted (Takagi, Sugeno 1985). The value is determined as a weighted average of the values obtained from the rules activated:

$$y = \sum_{k=1}^{90} \left(\mu_{WUB(n)}^{R_k} \cdot WUB(n) \big/ \mu_{WUB(n)}^{R_k} \right), \quad (10)$$

where: y – sharpened building use value; $WUB(n)$ – output variable values expressed as singletons; $\mu^{R_k}_{WUB(n)}$ – degree of belonging (activation) of the output variable $WUB(n)$ for each activated rule R_k.

2.4. Repair classification of buildings and designing variant-based repairs

Building repair recommendations are based on the calculated WUB. If several buildings are assessed $B = \{B_1, B_2, ..., B_k\}$ it is possible to choose those of them for which the profitability of repairs aimed at increasing their use value will be analysed. This can be performed in two ways, i.e. by assuming such buildings for which the WUB calculated does not exceed a specific determined threshold value, or those for which the difference in the WUB assessment is greater than a specific value.

The repairs (scope, technology) for the designated buildings are determined based on the evaluation of technical condition of components, energy and functional status. The objective is to propose an appropriate repair technology (preferably in several variants), for which it is required to estimate the cost of them and calculating the value increase of the criteria K_j, adopted in the paper, using the assessment method proposed in Section 2.2. All repair works proposed at this stage should ensure operation of the existing building at the standard complying with the provisions of the Construction Law and other legislation and standards. For each building $B_i \in B$ designated to repair, based on the K_j criteria assessment, a set of possible repair activities N_{B_i} is determined. Every repair $N_{i_S} \in N_{B_i}$ can be performed in a number of possible ways, so called variant, each from which represents a different solution in terms of the materials used, technology and cost of implementation.

2.5. Optimising the selection of repair solutions

The problem of selecting the repair solution, in the model developed, involves:

- maximising the increase of building use value while limiting;
- funds available to carry out the repair.

As a result of optimisation, out of the buildings repairs proposed N_{B_i} the w solution is determined which is a set of repair variants $W_r^{i_s}$, ensuring the highest use value increase for the amount assumed K (which is the limiting factor). An increase of building use value $\Delta WUB(B_i)$ is the result of the value increase of three input criteria $\Delta O^{K_j}_{B_i}$:

$$\Delta WUB(B_i) = \sum_{j=1}^{3} (w_{K_j} \cdot \Delta O^{K_j}_{B_i}), \qquad (11)$$

where: w_{K_j} – significance of the j^{th} criterion.

The increase of the use value of all buildings ΔWUB is a sum of use value increase of individual buildings $\Delta WUB(B_i)$. Considering, in the Eqn (12), of use area of each of the buildings $P_u(B_i)$, it is possible to determine the best repair solution resulting in the maximum use value increase for all buildings analysed altogether:

$$\Delta WUB = \sum_{i=1}^{k} (\Delta WUB(B_i) \cdot P_u(B_i)) / P_u(B_i). \qquad (12)$$

The most satisfactory solution, selected from a set of acceptable solutions, should correspond to the maximum value of adaptation function, ensuring the highest increase of building(s) use value. This solution is a combination of different repair variants, the cost of which should not exceed the funds available for the repair. The problem can be simplified as follows:

$$\max z : z = \Delta WUB(w), \;\; K(w) \le B, \;\; w \in W, \qquad (13)$$

where: w – solution including a set of acceptable repair solution variants of all buildings; $\Delta WUB(w)$ – building use value increase for the w solution; $K(w)$ – cost of the w solution.

To solve the optimising task, an evolutionary algorithm was applied, aimed at seeking optimal or sub-optimal (acceptable) solutions. Individual stages of the algorithm comprise the following steps:

1. Creating the initial population – initial solutions;
2. Generating repair solutions;
3. Evaluation of the repair solutions.

Representation of individuals (acceptable solutions) was adopted in a form of genes containing information of the building for which the repair variant is proposed. The value of individual genes in a chromosome is established randomly. Chromosome coding is contained in the genotype described in Table 1.

Symbols: B_i – number of buildings forming a chromosome, $i = 1, 2, 3,\dots, k$; repairs N_{i_S} from the set of repairs for every building $N_{B_i} = \{N_{i_1}, N_{i_2}, ..., N_{i_m}\}$ for $s = 1, 2, 3,\dots, m$; $W_r^{i_s}$ – repair variant for i^{th} building, $r = 1, 2,..., v$.

Generating possible repair solutions being assessed by the adaptation functions takes place in the tournament selection, one-point crossover and uniform mutation processes.

Optimal solutions are sought with two adaptation functions F_1 and F_2, which aim to find the best repair solution in terms of use value increase for the solutions which a) do not exceed the F_1 budged assumed and b) exceed the budget F_2:

Table 1. Representation (coding) of repair solutions

B_i	1				2				3				k
N_{i_S}	3	5	..	12	2	7	..	15	1	5	..	8	..
$W_r^{i_s}$	1	2	..	3	3	1	..	1	2	2	..	1	..

a) $$F_1 = \frac{\Delta WUB}{1 + k \cdot (|K - B| / B)}, \quad \text{for } K \le B, \tag{14}$$

b) $$F_2 = \frac{\Delta WUB \cdot (B / K)}{1 + k \cdot (|K - B| / B)}, \quad \text{for } K > B, \tag{15}$$

where: K – cost of generated solution; B – assumed cost (budget) for which the repair solution is sought; ΔWUB – building use value increase; k – penalty factor.

The adaptation function F_2 allows searching a broader range of possible acceptable solutions. The cost K of the solution can slightly exceed the budget assumed B. These results in solutions of higher effectiveness (repair cost-effectiveness in relation to the cost) presented with the formula:

$$EF = \Delta WUB / K. \tag{16}$$

The possibility to adjust the k factor in the Eqns (14) and (15) allows certain flexibility in finding solutions which are acceptable to the decision-maker, considering the possibility to exceed or not fully use the budget assumed. The penalty for exceeding depends on the k factor assumed, which makes it possible to control the possibility of potential exceeding of the budget assumed.

3. Model application example

On the basis of the proposed computational algorithm shown in Figure 1 and described in Section 2, a computer repair decision support system (SWDR) was developed. It enables optimalisation calculations. Building assessment against the K^j adopted criteria are entered to the system as input data, and *WUB* is the output.

At first, buildings were evaluated against the K_j criteria adopted, based on which the *WUB* use value was determined. The calculation results are listed in Table 2.

As a result of the calculations, it was assumed that the buildings whose *WUB* assessment exceeds 50 points will not be accepted for repair. Thus, all the analysed buildings (Table 2) require activities increasing their use value. With the agreement of a repair manager repair activities were proposed for these buildings of which some can be performed according to various methods – Table 3 (presentation of repairs) and Table 4 (example).

The kind and the method of repair were accepted on the basis of virtual status. The calculation data was obtained from archival documentation, e.g. annual and 5-year evaluation, energy audits, technical documentation. Then, the cost of suggested repair was estimated and the value increase for the assessed building statuses against the formula (1, 2, 3) was determined. Depending on the repair chosen, the increase may refer to one, two or even three building statuses – see Table 5.

Table 2. *WUB* calculated based on input data for 5 buildings

Building	Building assessment against criterion			P_u [m^2]	*WUB* [pt]
	K_1 [%]	K_2 [pt]	K_3 [kWh/m^{2}year]		
1	47.66	2.40	172.70	4017.2	40.03
2	50.96	1.95	143.12	4484.0	35.70
3	51.03	2.36	173.96	2862.5	35.80
4	45.58	2.63	172.87	2700.4	43.16
5	43.16	2.63	151.79	2703.0	46.18

The results are a starting point towards optimalisation, i.e. the choice of repair scope bringing the largest *WUB* increase assuming having limited repair funds.

The application of developed model was presented in the example of cases. The optimalisation task in the first case is to choose the repair scope for all the buildings altogether, while in the second one for each building separately.

In the first case all the repairs proposed by the administrator were sought, for which the cost will be within or slightly exceed the budget of PLN 4,500,000 and the largest *WUB* increase will be obtained. As a result of

Table 3. Proposed repair and variants for 5 buildings

Building	Repair activities	Repair variants
1	13	20
2	16	24
3	16	23
4	13	21
5	12	20

Table. 4. Façade wall repair variants of one building

Repair variants	Repair variants description
1/1	Façade walls thermal insulation
1/2	Façade walls thermal insulation First floor wall cladding
1/3	Façade wall painting

Table 5. Sample of repair variants possible for building B_1 (shown 5 out of 13 repairs)

	Repair component	Repair variant	$\Delta O_{B_1}^{K_1}$ [%]	$\Delta O_{B_1}^{K_2}$ [pt]	$\Delta O_{B_1}^{K_3}$ [kWh/m^2]	K [PLN]
1	Façade	1	3.60	0.00	27.12	434,625
		2	3.82	0.00	27.12	449,640
		3	1.34	0,00	0.00	67,053
2	Roof	1	0.06	0.00	0.00	27,773
		2	2.20	0.00	0.00	101,660
3	Building entrances	1	0.54	0.43	0.00	31,953
		2	0.54	0.85	0.00	87,953
4	Balconies	1	0.49	0.00	0.00	38,115
		2	1.96	0.44	0.00	301,617
		3	1.96	0.00	0.00	193,116
5	Gutters and downspouts	1	0.72	0.00	0.00	16,290

performed calculations, five repair solutions were obtained. Each repair solution presented in Table 6 consists of repair variants for 5 buildings considered. The solution number 1 is the mostly preferred due to the best *WUB* increase relation to the costs (Table 6).

Repair solution number 1 exceeded the assumed repair budget by PLN 18,144, providing the building use value increase Δ*WUB* 21.06 points, with the found use effectiveness factor *EF* of 4.66. To compare, the best repair solution not exceeding the budget (3 in Table 5) allows Δ *WUB* 20.35 pt, with the *EF* factor 4.53.

The repair solution 1 consists of over a dozen repair variants, which are assigned to each of five buildings (Table 7).

The description of repair variants presented in Table 7 together with their costs performance is shown in Table 8. For the sake of brevity, only four repair variants are presented for three of five buildings considered.

In the second case out of the repair set assigned to each building (Table 5 – example for building B_1) the ones were sought for which the largest building use value increase of each building will be obtained.

The cost of repair in a building is dependent on its P_u usable area. Accordingly, the budget *B* of PLN 4,500,000 was divided pro rata between 5 buildings, thereupon it was obtained for B_1 = 1,078,147; B_2 = 1,203,428; B_3 = 768,246; B_4 = 724,741; B_5 = 725,438.

As a result of calculations performed, the most favourable repair solutions were generated for each out of 5 buildings (Table 9).

The total cost of repair solutions for five buildings (Table 9) exceeded the assumed budget by PLN 20,834, resulting in Δ*WUB* of 18.87 points. This value is a weighted average, where the weights are the buildings' total usable floor area (P_u). The fund use effectiveness factor *EF* is 4.17. Chosen repair variants included in the repair solutions presented in Table 9 are listed in Table 10.

Table 6. Five best repair solutions

Solution	*F*	Δ*WUB* [pt]	*EF*	*K* [PLN]
1	20.89	21.06	4.66	4,518,144
2	20.35	20.51	4.54	4,517,378
3	20.32	20.35	4.53	4,491,967
4	20.26	20.30	4.52	4,492,982
5	20.20	20.36	4.51	4,518,058

Table 7. Comparison of repair variants (solution 1)

Building	Repair/variant	*K* [PLN]
1	1/3, 3/1, 5/1, 6/1, 7/2, 12/1	349,305
2	1/2, 2/2, 3/1, 4/3, 5/1, 6/2, 7/1, 8/1, 9/2, 10/1, 11/1, 12/1, 14/1, 16/1	2,343,659
3	1/3, 3/1, 5/1, 6/1, 7/1, 9/1, 16/1	319,895
4	1/2, 2/2, 3/1, 5/1, 6/2, 8/1, 9/2, 10/2	879,638
5	1/2, 3/1, 5/1, 6/2, 7/1, 8/1, 9/2, 10/2, 11/1	625,647
Total cost		4,518,144

Table 8. Details of the repair variants generated (solution 1)

Building	Repair	Variant	Repair description	*K* [PLN]
1	1	3	Façade painting	67,053
	3	1	Vestibule renovation	31,953
	5	1	Guttering replacement	16,290
	6	1	Staircase door and window replacement	66,617
2	1	2	Façade walls thermal insulation	573,356
	2	2	Roofing material replacement	146,733
	3	1	Vestibule renovation	18,922
	4	3	Renovation of balconies	153,482
3	1	3	Façade wall painting	47,144
	3	1	Vestibule renovation	12,080
	5	1	Guttering replacement	10,836
	6	1	Staircase door and window replacement	27,692

The calculations performed clearly prove that the highest increase of building use value of 21.06 points for the amount PLN 4,518,144 was achievable for the first example, i.e. the repair variants included in the repair solution were chosen from a set of all repair activities proposed for the buildings being analysed.

The second example shows other possible use of the model. Pro rata division of budget applied for the buildings and the choice of the most favourable repair solutions for each of them allowed the lowest increase of use value (calculated for all the buildings) that equals 18.87 points for the amount PLN 4,520,834.

It has to be stressed, however, that the approach presented in the second example is more appropriate when the buildings analysed are built with different construction technologies, since applying the first approach would result in priority being given to certain material solutions adopted in individual construction technologies.

Conclusions

The article presents a decision-making model for choosing repair solutions for the most cost-effective scope of repair in terms of the assessment criteria adopted. This required the authors to solve five tasks which constituted the model. At each step, an approach or methods were proposed to solve the specific task.

Table 9. Repair solutions for 5 buildings

Building	*F*	Δ*WUB* [pt]	*EF*	*K* [PLN]
1	14.78	15.24	1.39	1,092,546
2	20.16	20.19	1.68	1,204,010
3	19.91	19.97	2.60	767,342
4	19.33	20.12	2.72	739,085
5	19.47	19.65	2.74	717,851
Total cost				4,520,834

Table 10. Repair variants for 5 buildings

Building	Repair/variant	*K* [PLN]
1	2/2, 3/2, 4/2, 5/1, 6/1, 7/2, 8/1, 12/1, 13/1	1,092,546
2	1/1, 2/2, 3/2, 5/1, 6/2, 7/1, 8/1, 9/2, 10/1	1,204,010
3	1/1, 3/2, 4/1, 5/1, 6/2, 7/1, 16/1	767,342
4	1/1, 2/2, 3/1, 5/1, 6/2, 7/1, 9/2	739,085
5	1/2, 3/2, 5/1, 6/2, 7/1, 8/1, 9/2, 10/2, 13/1	717,851

The model developed becomes a key part of the need for strategic planning in building management. It can also be used as a tool supporting the administrator in multiple criteria building appraisal and the choice of the optimal repair solution bearing in mind the financial constraints.

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