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Research paper

Decision support method for optimal modernization of residential buildings

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Abstract: Decision-making for the refurbishment of multi-family residential buildings is a complex and computationally difficult task. Therefore, the authors have developed a model that supports modernization planning in a long-term and comprehensive manner, i.e. from assessing the building to indicating the optimal scope of modernization. The comprehensive scope of the model includes the acquisition and provision of relevant knowledge to the model. The original methods proposed for its acquisition are derived from common expert knowledge based on linguistic terms. The methods adopted are not mandatory and may be replaced by others that provide more reliable knowledge. The fundamental aim of the proposed approach, however, is to select the optimal modernization option and allocate it over the planned modernization time horizon. An innovative optimisation approach based on decision matrices is used, allowing the selection of possible scenarios of repair options at each stage. These matrices are a set of constraints written in binary variables allowing the optimisation calculus to maintain a fixed sequence of repairs. In addition, the solutions used in the optimisation modules make it possible to take into account assumptions regarding the assumed assessment of the building's condition and financial constraints. The developed model provides a practical and versatile tool that can be used by managers at the maintenance stage of residential buildings.

Keywords: long-term modernization planning, building modernization, environmental sustainability criteria, multi-criteria evaluation, decision support

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1. Introduction

The need to renovate residential buildings is gaining increasing attention in European countries. This is due to a number of reasons, among which are technical, economic, environmental, social and cultural factors. Recently, the topic of the so-called "green deal" has been raised in particular, with the aim of an energy transformation aimed at reducing the adverse environmental impact of many sectors of the economy. There is a noticeable need for change in the construction industry due to the relatively high share of environmental pollution from this area of the economy. Dauda and Ajayi [1] indicate that the need to renovate buildings is one of the key steps towards decarbonising the existing housing stock. These measures must be primarily focused on sustainability by reducing energy consumption, environmental impact and improving public perception.

Jagarajan et al. [2] believe that one logical solution to reduce the environmental impact of existing buildings is green retrofitting. Green building can be important in solving both environmental, economic and social problems. Li and Froese [3] presented an example of an integrated approach to support green modernization based on the SWAHO (Sustainability Weighting Assessment for Homeowners) conceptual tool that enables the building owner to optimise the choice of modernization solutions. A key role in supporting transformation to achieve sustainability goals is also played by sustainable certification schemes such as LEED or BREEAM, whose adaptation to the actual needs and attributes of existing buildings makes it possible to assess their performance [4].

Effective and efficient ways to mitigate climate problems are to promote energy modernization in existing residential buildings. European housing policy also introduces the need to bring buildings up to new energy standards. This aims to reduce global energy consumption and greenhouse gas emissions and accelerate the modernization of existing buildings. However, these measures are severely limited because, as outlined in studies [5, 6], there are many barriers preventing the modernization of existing buildings. Among these, financial constraints, low occupant awareness, regulatory uncertainty, and lack of expertise in available technologies were identified.

Modernization is a major challenge, also because of the involvement of many stakeholders, the lack of clear decision-making procedures and the varying impacts of modernization alternatives. Mostafazadeh et al. [7] indicate that achieving sustainable building goals is a difficult task requiring the investigation of a large number of energy modernization measures and contrasting objectives. Asadi et al. [8], on the other hand, believe that when faced with a large number of choices for building thermal modernization, the main problem is to identify those that are more efficient and reliable in the long term. Hauashdh et al. [9] note that the greatest potential for reducing energy consumption and carbon emissions is achieved through sustainable and efficient building maintenance strategies and improved behaviour of building occupants.

The study by Xue et al. [10] concluded that building modernization is not only an effective approach to increasing energy efficiency, but also has great potential to improve public acceptance. Kamari et al. [11], on the basis of their review of research on building modernization, note that holistic issues related to achieving sustainability goals are not comprehensively addressed in building modernization. Jensen et al. recognise the need to create more environmentally sustainable buildings, which is not limited to reducing energy consumption and greenhouse gas emissions. They point to the necessity of renovating buildings in a broader perspective that also includes social objectives such as improving quality of life [12]. Also Moschetti et al [13], emphasise the need to renovate buildings from a holistic sustainability

perspective when improving the energy efficiency of buildings. This is confirmed by their research focused on the design of modernization projects to achieve economic, environmental and social benefits.

Ensuring satisfaction with the use of a building requires the inclusion of a social aspect in a sustainable building assessment. Based on Maslow's Hierarchy of Needs, four basic social and humanistic needs relating to residential and public buildings can be distinguished, i.e. comfort and health, protection and safety, functionality, and intelligent management [14]. Examples of studies indicating the need for modernization with a social aspect are increasing in number and address a variety of issues. Mora et al. [15], while maximising the effects of reducing carbon emissions and reducing energy consumption, also focused on the need to improve thermal comfort, natural lighting, indoor air quality and acoustics. On the other hand, Awada and Srour [16], using a genetic algorithm (GA)-based method, investigated the relationship between potential building modernization opportunities and the improvement of IEQ conditions for a comfortable indoor environment which is the primary goal of facility management. In a different approach to promote the sustainable modernization of housing stock, Serrano-Jiménez et al. [17] propose the Architectural and Psycho-Environmental Modernization Assessment Method (APRAM) to support decisions that include architectural requirements and residents' social perceptions.

Sustainable modernization of existing buildings rarely addresses the technical aspect involving structural safety. However, it is a particularly important issue in view of Europe's ageing housing stock. Buildings deteriorating over time, due to natural causes, neglect and unattended defects, require maintenance measures to stop their deterioration. This will maintain the building's performance, preserve its original functions and ensure the quality of life of the residents. Passoni et al. [18], after a critical review of existing sustainable modernization methods, proposed a new framework for a comprehensive Sustainable Building Modernization (SBR) method including, in a holistic perspective, also the aspect of technical building assessment. The need for technical building assessment was also highlighted by Faqih and Zayed [19], who proposed an innovative condition assessment model for existing concrete buildings. It is based on ANP and considers both the physical condition of the building and the environmental condition. In turn, Kwon et al. [20] observe that degradation both due to ageing and negligent maintenance of buildings leads to excessive repair costs, and negatively affects the building's design, usability and occupants' safety. Therefore, Farahani et al. [21] proposed a systematic approach to cost-optimal maintenance and modernization planning. This aims to provide building management support, in the form of a technical and economic assessment of possible energy modernization scenarios, under time and budget constraints. Also Choi and Kim [22], through a combination of artificial neural network analysis and cost-benefit analysis, have developed a framework for a technical-economic method for residential buildings that can be applied at the initial stages of modernization projects.

2. Methods to support modernization decisions

Decision-making is a very difficult and multi-stage computational process that very often requires a multi-stage approach using appropriate computational techniques and methods. The methods and models presented in the literature that have been developed to support the

maintenance of residential buildings represent very different concepts. Generally, maintenance support systems for residential buildings can be divided according to the objective they pursue, the scope of the maintenance assessment – which includes comprehensive or partial maintenance – and the mathematical tools used.

Management of building maintenance in relation to performance and cost are very common. Innovative approaches promote a long-term view of building maintenance leading to the formulation of strategies based on proactive measures contributing to continuous improvement. Nägeli at al [6] presented a method for long-term planning of modernization investments, of existing residential buildings, for cost-optimised planning of maintenance and building modernization. Kwon et al. [20] proposed a method to support building managers in long-term building maintenance decision-making using case-based reasoning (CBR) using genetic algorithm (GA), multiple linear regression (MLR) and fuzzy AHP method. Bucoń and Czarnigowska [23, 24] focused on sequential linear programming models to support the condominium manager in defining a sequence of maintenance and improvement activities, the execution of which within a specified time horizon allows predefined levels of building performance to be achieved. A unique feature of the proposed models is the approach to constraints on sequential dependencies between activities and their selection within a defined time horizon. Another example of multi-objective optimisation in the planning of building modernization activities is presented in Richarz et al. [25]. For the study, mixed-integer linear programming (MILP) was used, considering constraints and boundary conditions that are updated for each year of the schedule horizon. The methodology developed enables planning of a programme of an optimal combination of modernization measures at the appropriate optimum point in a building's life cycle. For the evaluation of modernization strategies in terms of the benefit of the money invested, Junghans [26] proposed the sequential building optimisation method, which allows the financial long-term benefits of modernization investments to be assessed and the recommended strategies to be ranked on the basis of life cycle cost (LCC). Cho and Kim [27] proved that with the dynamic modernization planning method, in which the traditional logical dependencies between construction tasks are changed, the duration of modernization projects of office buildings can be significantly reduced and higher cost efficiency can be achieved. AlOtaibi et al. [28] used a model to optimise the modernization schedules of rented residential buildings. By considering the date of availability of the buildings, they ensured optimal starting dates of modernization and repair sequences for minimising the total cost of renovating residential buildings.

Cho et al. [29] determined the effectiveness of maintenance strategies for residential buildings in the long term, for which based on a probabilistic methodology, they analysed the risk of disruptions due to the unpredictability of the repair time of individual residential building components. Shiue et al. [30] considering the key factors affecting building modernizations, i.e. building type, type of repairs and resource availability constraints proposed a model based on a genetic algorithm and simulation method for the long-term maintenance of university campus buildings. Farahani et al. [31] proposed a systematic approach based on a condition-deterioration model that allows the cost-effectiveness of different maintenance/repair schedules to be compared in a selected scenario to determine the optimal maintenance interval for building elements. Matos et al. [32] for supporting building condition assessment (BCA)

and its management, on the other hand, applied building information modelling (BIM) and prioritised maintenance activities using key performance indicators. Petkov et al. [33], in order to obtain a long-term modernization strategy for existing buildings, developed a model that is based on a innovative approach that provides the technical and economic data necessary for the MANGOret optimisation model MANGOret (Multi-stAge eNerGy Optimisation – retrofitting), which aims to perform a multi-stage and multi-objective optimisation (cost vs. CO2) and DCF (Discounted Cash Flow) valuation based on rental income. Al-Smadi et al [34], on the other hand, focused on designing and developing a maintenance optimisation model for minimising the total maintenance cost but also maximising the building condition. Whereas Son and Kim [35] used an evolutionary EO multi-objective optimisation algorithm (NSGA-II, MOPSO, MOEA/D and NSGA-III) to solve the multi-objective optimisation problem of minimising energy consumption, CO2 emissions and modernization costs and maximising thermal comfort.

Decision support systems based on MCDM methods are the ones most commonly used. A complete decision support method based on multiple decision criteria to support decision-making in modernization was presented by Amorocho and Hartmann [36]. The proposed method allows different stakeholders to compare modernization proposals and then evaluate and rank them using the Topsis method. Serrano-Jiménez et al. [37] presented a decision support method for housing managers to determine the most appropriate modernization strategy, which combines a multi-criteria evaluation of ten modernization factors with an economic feasibility analysis. In contrast, Si et al. [38] used a multi-criteria decision-making method (MCDM) to select green technologies for renovating existing residential buildings. The proposed approach for evaluating and ranking modernization measures is based on environmental and economic criteria. Besiktepe et al [39] developed and ranked a set of criteria needed to construct a multi-criteria decision model for use in residential building management and maintenance processes. In response to the need for more holistic modernization scenarios that meet a broader set of sustainability objectives and criteria, Kamari et al. [40] presented a methodology for the development of the PARADIS decision support system, which supports deliberate decision-making to develop an optimal modernization scenario.

Understanding and analysing the methods and models for assessing the condition of a building and those used in DSS systems for managing building properties formed the basis for the development of an original decision-support method that considers both the balanced multi-criteria assessment of the building, the technological dependencies of the repairs, the constraints on financial resources and the phasing of the repairs.

3. Proposed method for modernization support

The method consists of six calculation steps. In the first one, criteria are selected, their validity is determined and a multi-criteria assessment of the building condition is carried out. In the second step, on the basis of the assessment of the building condition, various repair proposals are developed with the determination of increment values for the assessments of each criterion. In the next step, the technological dependencies occurring between the proposed

repairs are determined, possible repair options consisting of one or more repairs are identified – in an established sequential order. In the fourth step, the selection of the cost-optimal repair variant is carried out, the execution of which will make it possible to achieve the assumed values of the criteria. In the next stage, calculations are carried out to determine the budget needed to perform the repairs at each stage of the planned modernization. In the final sixth stage, taking into account financial constraints, optimisation is carried out to allocate repairs to the selected modernization variant over the time horizon considered.

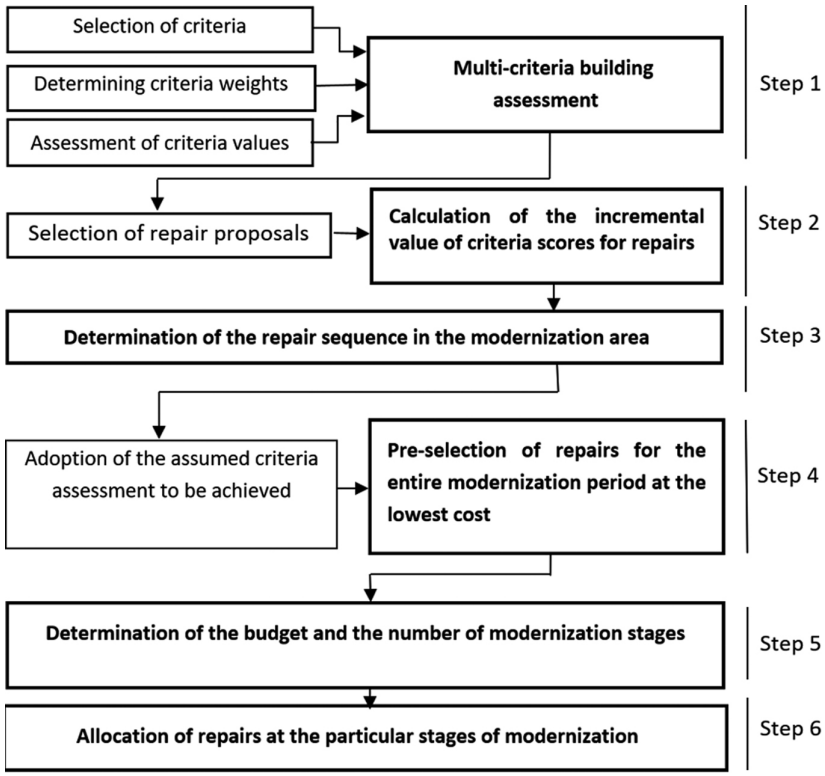

Fig. 1. Modernization decision support method

3.1. Building condition assessment

Carrying out a multi-criteria assessment of the building's condition takes place in four stages:

- Selection of criteria to assess the condition of a building. A numer of j-th criteria are adopted that can refer to sustainable building factors, i.e. environmental, economic, social, technical and cultural assessment
- Calculation of the weights of the adopted criteria (w_j). Estimating their value can be carried out e.g. using the AHP (Analytic Hierarchy Process) method

– Assessment of j-th building criteria. It is carried out using a point rating scale of (1–5) pts, where very good (BD) is assigned a value of 5 pts, good (D) 4 pts, average (S) 3 pts, poor (Z) 2 pts, very poor (BZ) 1 pt
– Multi-criteria assessment of the building's condition (o_j). It is a weighted sum of the scores of j-th criteria and is calculated using the equation (3.1)

$$o = \sum o_j \cdot w_j, \quad j = 1, 2, \ldots, m. \tag{3.1}$$

3.2. Calculation for repairing the incremental value of criteria scores

The proposed scope of modernization comprises a set of q-th repairs in their r-th variants, and results from the assessment of the building's condition. Each of the repair variants achieves an increment for one or more criteria and provides varying degrees of improvement. In order to determine the value of the increment, it is necessary to calculate the contribution (weight) of q-th repair to the achievement of the assumed final value of the criteria (Z_j). They are calculated using equation (3.2), where to assess the importance of the repair (u_j^q) linguistic terms are used, i.e.: very large BD (5pts), large D (4pts), medium S (3pts), small M (2pts), very small BM (1pt), insignificant BZ (0pts).

$$w_j^q = \frac{u_j^q}{\sum\limits_{q \in Q} u_j^q}, \quad \forall j = 1, 2, \ldots, m, \quad \forall q = 1, 2, \ldots, s. \tag{3.2}$$

In the next step, the degree of realisation of each repair variant ($t_j^{q,r}$) is determined. For this purpose, each r-th variant of q-th repair is assessed using linguistic ratings, where ($o_j^{q,r}$) denotes the degree to which it has been realised, while ($o_{j,\max}^{q,r}$) indicates the maximum possible rating. For the assessment, linguistic terms are used, i.e.: very high BW (5pts), high W (4pts), average P (3pts), low N (2pts), very low BN (1pt), none B (0pts). Repair variants are assessed for each of the adopted criteria, according to equation (3.3).

$$t_j^{q,r} = \frac{o_j^{q,r}}{o_{j,\max}^{q,r}}, \quad \forall j = 1, 2, \ldots, m, \quad \forall q = 1, 2, \ldots, s, \quad \forall r = 1, 2. \tag{3.3}$$

The calculation of the incremental value of repair variants for each criterion is carried out according to equation (3.4). The assumed final value Z_j is determined by the possibility of the proposed repairs – denotes the maximum possible score to be obtained for the criterion.

$$p_j^{q,r} = (Z_j - o_j) \cdot t_j^{q,r} \cdot w_j^q, \quad \forall j = 1, 2, \ldots, m, \quad \forall q = 1, 2, \ldots, s, \quad \forall r = 1, 2. \tag{3.4}$$

3.3. Identification of modernization variants including repair sequence

Individual repairs can be assigned to the locations where they will be carried out, e.g. within a stairway, roof, basement or facade, etc. Repairs assigned to a particular site must be carried out in accordance with the agreed order. The ordered repair/modernization activities

assigned to a site are called sequences of activities. A sequence is modelled by a network of actions on nodes, thus by a directed acyclic graph $S = \langle R, G \rangle$, where R is the set of nodes representing repair variants, and G represents the graph's arcs and their sequential relations. Therefore, variants of the activity sequence v_h were defined, where h is the identifier of the variant. The nodes of a directed graph are the activities and all their predecessors connected by sequential relations. The total number of variants results from the number of possible combinations of their execution – Figure 2.

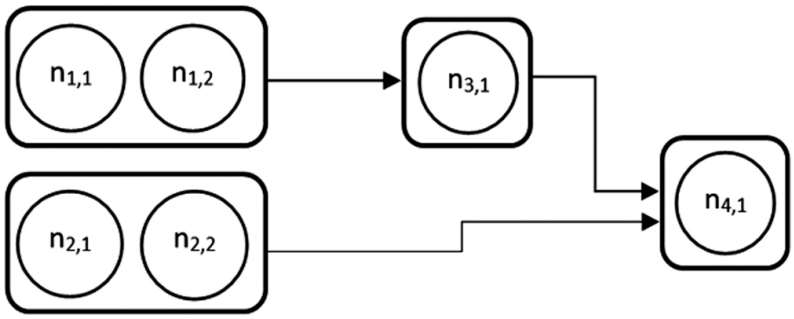

Fig. 2. Example graph with a defined sequence of repair variants

The generation of repair variants can only take place within the constraints of the decision matrix D, which is written in binary form. Its purpose is to enable the selection of possible repair variants at each stage of the modernization process, while respecting the repair sequence established for it – excluding the possibility of selecting two alternative variants for the same repair. In this way, each h-th repair variant will contain a certain number of q-th repairs in r-th variants. The mathematical notation of the above constraints is written as follows:

$$D = \left[d_h^{q,r} \right]_{Q,RxH}, \quad \forall h = 1, 2, 3, \ldots, l, \tag{3.5}$$

$$d_h^{q,r} = \begin{cases} 1, & q\text{-th repair in its } r\text{-th variant}, \\ 0, & \text{otherwise}. \end{cases} \tag{3.6}$$

In Table 1, for the graph shown above (Fig. 2), matrix D was developed from which 18 modernization variants could be generated during the optimisation phase.

The generated hypothetical modernization variants may contain one or more repairs for which an order of execution is determined. None of the possible modernization variants shown in the graph (Fig. 2) contains two variants of the same repair. Each modernization variant has a specific order of execution of the repairs included in it, e.g. the execution of a repair $q = 3$ in a variant $r = 1$ entails the necessity of carrying out two preceding repairs ($q = 1$ and $q = 2$), with each repair being possible in any variant $r = 1$ or $r = 2$.

Table 1. Matrix D defining the possible content of modernization variants

Repair variant (q/r)	Modernization variant (h)																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1/1	1	0	0	0	1	0	1	1	0	0	1	1	0	0	1	1	0	0
1/2	0	1	0	0	0	1	0	0	1	1	0	0	1	1	0	0	1	1
2/1	0	0	1	0	0	0	1	0	1	0	1	0	1	0	1	0	1	0
2/2	0	0	0	1	0	0	0	1	0	1	0	1	0	1	0	1	0	1
3/1	0	0	0	0	1	1	0	0	0	0	1	1	1	1	1	1	1	1
4/1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1

3.4. Optimization/allocation of modernization variant and determination of budget

The optimisation calculations are performed in two stages using binary linear programming. Firstly, using the objective function (3.7), optimisation is carried out to select the initial modernization variant (v_h), whose total cost C expressed in equation (3.8) is minimised. Value increments for j-th criteria (3.9) together with the original value of the building condition assessment (3.10) must ensure that the values assumed for them are achieved (3.11). The total increment of the multi-criteria assessment value is expressed by equation (3.12). The selection of the repairs that make up the modernization variant is done using a binary variable (3.13 and 3.14). The mathematical notation of the task is shown below.

$$\text{Stage 1.} \quad \min z : z = C, \tag{3.7}$$

$$C = \sum_{q \in Q} \sum_{r=R} \sum_{h \in H} c_h^{q,r} \cdot d_h^{q,r} \cdot x_h, \quad q = 1, 2, \ldots, s, \quad r = 1, 2, \quad h = 1, 2, .., l, \tag{3.8}$$

$$P_j = \sum_{q \in Q} \sum_{r=R} \sum_{h \in H} p_j^{q,r} \cdot d_h^{q,r} \cdot x_h, \quad \forall j = 1, 2, \ldots, m, \tag{3.9}$$

$$O_j = o_j + P_j, \quad \forall j = 1, 2, \ldots, m, \tag{3.10}$$

$$O_j \geq Z_j, \quad \forall j = 1, 2, \ldots, m, \tag{3.11}$$

$$P_h = \sum_{j=1}^{m} P_j, \quad j = 1, 2, \ldots, m, \tag{3.12}$$

$$x_h \in \{0, 1\} \quad h = 1, 2, \ldots, l, \tag{3.13}$$

$$x_h = \begin{cases} 1, & \text{when } h\text{-th renovation variant was chosen,} \\ 0, & \text{otherwise,} \end{cases} \tag{3.14}$$

where: $c_h^{q,r}$ – cost of h-th variant consisting of r-th variants of q-th repairs, P_j – the increment of the assessment value of j-th criterion, Z_j – the assumed assessment value of -th criterion.

The number of modernization stages adopted depends on the ability to raise the funds needed for the modernization. The suggested approach assumes that the funds needed for the

modernization come from the modernization budget (B), while the missing part is obtained from the established special purpose fund. Its amount is derived from the monthly contribution calculated from equation (3.15). The amount of the budget to be used for each y-th stage of modernization is calculated on the basis of equation (3.16). It can be increased if it is not fully spent in the previous stage (3.17).

$$s = \frac{C - B}{12 \cdot y \cdot a}, \tag{3.15}$$

$$B_y = (s \cdot a \cdot 12) + F_y, \quad \forall y = 1, 2, \ldots, Y, \tag{3.16}$$

$$F_y = B_{y-1} - C_{y-1}, \quad \forall y = 1, 2, \ldots, Y, \quad \text{where: } F_1 = B. \tag{3.17}$$

During the last optimisation stage, the allocation of repairs of the selected modernization variant within the planned time horizon (expressed in y-th stages). The objective function (3.18) is intended to indicate the optimum repair variants at a given modernization stage (from the selected initial modernization variant). The selected repair variants are expected to provide the maximum increase in the value of the building assessment at each stage of modernization, taking into account financial constraints (3.19). A simplified mathematical notation of the above task is formulated as follows:

$$\text{Stage 2.} \quad \max z : z = P_{h,y}, \quad \forall y = 1, 2, \ldots, Y, \tag{3.18}$$

$$C_y \leq B_y, \quad \forall y = 1, 2, \ldots, Y. \tag{3.19}$$

As a result of the optimisation activities, selected at y-th stage of the time horizon, the r-th variants of q-th repairs ($n_{q,r,y}$) are removed from h-th modernization variant and allocation optimisation of the reduced variant content is carried out at the next modernization stage. This is written as follows.

$$v_{h,y} = \left(v_{h,(y-1)} - \sum_{q,r \in h} n_{q,r,y} \right), \quad \forall y = 1, 2, \ldots, Y. \tag{3.20}$$

4. Calculation example

The application of the method is shown on the example of a multi-family residential building with a floor area of $a = 2000$ m^2, constructed intraditional technology. The scope of the building assessment was limited to the external elements of the building, i.e. window and door frames, external wall partitions, balconies, basement walls and entrances to the building. Four criteria were used to assess the building with reference to the economic, technical and social aspects. Determination of the impact of the adopted criteria was conducted using the AHP method. The results of the building criteria assessments are summarised in Table 2.

Based on the assessment of the building's condition, six repairs were proposed. For four of these, two execution variants each have been adopted, and these are alternatives to each other. Carrying out each of the proposed repairs contributes to improving the value in relation to one or more criteria. The repairs in the example have been selected to achieve the specified tasks,

which are the modernization of the facade and the entrances to the building. Based on the proposed set o repairs, calculations were applied to determine the importance of each repair in achieving their assumed value. For this purpose, the linguistic rating scale presented in section 3.2. was used. The results of the calculations are summarised in Table 3.

Table 2. Assessment of the building according to the accepted criteria

Aspect	Economic	Technical	Social	
Criteria j	Maintenance costs	Technical efficiency	Comfort and safety	External aesthetics
Rating /weight o_j/w_j	Z/0,46	S/0,2	BZ/0,22	Z/0,12

Table 3. Calculated repair weights for the accepted criteria

Repair q	Name of repair	Impact of the repair on the assumed value of the criterion u_j^q/w_j^q			
		$j = 1$	$j = 2$	$j = 3$	$j = 4$
1	Replacement of window frames	S/0,250	BM/0,071	D/0,235	S/0,176
2	Repair/insulation of balconies	M/0,167	M/0,143	BM/0,059	M/0,118
3	Insulation of external walls	BD/0,417	BD/0,357	BD/0,294	BD/0,294
4	Balcony enclosing	BM/0,083	B/0,000	M/0,118	M/0,118
5	Repair/insulation of basement walls	BM/0,083	BD/0,357	M/0,118	S/0,176
6	Modernization of the building entrance	B/0,00	BM/0,071	S/0,176	M/0,0118

The proposed repairs can be delivered in a variety of alternative repair variants. Hence, to varying degrees, they may provide the feasibility of the assumed final criteria assessment. This is due to the fact that each repair variant can provide the possibility of realising the repair to a different degree. In order to calculate this degree for each criterion, the linguistic rating scale proposed in section 3.2 was used. On the basis of the assessments carried out, which determine the potential for the repairs to be completed, an assumed final assessment was adopted for each criterion. A summary of the assessments of the degree of realisation of repairs and the obtained incremental values of the repair options are presented in Table 4.

Figure 3 illustrates a graph of the building modernization, in which the sequences of execution of the individual repairs are defined. On its basis, it is possible to generate 68 modernization variants, each of which consists of unique repair sequences.

Table 4. Assessment of the extent to which repair variants have been realised and their increase in value for the criteria

No. of repair/ variant		Name of repair	$o_j^{q,r}(p_j^{q,r})$				$c^{q,r}$ [PLN]
q	r		$j = 1$	$j = 2$	$j = 3$	$j = 4$	
1	1	Replacement of window frames with simple installation	P (0,450)	BW (0,143)	W (0,753)	W (0,424)	150,000
	2	Replacement of window frames using warm installation system	BW (0,750)	BW (0,143)	BW (0,941)	BW (0,529)	210,000
2	1	Installation of waterproofing with ceramic cladding	B (0,000)	BW (0,286)	B (0,000)	P (0,212)	55,000
	2	Installation of waterproofing and thermal insulation with resin cladding	BW (0,500)	BW (0,286)	BW (0,235)	BW (0,353)	85,000
3	1	Insulation of walls with polystyrene with mineral plaster	W (1,000)	BW (0,714)	W (0,941)	P (0,529)	255,000
	2	Insulation of walls with mineral wool with silicate plaster	BW (1,250)	BW (0,714)	BW (1,176)	BW (0,882)	290,000
4	1	Installation of balcony enclosing	BW (0,250)	B (0,00)	BW (0,471)	BW (0,353)	80,000
5	1	Installation of waterproofing and mosaic plaster	B (0,00)	BW (0,714)	B (0,000)	W (0,424)	45,000
	2	Installation of waterproofing and thermal insulation with mosaic plaster	BW (0,250)	BW (0,714)	BW (0,471)	BW (0,529)	60,000
6	1	Modernization of building entrances	B (0,00)	BW (0,143)	BW (0,706)	BW (0,353)	45,000
Z_j			BD	BD	BD	BD	$\sum$ 1275

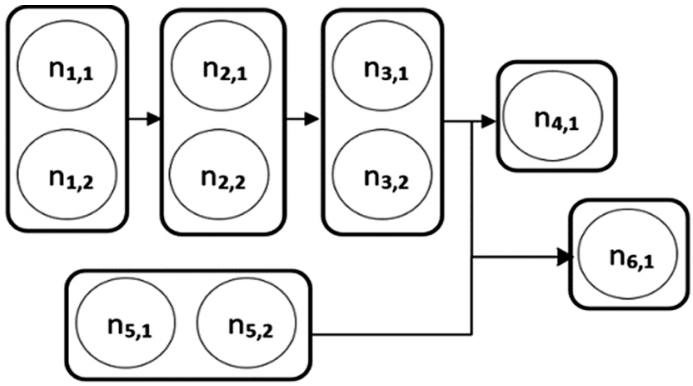

Fig. 3. Modernization graph with established order of sequence

Table 5, for the above graph, presents a set of constraints that are used to develop a decision matrix representing the acceptability of solutions (modernization variants). The constraints are presented only for the first 20 – modernization variants.

Table 5. Set of constraints for the first 20 modernization variants

Modernization variants (h)	Repair variant (q/r)										Condition
	1/1	1/2	2/1	2/2	3/1	3/2	4/1	5/1	5/2	6/1	
1–20	1	1	0	0	0	0	0	0	0	0	≤ 1
	0	0	1	1	0	0	0	0	0	0	≤ 1
	0	0	0	0	0	0	0	1	1	0	≤ 1
	1	1	0	0	0	0	0	0	0	0	≥ 1
	0	0	0	0	1	1	1	0	0	1	≤ 0

The set of constraints presented in Table 5 was used to develop the decision matrix D. Its variables define the possible content of each modernization variant, where ($d_h^{q,r} = 1$), denotes the affiliation of q-th repair in r-th variant for h-th modernization variant. Table 6 shows the contents of the matrix for the first 20 out of 68 possible modernization variants.

In Table 7, the possible modernization variants to be generated are shown with a specific order of repair variants – not including two alternative variants for the same repair. At the first optimisation stage, only one repair variant is selected. Table 7 shows the possible sequences of repair variants comprising the first twenty repair variants.

As a result of the optimisation measures carried out, three variants were generated which would achieve the assumed criteria values (Z_j) at the lowest cost. Variant 1 allows (for each criterion) a final score of very good (BD), 2 a score of good (D) and 3 a score of medium (S). Table 8 shows the selected modernization variants and the total increment values obtained for the building, as well as their implementation costs.

Table 6. Matrix D defining the possible contents of h-th modernization variants (1–20)

Repair variant (q/r)	Modernization variant (h)																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1/1	1	0	0	0	1	1	0	0	1	1	0	0	1	1	1	1	0	0	0	0
1/2	0	1	0	0	0	0	1	1	0	0	1	1	0	0	0	0	1	1	1	1
2/1	0	0	0	0	1	0	1	0	0	0	0	0	1	0	1	0	1	0	1	0
2/2	0	0	0	0	0	1	0	1	0	0	0	0	0	1	0	1	0	1	0	1
5/1	0	0	1	0	0	0	0	0	1	0	1	0	1	1	0	0	1	1	0	0
5/2	0	0	0	1	0	0	0	0	0	1	0	1	0	0	1	1	0	0	1	1

Table 7. Possible h-th of modernization variants

h	Modernization variants v_h				
1–20	$v_1 = n_{1,1}$	$v_5 = v_1 + n_{2,1}$	$v_9 = v_1 + n_{5,1}$	$v_{13} = v_5 + n_{5,1}$	$v_{17} = v_7 + n_{5,1}$
	$v_2 = n_{1,2}$	$v_6 = v_1 + n_{2,2}$	$v_{10} = v_1 + n_{5,2}$	$v_{14} = v_6 + n_{5,1}$	$v_{18} = v_8 + n_{5,1}$
	$v_3 = n_{5,1}$	$v_7 = v_2 + n_{2,1}$	$v_{11} = v_2 + n_{5,1}$	$v_{15} = v_5 + n_{5,2}$	$v_{19} = v_7 + n_{5,2}$
	$v_4 = n_{5,2}$	$v_8 = v_2 + n_{2,2}$	$v_{12} = v_2 + n_{5,2}$	$v_{16} = v_6 + n_{5,2}$	$v_{20} = v_8 + n_{5,2}$

Table 8. Selected modernization variants – to achieve the assumed criteria values

Assumed criteria values Z_j/P_j				Repair variants (q/r) and value increments obtained $p_j^{q,r}$ [pts]	Increment for the building P [pts]	Cost of renovation variant C [PLN]
$j = 1$	$j = 2$	$j = 3$	$j = 4$			
BD/1,38	BD/0,4	BD/0,88	BD/0,36	1/2 (0,644); 2/2 (0,381); 3/2 (1,083); 4/1 (0,261); 5/2 (0,425); 6/1 (0,226)	3,02	770,000
D/0,92	**D/0,2**	**D/0,66**	**D/0,24**	**1/1 (0,452); 2/2 (0,381); 3/1 (0,873); 5/2 (0,425); 6/1 (0,226)**	**2,36**	**595,000**
S/0,46	S/0,0	S/0,44	S/0,12	1/1(0,452); 2/1 (0,083); 3/1 (0,873); 5/2 (0,425)	1,83	520,000

Taking into account the cost of the presented modernization variants, the variant to be executed was adopted, the completion of which would ensure the achievement of the assumed final grade of good (D)-for all criteria. The modernization will be financed from the own funds, which partly come from the disposable budget in the amount of PLN 200,000, and the missing part comes from the established special purpose (modernization) fund. The amount of PLN 395,000 will be raised from a monthly contribution (s) of PLN 5.5 per square metre over a period of three years, which makes it possible to obtain the amount of PLN 131,670 in a year ($S = \sum s \cdot 12 \cdot a$). Due to the financing system adopted in this way, the modernization

was also planned in three stages – equal to the 3-year period. The budget for each y-th stage of modernization is the sum of the funds obtained from contributions and the funds not used in the previous stage – at the first stage, these are funds from the disposed budget. As a result of the optimisation activities completed, the allocation, over the planned time horizon, of the repair variants constituting the selected modernization variant was made (Fig. 4).

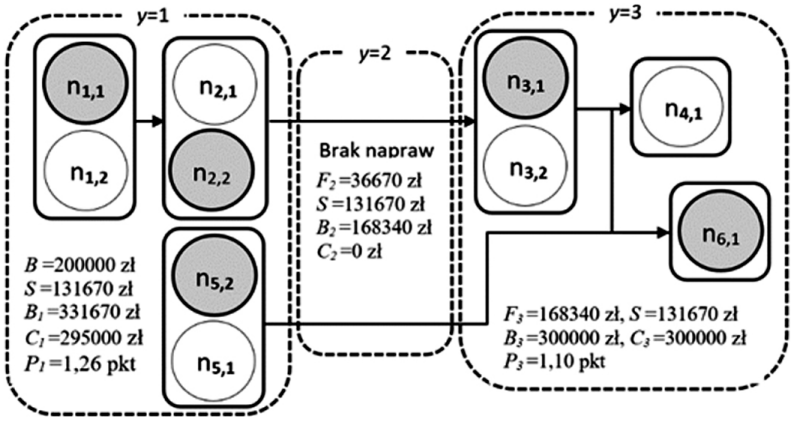

Fig. 4. Stages of implementation of the selected modernization variant for the dopted time horizon

5. Summary

The method presented in this paper to support the manager in the long-term optimisation of the choice of modernization measures provides a comprehensive tool for modernization planning, i.e. starting from the assessment of the building to the identification of a modernization variant that considers the financial possibilities of the residents. The solution of its various stages required the application of various techniques and computational tools, including the AHP method, the use of linguistic assessments to evaluate the condition of the building and the incremental value of the assessments resulting from the proposed repairs. The essential and main part of the proposed approach focuses on the implementation of two optimisation activities, resulting in an initial selection of a repair variant and then, after considering financial potential, an allocation within an assumed time horizon. At the optimisation stage, mathematical tools based on binary linear programming are used. The computational capabilities of the method allow a number of important factors to be taken into account in the optimisation calculus, including the assumed degree of fulfilment of the requirements for the buildings (the values of the criteria assessments), the time taken to carry out the repairs, the optimum allocation of repairs, financial constraints and the maintenance of the sequence of repairs, which results from the technological dependencies that occur between repairs. Consideration of all the attributes/characteristics of the approach developed constituted a complex computational problem, for which the Matlab computational platform was used. The application of the method is shown on the example of a multi-family residential building. Its applicability can make it

a practical and versatile tool for planning long-term modernization strategies for multi-family residential buildings. However, when using it, it should be noted that it is deterministic in nature and does not consider, within the planned modernization time horizon, both changes due to the ageing of the building as well as changes in the pre-estimated repair costs.

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Metoda wspomagania decyzji dla optymalnej modernizacji budynków mieszkalnych

Słowa kluczowe: długoterminowe planowanie, modernizacja budynku, kryteria zrównoważonego rozwoju, ocena wielokryterialna, wspomaganie decyzji

Streszczenie:

W Europie coraz większą uwagę przykłada się do modernizacji budynków mieszkalnych, co ma na celu zmniejszenia niekorzystnego oddziaływania budynków mieszkalnych generujących duże ilości zanieczyszczeń środowiskowych. Modernizacja budynków stanowi kluczowy krok w kierunku dekarbonizacji istniejących zasobów mieszkaniowych. Stąd też działania te muszą być ukierunkowane przede wszystkim na redukcję zużycia energii, wpływu na środowisko, ale również poprawę odbioru społecznego [10]. Osiągnięcie celów zrównoważonego budownictwa jest trudnym zadaniem wymagającym zbadania dużej liczby środków modernizacji i kontrastujących celów. W obliczu wielu możliwości wyboru sposobu modernizacji budynków głównym problemem jest identyfikacja tych, które są bardziej efektywne i niezawodne w długim okresie czasu [8] i które w największym stopniu przyczynią się do rozwiązywania problemów środowiskowych, ekonomicznych i społecznych [2]. Promowanie modernizacji energetycznej w istniejących budynkach mieszkalnych jest jednym z najistotniejszych celów polityki zrównoważonego rozwoju. Konieczność dostosowywania budynków do nowych standardów energetycznych ma na celu ograniczenie globalnego zużycia energii i emisji gazów cieplarnianych i przyspieszenie modernizacji istniejących budynków. Zauważalne jest jednak, że przy renowacji budynków nie są uwzględniane w sposób kompleksowy zagadnienia holistyczne związane z realizacją celów zrównoważonego rozwoju [11]. Potrzeba zatem tworzenia bardziej zrównoważonych ekologicznie budynków, ze wskazaniem na konieczność modernizacji budynków w szerszym ujęciu, które uwzględnia również cele społeczne, takie jak poprawa jakości życia [15]. Wiąże się to z uwzględnieniem w renowacji potrzeb związanych z: komfortem i zdrowiem, ochroną i bezpieczeństwem, funkcjonalnością i inteligentnym zarządzaniem co przekłada

się na komfortowe warunki środowiska wewnętrznego – termicznego, oświetlenia naturalnego, jakości powietrza wewnętrznego oraz akustyki [16]. Renowacja budynku powinna również uwzględniać aspekt techniczny odnoszący się do bezpieczeństwa konstrukcji, co jest szczególnie ważne z uwagi na starzejący się zasób budynków mieszkalnych. Z tego tez powodu zwraca się uwagę na utrzymanie odpowiednich parametrów budynku, zachowanie jego pierwotnych funkcji oraz zapewnienie odpowiedniej jakości życia mieszkańców w kontekście zrównoważonej modernizacji budynków [18]. Biorąc pod uwagę powyższe wymagania autorzy opracowali metodę, która składa się z sześciu etapów obliczeniowych. W pierwszym dobierane są kryteria, określana jest ich ważność, a następnie dokonywana jest wielokryterialna ocena stanu budynku. W drugim etapie, na podstawie przeprowadzonej oceny stanu budynku, opracowywane są różne propozycje napraw wraz z określaniem wartości przyrostu dla ocen każdego z kryteriów. W kolejnym kroku określane są zależności technologiczne występujące pomiędzy proponowanymi naprawami i na tej podstawie określane są możliwe warianty remontu, składające się z jednej lub większej ilości napraw – w ustalonym porządku kolejnościowym. W czwartym etapie przeprowadzany jest wybór optymalnego pod względem kosztów wariantu modernizacji, którego wykonanie umożliwi uzyskanie zakładanych wartości kryteriów. W kolejnym etapie przeprowadzane są obliczenia związane z określeniem budżetu potrzebnego do przeprowadzenia napraw na poszczególnych etapach planowanej modernizacji. W ostatnim szóstym etapie, biorąc pod uwagę ograniczenia finansowe, przeprowadzana jest optymalizacja mająca na celu alokację napraw w rozpatrywanym horyzoncie czasowym. Proponowana metoda w sposób długoterminowy i kompleksowy wspomaga planowanie remontów, tj. począwszy od oceny budynku, a skończywszy na wskazaniu optymalnego zakresu modernizacji. Kompleksowy zakres proponowanej metody obejmuje pozyskanie i dostarczenie odpowiedniej wiedzy. Zaproponowano autorskie metody do jej pozyskania oparte są na powszechnej wiedzy eksperckiej bazującej na określeniach lingwistycznych. Przyjęte metody nie są obligatoryjne i mogą być zastąpione innymi, które dostarczą bardziej wiarygodnej wiedzy. Zasadniczym celem proponowanego podejścia jest jednak wybór optymalnego wariantu modernizacji i jego alokacja w planowanym horyzoncie czasu. Zastosowane nowatorskie podejście optymalizacyjne oparte na macierzach decyzyjnych, umożliwia wybór możliwych scenariuszy wariantów modernizacji na każdym jej etapie. Macierze te stanowią zbiór ograniczeń zapisanych zmiennymi binarnymi pozwalające w rachunku optymalizacyjnym zachować ustaloną kolejność wykonywania napraw. Ponadto zastosowane w modułach optymalizacyjnych rozwiązania umożliwiają uwzględnienie założeń dotyczących zakładanej oceny stanu budynku oraz ograniczeń finansowych. Opracowana metoda stanowi praktyczne i uniwersalne narzędzie, które może być wykorzystywane przez zarządców na etapie utrzymania budynków mieszkalnych.

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