Sequential Model for Long-Term Planning of Building Renewal and Capital Improvement

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Abstract: The paper puts forward a mixed integer linear programming model to support the long-term planning and budgeting for renewal and capital improvements of residential buildings, i.e., to select the optimal sequence of repair and improvement actions over a predefined planning horizon. The input is provided by the evaluation of the building performance according to a set of criteria. Then a set of possible repairs, replacements and improvements needs to be proposed together with the estimates of their cost and benefits; the latter are expressed by increments of building performance ratings according to predefined criteria. The renewal and modernization measures are not mutually independent: at least some of them are complementary and should be carried out in a specific order. The optimization problem was to define the order of renewal/improvement measures resulting with the highest benefits available within the budget, or to achieve the required levels of building performance at the lowest cost. A unique feature of the model is the approach to the constraints on sequential relationships between the measures and to their selection. The model can be used to construct long-term renewal and capital improvement plans.

Keywords: renovation planning; facility management; sustainability; multi-criteria assessment; decision support; maintenance strategy

1. Introduction

Assuring the desired level of maintenance for multifamily residential buildings is the art of compromise that requires a great deal of commitment, technical expertise, and experience, as well as social competences [1]. Facility maintenance involves pursuing multiple goals: from the obvious of keeping the facility safe and operational at reasonable cost, to reducing the negative environmental impact of the building, in particular reducing the energy consumption during its service life, as well as protecting the value of the built heritage and respecting the needs of the society [2,3].

To think of balancing all aspects of the building performance by means of renovation and improvement measures, one needs first to assess the building condition and performance. This assessment is naturally a multi-criteria one [4,5]. Although the knowledge on building performance aspects and impacts is already considerable, it constantly changes. Criteria that were not previously considered, such as those related to environmental and social issues, gain importance and get new measures [6–8].

Depending on the actual and the desired condition of the building, the managers consider a variety of maintenance scenarios. Older and worn buildings with higher renovation and modernization costs require sustainable maintenance scenarios, which will balance today’s and future needs [9]. The planner’s task is to consider not only what actions are desirable and technically viable, but how they can be financed [10]. An important issue to account for in the preparation of the maintenance plans is the sequence and timing of activities. They cannot be carried out in a chaotic, inconsiderate way. The manager’s decisions should be optimized and affordable for the tenants or condominium
members. Economies can be looked for in careful long-term scheduling and combining improvements and repairs to make the most of the components’ service life [11]. Achieving the multiple objectives in maintenance is not possible without efficient strategy planning. In other words, allocating the budget to most reasonable actions and minimizing the degradation of the building performance during its life cycle are essential in strategic maintenance planning [12].

Considering the complexity of the decision-making process in maintaining multifamily buildings, the authors propose a model to assist the residential real estate manager in preparing the long-term renewal and capital improvement plans. The analysis includes the selection of criteria for evaluating the building performance, and the determination of building performance rating increments being the result of renovation and modernization activities. A binary linear programming model is proposed to identify the most advantageous scope of activities and their schedule for a long-term maintenance strategy. The model accounts for both the availability of funds (assuming the money comes from the sinking fund collected systematically to afford the desired scope of works) and constraints coming from the sequential and complementary character of the works. The application of the model is illustrated by a numerical example to show the advantages and the limitations of this approach to long-term planning.

The paper is organized as follows: Section 2 provides literature-based support on the idea of considering built asset management decisions as multi-criteria problems. Section 3 reviews decision-support methods for built asset management put forward by recent literature on the subject. Section 4 presents the model: its assumptions and mathematical formulation. Section 5 is devoted to presenting the model in action: the type of results it generates and their use in the decision-making process. Section 6 discusses the results and gives directions for future research.

2. Management of Built Assets as a Multi-Criteria Problem

It is obvious that the selection of building assessment criteria strongly affects the selection and the extent of repairs, replacements and improvements. The literature points to three basic aspects to be considered when evaluating building retrofit projects, i.e., environmental, social and economic aspects [13] proposing numerous measures that capture them. Nevertheless, other aspects, such as technical and historical, are frequently included [14–17].

The economic aspect is directly related with the operating costs of the building—and the most frequent rationale for building improvement [13,18]. The economic evaluation of a building may refer both to the building maintenance of the building’s fabric (including repairs and modernization), as well as to the utility costs (heating, cooling, lighting, water and sewage, etc.). These costs are interdependent: economic evaluations of the building are carried out to indicate repairs or modifications that translate into reduction in utility costs [11,19,20]. Selecting measures to improve energy performance of buildings through the selection of design solutions is a frequently analyzed problem [21]. Most measures to improve the energy efficiency of a building are expensive and, if implemented only to improve energy performance, might be economically unjustified [11].

The ongoing global climate change makes the environmental aspect of building assessment increasingly important. The need to control air temperature and quality in buildings results in increasing energy consumption, thus the global turn to sustainable energy sources and systems [22,23]. Retrofitting existing buildings is an important part of the strategy to mitigate climate change [24]. Typical changes concern the use of installations using solar or wind power, or aim at sparing water [13,25]. However, “greening” the existing building stock is subject to many technical, financial and organizational constraints: the process tends to go deep into the building’s fabric, and frequently concerns buildings that must stay operational during modifications.

Many methods have been developed for certification of buildings with at least partial focus on their environmental impact. Some of them can be used in the evaluation of
renovation projects. The most popular are BREEAM (Building Research Establishment Environmental Assessment Methods use in UK), LEED (Leadership in Energy and Environmental Design), GBA (Green Building Assessment), GREEN STAR in Australia, DGNB (German Sustainable Building Council) [26–31]. The sets of environmental criteria used by them are similar, though their number and approaches to evaluating them differ.

The social aspect of assessing buildings to plan maintenance and improvements seems neglected. It is naturally considered by architects in the course of the design process, by urban planners, and by municipal officers dealing with “problematic areas” that call for urban renewal. It increasingly makes its way into facility management analyses [1,32]. Most frequently, this aspect focuses on the owners and direct users (their satisfaction with the building performance), but other stakeholders (“the public” or clearly defined stakeholder groups) are also being addressed [33]. Drawing from Maslow’s Hierarchy of Needs, Taormina and Gao [34] claim that there are four basic human needs relating to residential and public buildings: the sense of comfort, security and safety, facilitating functions, intelligent management. Translating this to the performance of a building means that it should provide the users with appropriate conditions in terms of lighting, temperature, noise, hygiene, fire protection, and accessibility. They are, in fact, the basic requirements, but meeting them in the case of old buildings erected according to historic standards may be both costly and technically difficult to implement. However, the importance of the social aspect cannot be diminished or marginalized despite the lack of tangible financial or environmental benefits [33].

The technical aspect of assessing residential buildings refers to ensuring that the structural components’ finishes as well as the systems serve their purpose. The technical performance plays an essential role in ensuring the safety of the occupants of residential buildings and is a fundamental factor in determining the building’s usability [16]. Various methods are used to assess the technical condition. Its frequently used indicator is the technical wear of building components. Commonly used methods for assessing technical condition are time-based methods (proportionality, Ross, Unger and Eytelwein) and visual methods, which assume that the wear and tear of a building depends on the diligence of maintenance (repairs, ongoing maintenance and repairs, etc.) [16]. In assessing the condition of a building, the technical performance is the key aspect, as components’ malfunction affects operation of the building being a system of components [1,35]. Maintaining the technical efficiency of a building primarily requires repairs, replacements, or upgrading.

Since approaches to building performance criteria are constantly evolving, the authors decided to adopt their own set of criteria based on a comprehensive literature review. These are presented in a numerical example in Section 5. However, the proposed decision-support model has been constructed in such a way that users can modify the type and number of criteria depending on their specific needs.

3. Decision-Support Methods in Building Renewal and Capital Improvement Planning

Selecting the building performance criteria, and determining their relative importance is just the first step of the multi-criteria decision-making process. To help handle complex input on the building condition, the desired performance levels, possible actions and their multiple effects, one often refers to decision-support systems (DSS) [36]: complex mathematical algorithms aimed at indicating the optimal renovation decisions. The search for optimal solutions is thus supported by a plethora of multi-criteria decision-making techniques, expert systems, artificial intelligence (fuzzy sets, neural networks, evolutionary algorithms) or linear programming.

The choice of multi-criteria ranking and selection methods is very broad [37,38]. Among the methods well suited for qualitative data, the Analytic Hierarchy Process (AHP) seems to be the most frequently chosen by authors dealing with building assessment [39–41]. Considering the specific decision-making environment, many authors argue for other methods such as Analytic Network Process (ANP) [42], Step-Wise Weight Assessment Ratio Analysis (SWARA) [43,44], Additive Ratio A5seessment (ARAS) [45], Evaluation
Based on Distance from Average Solution (EDAS) \[46,47\], or Fuzzy Delphic-Eckenrode Likert-type Scale-based Rating Technique (FDERT) \[48\], to name only a few. They are used in assessing the condition of a building \[49,50\], and selecting repair options \[51,52\]. Turskis et al. \[47\] propose a hybrid approach based on AHP and EDAS method to evaluate and rank historic buildings according to their cultural value in order to prioritize them for renovation. Zavadskas et al. \[53\] evaluate the indoor environmental quality of dwellings using WASPAS, while Ighravwe and Oke \[8\] integrated methods: Weighted Aggregated Sum Product Assessment (WASPAS), Fuzzy Axiomatic Design, ARAS and SWARA to consider sustainability criteria in maintaining public buildings.

Methods based on linear programming are often used to select the best renovation and modernization solutions out of proposed sets. Depending on the optimization goal, they prompt the best renovation scope (assuring maximal increase of the building performance metrics achievable within a predefined budget) or indicate the most economical renovation variants that offers the required improvement of the building condition \[4,10\]. Wang, Xia and Zhang \[54\] used linear programming to plan retrofit actions that maximize energy savings and economic benefits based on net present value (NPV) considering the building’s life cycle costs.

Combinatorial optimization techniques are applied to support finding best solutions of complex problems of selecting renovation measures. An example of a decision-support system based on the knapsack problem was Sustainability Weighting Assessment for Homeowners (SWAHO) for selecting sustainable building renovation \[55\]: it integrates all green renovation tasks, from the decision of renovation activities to the selection of material solutions. SWAHO considers 48 renovation actions that are determined by 12 sustainability criteria. Liu and Rodriguez \[22\] applied a new metaheuristic algorithm called Adaptive Sparrow Search Optimization Algorithm (ASSOA) to optimize integrated sustainable energy systems in a building. Its objective was to find a combination of sustainable energy source systems for minimizing the objective functions determining the initial energy demand and capital expenditure. In contrast, Chang et al. \[56\] developed a multi-objective optimization model to support building envelope selection decisions. The optimal choice includes new materials and technologies that are available as building envelope renovation options for indoor thermal comfort, energy balance, environmental emissions and economic aspects. The optimization model and framework proposed in this study is expected to contribute to the mapping for transforming existing buildings into smart and sustainable buildings. Evolutionary algorithms are a frequently used technique to search for globally optimized solutions. They are used in multi-objective optimization in supporting building retrofit decisions by providing optimal design solutions. Their application in modeling the relationship between possible building retrofit options and improvement of indoor environmental quality enabling the selection of optimal retrofit options, taking into account cost constraints and performance requirements, is presented in \[57\]. Penna et al. \[58\] used a genetic algorithm in combination with TRNSYS energy simulation to optimize comfort costs and energy consumption depending on the insulation level of the building envelope, glazing systems and mechanical systems. An example of an integrated system for determining the optimal maintenance strategy for deteriorating buildings through multi-objective optimization was presented by Chiu and Lin \[59\]. This system uses particle swarm optimization and Pareto optimal solution to achieve multi-objective optimization, viz.: economy safety, serviceability, rationality, and long service life.

The use of fuzzy sets and stochastic networks provides an opportunity to apply imprecise data contained in the form of expert knowledge. An example of its application in assessing the value of a building, which formed the basis for further optimization stages using an evolutionary algorithm, is presented in \[4\]. This decision-making model indicates the renovation variant ensuring the highest increase of the value of the building in relation to the engaged financial means. A method for planning construction projects involving the reconstruction of historic buildings was proposed in \[60\]. The authors applied stochastic networks to model the undetermined structure of such projects, and
used interval sets to model the uncertainty of estimating the parameters of reconstruction works. An example of a system supporting the selection of priorities of reconstruction activities for the management of large building stock, based on Bayesian networks, was presented by Carbonari et al. [61]. The proposed system evaluates the values of three building quality indicators: accessibility, energy efficiency, and acoustics; it predicts the future costs of renovation actions. Ferreira et al. [62] developed a probabilistic method for quantifying maintenance activities based on a stochastic maintenance model (Petri nets). Based on the components’ condition, the model prompts one of four levels of intervention (inspection, cleaning, intervention, and total replacement).

An interesting approach for determining the repair schedule of building components based on Case-Based Reasoning (CBR) and Fuzzy Analytic Hierarchy Process (FAHP) was proposed by Park et al. [63]. Using a database of maintenance records of 257 components of residential buildings, and expert knowledge to derive attributes, the authors were able to predict the timing of first repairs to particular building components with a satisfactory precision. CBR was applied also in [64] to select best measures of “green retrofitting” of existing buildings based on the knowledge derived from past projects carried out in China.

Large quantities of building data can be handily stored in Building Information Models (BIM). A conceptual model for building renovation based on BIM creating a decision-making environment for the selection of renovation strategies and quality control is presented in [65]. The model using optimization systems and BIM enables the assessment of building energy demand and makes a comprehensive evaluation of renovation activities considering energy efficiency, eco-efficiency and economic parameters. The model presented in [36] assists in making informed decisions when choosing a maintenance strategy. It is based on building performance evaluation indicators providing useful information that is the basis for maintenance interventions of building components and systems. Motawa and Almarshad [66] presented an integrated maintenance decision-support system combining a CBR maintenance knowledge acquisition system with an information management system operating under BIM, whereas Pavlovskis et al. [67] pointed out the ease of extracting information from BIM models which streamlines the multi-criteria comparisons of options of complex projects. Building maintenance management based on intelligent systems for providing visual information about the building condition is presented in [68]. Based on this, the system inspects the building and indicates repairs based on automated algorithms that compare the image of the digital building model stored in the BIM with the images coming from cameras and transmitted to the system via Quick Response codes. An example of combining ontology and BIM for Building Knowledge Management is presented in [2]. The proposed approach uses FMEA (Failure Modes and Effects Analysis), which combined with a cloud computing model processes uncertain information using gray relationships to improve the efficiency of maintenance management of historic buildings.

An extension of the BIM concept is an efficient (ongoing) building maintenance system based on data from sensors monitoring passive building systems providing the basis for maintenance decisions that reduce maintenance costs and ensure high building performance while maintaining occupant comfort [69]. The information collected in the system will help to set policy, predict anomalies, plan proper maintenance, prioritize investments, and intervene quickly to stop the building degradation process. In the modern approach to managing buildings with seemingly contradictory requirements: minimizing energy consumption while maintaining occupant comfort, and intelligent building management systems that manage plumbing systems can also be used. They provide a natural solution for optimal energy efficiency, energy security and user comfort in buildings [70].

The above brief overview of recent publications in building maintenance decision support points to a large variation in the methodological approaches. In this paper, the authors present another concept of a comprehensive method (DSS system) for the long-term planning of renovation and improvement measures: from data collection, through setting targets, to selecting, budgeting, and scheduling measures to bring the building to satisfactory condition. The focus of the analysis is the model’s optimization module.
Though a well-established technique of mixed integer linear programming is applied, the originality of the analysis lies in considering the fact that the renovation and improvement measures should come in certain sequences and may be complementary. Another requirement, rather natural and shared with many other models, is considering affordability. In this particular model, the measures need to be scheduled to consecutive periods of the planning horizon only if they can be paid for from the cumulated sinking fund. The model is intended to be a practical tool for building managers in helping select and justify the scope of interventions to the building’s fabric.

4. Materials and Methods

4.1. Methodology

The problem focuses on the optimal selection of activity sequence variants and then assigning them to periods of the planning horizon, with the optimal being understood as minimum cost or maximum benefit (increase in the building’s total performance rating). The decision variables are binary (the planner wants to decide if to select a particular activity sequence variant or not, and if to assign it to a particular period of the planning horizon or not). The constraints can be expressed in a linear form. All parameters are treated as “certain” and expressed by numerical values. Therefore, the problem was formulated as a binary linear program. To solve it, MATLAB bintprog was applied. Sections 4.3–4.7 present the mathematical formulation of the model. The complete list of symbols is located in Tables A1–A4 in Appendix A.

4.2. Model Overview

The complete analysis includes five steps (Figure 1). The first three, not covered in detail in this paper, are devoted to collecting the input. The fourth and fifth are devoted to applying the proposed mathematical model to elicit the optimal solution.

Figure 1. Conceptual model for building renewal and capital improvement planning.

The analysis starts with evaluating the building’s performance “as it is”. This step includes selecting the building performance criteria and determining their relative impor-
tance. Both these tasks belong to the decision-maker and express their subjective point
of view. Then, using building maintenance records, user feedback, and results of expert
surveys (so, hard evidence on the condition and performance of the building), the expert
is to provide a set of criteria-wise performance ratings for the building as a whole. With
this input, a general rating of the building can be calculated defining the “starting point”
for improvements.

The criteria-wise and the generalized ratings are intended to be improved by im-
plementing technical measures, later referred to as activities, over a predefined planning
horizon to reach the performance rating targets set by the decision-maker. The activities
include repairs, renewal, and improvement works. Thus, in the second step, an expert
proposes a pool of such activities. Each activity must be assessed in terms of benefits
generated by its implementation (the increments in the criteria-wise ratings of the building)
as well as costs. Please note that urgent repairs are excluded from this analysis, and the
pool of activities comprises only those that can be spread over the planning horizon.

Before the best set of activities can be selected out of the pool proposed by the expert,
one needs to consider relationships between them: they are likely to be viable only in
certain sequence as being complementary or to avoid rework. To account for this fact, the
activities are grouped according to functional components or spaces of the building, and
ordered according to the logic of the works, forming separate sequences. The actual object
of selection in the course of this analysis are sequence variants (fragments of sequences)
and not particular activities.

The next step is the actual selection of the renewal and improvement measures, so the
activity sequence varies. Depending on the decision situation, the starting point can be
available money (to make the most of the budget in terms of building’s rating improve-
ment), or the desired increase in the building’s rating (to find the cheapest combination of
measures to achieve the rating goals).

The final step and the product of the analysis is the schedule: allocation of activities to
the unit periods of the planning horizon that meets the constraints of the logic of works
(sequential relationships).

4.3. Building Performance Assessment According to Sustainability Criteria

The building evaluation comprises four steps:
1. Adopt criteria for assessing building condition;
2. Define criteria weights using AHP;
3. Rate the condition of the building according to each criterion;
4. Calculate the weighted score of the building.

Assessment of the condition of a residential building can be based on any number of
criteria related to the technical, economic, social, environmental and visual aspects.
The multi-criteria rating of the building condition, $O$, is calculated as the weighted
sum of the individual ratings according to these criteria, according to Equation (1).

$$ O = \sum_{j=1}^{m} w_j \cdot o_j, \quad (1) $$

where $w_j$ is the weight of a criterion $j$, and $o_j$ is the building’s rating according to criterion $j$.

The criteria weights, $w_j$, are proposed to be calculated on the basis of the decision-
maker’s judgements using AHP. AHP was selected as it enables turning subjective and
imprecise judgments (pairwise comparisons of the importance of criteria as perceived by
the decision-maker) into numerical values required in the further steps of the analysis.
Moreover, it leaves clear evidence on how the numerical values were elicited. The prop-
erties of AHP make it a frequent choice in weight assessment for multi-criteria problems in
facility management (among others, [1,4,5,7,10,17,36,71]). The criteria-wise ratings of the
building, $o_j$, are to be derived from the judgements provided by an expert who inspects
the building and analyzes building records. They are expressed directly in a linguistic ordinal
scale transferred artificially to “points”, as numerical values are needed in the analysis to follow. For this purpose, the following scale is proposed: very good VG (10 points), good G (8 points), average A (6 points), bad B (4 points), very bad VB (2 points), none N (0 points).

4.4. Renewal/Improvement Activities and Increments of Criteria-Wise Building Ratings

The building’s criteria-wise ratings are to be increased to the predefined levels by means of renewal or improvement activities \( i \) to be conducted over the predefined planning horizon. The activities may result in big or small changes of ratings according to one or more criteria. Thus, once the complete potential set of activities is proposed by an expert, the rating increments caused by the activities, if implemented, need to be assessed.

The increment of the building’s rating according to criterion \( j \) on completion of activity \( i \), \( p_{a,j,i} \), is readily weighted to enable summation into increments of the total rating of the building. It is expressed by Equation (2):

\[
p_{a,j,i} = \frac{o_{a,j,i} \cdot (z_j - o_j) \cdot w_j}{\sum_{j=1}^{n} o_{a,j,i}} \quad \forall \, j = 1, 2, \ldots, m \quad i = 1, 2, \ldots, n
\]

where \( o_{a,j,i} \) is the rating of activity’s \( i \) impact on the building’s performance according to criterion \( j \); \( z_j \) is the value of the rating according to criterion \( j \) on completion of all proposed activities; \( o_j \) is the baseline rating of the building according to criterion \( j \) (before any activities are implemented); \( w_j \) is the weight of criterion \( j \). Please note that the role and meaning of index \( a \) is explained in the section to follow. As in the case of \( o_j \), the values of \( o_{a,j,i} \) come from the expert’s judgement on the effects of the proposed activities. The impact ratings are expressed in a linguistic ordinal scale and transferred to numerical values as follows: very large VL (10 points), large L (8 points), medium M (6 points), small S (4 points), very small VS (2 points), no impact N (0 points).

Apart from assessing the effect of activities on the building’s criteria-wise ratings, the expert is asked to estimate the cost of each activity, \( c_{i,j} \).

4.5. Defining Activity Sequence Variants Considering Sequential Relationships between Activities

The proposed activities are to be grouped according to their relationship with a particular functional component or space of the building. For instance, one can consider a group of activities addressed for renewal or improvement of the staircase, the roof, the basement or the façade. The groups may encompass any number of activities, but an activity may belong to only one group.

These activities, if to be implemented, should be completed in a predefined order according to the logic of works and their complementary character (for instance, cracks in the plaster should be sealed before the wall is painted, thus the activity of “sealing wall plaster cracks” should precede “painting walls”). Therefore, the activities assigned to a group are not an unordered set. Instead, they form a sequence. Their attribution to a sequence is marked by index \( a \), and their position in the sequence by index \( i \).

At a particular point of time, there is a possibility to select and execute only some activities from the sequence, but the selection is constrained by the relationships between the activities. For instance, one cannot pick solely the third activity from the sequence unless its predecessors are selected with it, or had been selected in the previous unit of time. The partial sequences are thus the object of selection in the steps to follow, and they are further referred to as activity sequence variants.

The idea of activity sequence variants is explained in Figure 2 and Table 1. A complete sequence comprises activities marked as \( q_{a,i} \), where \( a \) is the identifier of a sequence \( (n = 1, 2, \ldots, A) \), and \( i \) stands for the number of the activity in this sequence \( (i = 1, 2, \ldots, I_{a}) \). Let us describe a variant of sequence \( a \) by \( v_{a,h,i} \), with \( h \) representing the identifier of the variant. The first variant of the sequence, \( v_{a,1,i} \), contains the first activity in the sequence, whereas each subsequent variant \( v_{a,h,i} \) adds another activity in the established order. Thus
the number of variants is equal to the number of all activities included in the sequence
\((h = 1, 2, \ldots, H_h = I_h)\).

![Diagram of activities sequence variants](image)

**Figure 2.** An example of activity sequence for a component: defining activity sequence variants.

**Table 1.** A fragment of a matrix of constraints \(G = \left[ g_{a,h,u} \right] \) in a tabular form to explain the role of Equations (3)–(5) (description in the text).

| \(a\) (Sequence ID) | \(h\) (Variant ID) | Condition |
|---------------------|---------------------|------------|
| 1                   | 1                   | \(\leq 1\) |
| 2                   | 1                   | \(\leq 1\) |
| \ldots             | \ldots              | \(\leq 1\) |

The variants \(v_{a,h}\) of each sequence represent a set of elements whose selection is the aim of the optimization procedure. Symbolically, the complete set of variants \(V\) of activities assigned to “groups” (or “sequences”) is \(V = V_1 \cup V_2 \ldots V_A\), where \(V_a = \{v_{a,1}, v_{a,2}, \ldots, v_{a,H_h}\}\).

In the course of optimization, a variant number \(h\) of a sequence number \(a\) is selected for execution at each consecutive period \(u\) of the planning horizon, and only one variant related with a particular sequence is allowed to be picked at a time. The mathematical notation of this constraint is written as follows:

\[
G = \left[ g_{a,h,u} \right]_{A \times H \times U}, \quad \forall a = 1, 2, \ldots, A, \quad \forall h = 1, 2, 3, \ldots, H, \quad \forall u = 1, 2, \ldots, U, \quad (3)
\]

\[
\sum_{h=1}^{H_h} g_{a,h,u} \leq 1, \quad \forall a = 1, 2, \ldots, A, \quad \forall u = 1, 2, \ldots, U, \quad (4)
\]

\[
g_{a,h,u} = \begin{cases} 
1 & \text{if variant } h \text{ of sequence } a \text{ can be selected in period } u, \\
0 & \text{if variant } h \text{ of sequence } a \text{ does not exist.} 
\end{cases} \quad (5)
\]

Its operation can be explained using an example (analyzed in detail in Section 5). Let Table 1 represent a fragment of matrix \(G\) prepared for period \(u = 1\), for a case of a building where a number of sequences are considered. The first sequence has 5 variants (which means that up to 5 activities ordered one after another were proposed for the component or space denoted by \(a = 1\), and the whole row of Table 1 is filled with “1” corresponding to \(g_{1,h,1} = 1, h = 1, 2, 3, 4, 5\)). The second sequence has only 3 variants (3 activities proposed, so three cells in the row are “1” and two cells in the row are “0” as variant \(h = 4\) and \(h = 5\) do not exist for sequence 2).

Let us consider sequence \(a = 2\) and its variants: \(V_2 = \{v_{2,1}, v_{2,2}, v_{2,3}\}\). The first variant comprises one activity; the second comprises the first variant plus the second activity, and the third variant comprises the second variant plus the third and last activity (so, all three activities). Thus, selecting two or more variants at the same time would make no sense. Therefore, if, at a particular point of time, variant \(h = 1\) is selected and variant \(h = 2\) is selected, condition (4) would not be fulfilled, as the sum of selected variants from the row would be 2, so greater than 1.

As a particular variant is selected in a unit of time \((u − 1)\), the pool of variants available for the period to follow \((u)\) is reduced: \(V_u = (V − V_{u−1})\), \(\forall u = 2, \ldots, U\). Returning
to the example, let us assume that, at period \( u = 1 \), variants \( v_{a=1,h=2} \) (so composed of two activities, which means the same as the first variant plus the second activity) and \( v_{a=2,h=1} \) (composed of one activity) were selected for execution. Then, for period \( u = 2 \), matrix \( G \) is different (as shown in Table 2): the “consumed” variants are eliminated from further choice. This means, their \( g_{a,h,u} = 0 \), (the variants cease to exist at period \( u = 2 \)).

Matrices \( G \) are created by defining sets of conditions, for instance: if \( g_{1,2,1} = 1 \) then \( (g_{1,1,2} = 0 \land g_{1,2,2} = 0 \land g_{1,3,2} = 1 \land g_{1,4,2} = 1 \land g_{1,5,2} = 1) \).

Table 2. A fragment of a matrix of constraints \( G = [g_{a,h,u}] \) in a tabular form to explain the role of Equations (3)–(5) (description in the text), \( u = 2 \).

| (Sequence ID) | \( h \) (Variant ID) | Condition |
|---------------|----------------------|-----------|
| 1             | 0 0 1 1 1            | \( \leq 1 \) |
| 2             | 0 1 1 0 0            | \( \leq 1 \) |
| ...           | ... ... ... ...     | \( \leq 1 \) |

Selecting a next sequence variant for the next unit of time means that its scope must be reduced by all activities related with previously selected variants (the activities that belonged to the part of the sequence done in the previous period cannot be repeated in the next, the sequence can only be continued). However, this is modeled in the next steps of analysis (Equations (13)–(16)), in the course of calculating the period-wise increments of criteria ratings and costs incurred in particular periods.

Execution of activities that belong to \( h \), the variant of sequence \( a \), so \( v_{a,h} \), results in a particular increase in the building’s rating according to one or more criteria \( j \) (this rating increment is \( p_{a,h,j} \) described by Equation (6) and comes at a particular cost \( c_{a,h} \) Equation (7)):

\[
p_{a,h,j} = \sum_{i=1}^{h} p_{a,i,j} \quad \forall a = 1, 2, \ldots, A, \quad \forall h = 1, 2, \ldots, H_{a}, \quad \forall j = 1, 2, \ldots, m,
\]

\[
c_{a,h} = \sum_{i=1}^{h} c_{a,i} \quad \forall a = 1, 2, \ldots, A, \quad \forall h = 1, 2, \ldots, H_{a}
\]

4.6. Defining the Budget Available at Consecutive Periods of the Planning Horizon

It is assumed that all money available for renewal and improvements come solely from the sinking fund—thus, parts of the monthly maintenance fees paid by the tenants/condominium members per square meter of usable floor area of their apartments. The money collected over one full period of the planning horizon is:

\[
B = s \cdot d \cdot o,
\]

where \( d \) is usable floor area of apartments, \( m^2 \); \( s \) is fixed monthly rate of the fee towards the sinking fund, PLN/m\(^2\); \( o \) is number of months of \( u \)th period of the planning horizon.

The monthly fee, \( s \), is to be defined by the decision-maker. One can experiment with this value to find a trade-off between the tenants’ or condo members’ willingness to pay and the increment of the building’s rating achievable by the end of the planning horizon.

Any activities can be scheduled for implementation in a particular unit of the planning horizon (a particular year) only if the accrued funds are high enough. The amount available in the first unit of time, \( B_1 \) (beginning of unit 1), was assumed to equal the “base” budget, \( B \), so the sum of all fees towards sinking fund collected over one period calculated according to Equation (10). This means that the facility manager started collecting money one period ahead of the first intended spending.

The funds available by the beginning of the periods to follow (period \( u \), Equation (11)) are funds left from the previous period \( (u - 1) \), so the budget available at the beginning of
period \((u-1)\) meant less money spent that period, increased by fees collected during year \((u-1)\), so B:

\[
B_u = B + B_{u-1} - C_{u-1} \quad \forall \, u = 2, \ldots, U,
\]

where \(B_u\) is the budget available at the beginning of \(u\)th period of the planning horizon; \(C_u\) is total cost of activities conducted in the \(u\)th period.

The budget for the whole planning horizon, \(D\), is expressed by Equation (10) and it is the sum of yearly fees collected over the whole planning horizon:

\[
D = U \cdot B
\]

4.7. Selecting Optimal Renewal Variants and Allocating Activities to the Periods of the Planning Horizon

Two different approaches based on different initial assumptions and optimization objectives have been developed to select the best scope of renewal and improvement activities.

4.7.1. Approach 1: Select Activities to Maximize the Building’s Performance Ratings within a Predefined Budget

The first approach, with the objective function defined by Equation (11), aims at identifying variants that result in the highest increment, period by period, of the total building rating, \(P_u\). The increment of the total building rating is a sum of weighed criteria-wise increments achieved in period \(u\), so \(P_j, u\) (Equation (12)), and these are the effect of implementing activities encompassed by selected variants (Equation (13)):

\[
\max z : z = P_u, \quad \forall u = 1, 2, \ldots, U,
\]

\[
P_u = \sum_{j=1}^{m} P_{j, u}, \quad \forall u = 1, 2, \ldots, U,
\]

\[
P_{j, u} = \sum_{a=1}^{A} \sum_{h=1}^{H_a} P_{a, h, j} \cdot S_{a, h, u} \cdot x_{a, h, u}, \quad \forall j = 1, 2, \ldots, m,
\]

Naturally, the cost of activities scheduled for a particular period (Equations (15) and (16)) is constrained by the budget available for each period (Equation (17)).

\[
C_{u=1} = \sum_{a=1}^{A} \sum_{h=1}^{H_a} c_{a, h} \cdot S_{a, h, u} \cdot x_{a, h, u},
\]

\[
C_u = \sum_{a=1}^{A} \sum_{h=1}^{H_a} c_{a, h} \cdot S_{a, h, u} \cdot x_{a, h, u} - \sum_{a=1}^{A} \sum_{h=1}^{H_a} c_{a, h} \cdot S_{a, h, u-1} \cdot x_{a, h, u-1}, \quad \forall u > 1,
\]

\[
C_u \leq B_u, \quad \forall u = 1, 2, \ldots, U.
\]

The increment of the total building rating achieved by the end of the planning horizon, \(P\), is expressed by Equation (18), while the final increments of the ratings according to particular criteria is expressed by Equation (19):

\[
P = \sum_{j=1}^{m} P_j,
\]

\[
P_j = \sum_{u=1}^{U} P_{j, u}, \quad \forall j = 1, 2, \ldots, m.
\]
To enable selection of repair variants, a binary variable is used (Equations (20) and (21)).

\[ x_{a,h,u} \in \{0, 1\}, \quad a = 1, 2, \ldots, A, \quad h = 1, 2, \ldots, H, \quad u = 1, 2, \ldots, U, \]  

\[ x_{a,h,u} = \begin{cases} 1 & \text{if variant } h \text{ of sequence } a \text{ is selected in period } u, \\ 0 & \text{otherwise}. \end{cases} \]  

4.7.2. Approach 2. Select the Least Costly Measures That Assure Reaching the Building’s Performance Targets

The other model’s objective function, minimizing the cost of renovation and improvement measures, is defined by Equation (22):

\[ \min z : z = C_u, \quad \forall u = 1, 2, \ldots, U. \]  

Here, the decision-maker is assumed to search for the cheapest combination of activities that make the resulting building’s rating, \( O_u \), at least as high as the desired value of the building’s rating, \( Z_u \), by the end of each period \( u \) of the planning horizon (Equation (23)):

\[ O_u \geq Z_u, \quad \forall u = 1, 2, \ldots, U. \]  

This desired rating is to grow period by period at a steady rate, calculated according to Equation (24):

\[ Z_u = \frac{Z - O_{U+1}}{U} \cdot u + O_u, \quad \forall u = 1, 2, \ldots, U, \]  

The total building’s rating achieved by the end of any unit period \( u \), being the result of all activities conducted so far, is defined by Equation (25):

\[ O_u = O_{(u-1)} + P_u, \quad \forall u = 1, 2, \ldots, U, \]  

The sum of rating increments due to implementation of \( h \)th variants across all periods is expressed by Equation (26), and the accompanying cost is expressed by Equation (27).

\[ P = \sum_{u=1}^{U} P_u, \]  

\[ C = \sum_{u=1}^{U} C_u, \]  

To assess efficiency of variant selection, a benefit to cost ratio is used, expressed as building rating’s increment per one million of currency spent on renovations and improvements, as in Equations (28) (period by period), and (29) (the average of the planning horizon):

\[ w_u = \frac{P_u}{C_u} \cdot 1000000, \quad \forall u = 1, 2, \ldots, U, \]  

\[ w = \frac{1}{U} \sum_{u=1}^{U} w_u. \]  

where \( C_u \) is the cost of activities selected for \( u \)th period; \( P_u \) is the increment of the total building’s rating due to activities conducted in period \( u \); \( O_u \) is the total building’s performance rating achieved by the end of period \( u \); \( Z \) is the target total rating of the building to be achieved by the end of the planning horizon.

5. Numerical Example

The model’s operation is presented using a case study of selecting the optimal repair, renovation and improvement measures for a five-story apartment block. The input (the selection of criteria, the assessment of their relative importance, the criteria-wise ratings of
the building’s performance at the beginning of the analysis, the choice of repair, renovation, and improvement measures, as well as the values of their contribution to the building’s rating and their estimated cost) was based on a real-life case of a building managed by a housing cooperative located in Lublin, Poland. The data were gathered in the course of an interview with the members of the estate management team (the people later referred to as “the expert”), the building’s maintenance documents review, and own elaboration. However, they serve only demonstrating purposes.

The building’s total usable floor area of apartments is \( d = 1953 \text{ m}^2 \). The building was erected in the 1970s. Its structure is of large precast concrete elements. Its systems (wiring, water supply and sewage, district heating) are still original. The building was not modernized, just kept operational. It is structurally sound, the systems are still working, though obsolete, and the less durable components (internal and external finishes) are worn.

The building was evaluated according to the following set of ten criteria: 1—water efficiency, 2—use of renewable energy sources, 3—operating costs, 4—utility costs, 5—usability and functionality, 6—the technical safety of the building, 7—aesthetic and thermal comfort, 8—air quality, 9—appearance of the building, 10—interior appearance of the building. These are also the criteria of the building’s improvement.

The criteria-wise building performance ratings \( o_j \) in the linguistic scale were provided by an expert, and the criteria weights \( w_j \) calculated by the decision-maker (here, the authors applying AHP to raw judgements provided by the expert). Values of the input, \( o_j \), \( w_j \), and the total building rating \( O \) (calculated using Equation (1)) are summarized in Table 3.

Table 3. Building performance evaluation (original state).

| Criteria j | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 |
|------------|----|----|----|----|----|----|----|----|----|----|
| \( o_j \)  | N  | N  | B  | VB | VB | A  | VB | B  | VB | VB |
| \( w_j \)  | 0.061 | 0.061 | 0.116 | 0.234 | 0.140 | 0.069 | 0.140 | 0.069 | 0.055 | 0.055 |
| \( O \)    | 2.402 |

Note: Very good VG (10 points), good G (8 points), average A (6 points), bad B (4 points), very bad VB (2 points), none N (0 points).

Considering the condition and performance of the building, the expert proposed 23 renovation and improvement activities expected to enhance the building’s performance in terms of the predefined criteria. They are listed in Table 4 together with the expert’s raw assessments on their impact on criteria-wise ratings, \( a_{a,j} \) (expressed the linguistic scale), and their costs, \( c_{a,i} \) (estimated by the expert).

The activities were grouped according to their relationship with a functional component or space and numbered according to the logic of works. This way, activity sequence variants \( a_{a,j} \) can be distinguished, where \( a \) is the identifier of the sequence of activities intended for a functional component or space. The first variant of a sequence is composed of one activity, the second—of two activities, and so on. The composition of possible activity sequence variants is presented in Table 5.

In this particular case, conducting even all of the proposed activities is decided not enough to reach the top rating according to criteria \( j = (2 \div 7) \); only “good” (G, \( z_j = 8 \) points) rating would be possible. With these criteria, doing more is arbitrarily decided to be beyond the financial capacity of the condominium. As for criteria \( j = (1, 8, 9, 10) \), if all proposed activities are performed, the corresponding criteria-wise ratings would be \( z_j = 10 \) points (very good, VG). Nevertheless, conducting any of the proposed activities would result in an increase of the building’s rating according to at least one criterion.
Table 4. The set of proposed renovation and improvement activities, their impact on the building’s performance according to each criterion, and activity costs; activities already grouped according to functional unit or space and numbered according to their order in a sequence.

| a | i | Proposed Activity | The Impact of Activity on Criteria-Wise Rating \( (a_{a,i}) \) | Activity Cost, \( c_{a,i} \) (PLN) |
|---|---|----------------|---------------------------------|-------------------------------|
| 1 | 1 | Replacing windows and doors | N N VS M S S L S S VS | 181,000 |
| 2 | 2 | Replacing balcony cladding | N N S N S S N N S N | 94,500 |
| 3 | 3 | Installing ETICS | N N N VS N N VS N NVS N | 215,000 |
| 4 | 4 | Installing canopies over balconies | N N N N VS N N VS N | 18,700 |
| 5 | 5 | Replacing balcony railings | N N N S N N S N S N | 91,500 |
| 1 | 1 | Thermal insulation of flat roof | N N N M N N S N N L | 32,200 |
| 2 | 2 | Replacing roof cladding | N N M N N M N N N N | 41,500 |
| 3 | 3 | Replacing gutters | N N VS N N VS N N VS N | 12,700 |
| 1 | 1 | Thermal insulation on basement ceiling | N N N S N N S N N N | 18,400 |
| 2 | 2 | Installing thermal insulation and waterproofing basement walls | N N S VS N N VS N N N | 31,500 |
| 3 | 3 | Replacing basement flooring | N N VS N N VS N N N | 18,500 |
| 1 | 1 | Replacing external stair cladding | N N S N M VS N N VS N | 2500 |
| 2 | 2 | Installing ramp | N N N M N N N N N N | 23,500 |
| 3 | 3 | Installing canopy over the entrance | N N N S N N N N VS N | 6500 |
| 1 | 1 | Installing solar collectors | N M N S N N N N N N | 95,000 |
| 2 | 2 | Installing photovoltaic system | N M N M N N N N N N | 110,000 |
| 3 | 3 | Installing mechanical ventilation with recuperator | N VS N M N N N N L N | 125,000 |
| 4 | 4 | Installing gray water system | VL N N S N N N N N N | 180,000 |
| 5 | 5 | Installing fire suppression system | N N N M N N N N N N | 25,000 |

Note: Very large VL (10 points), large L (8 points), medium M (6 points), small S (4 points), very small VS (2 points), no impact N (0 points).

Table 5. Composition of activity sequence variants for the example.

| Activities \( q_{a,i} \) | a | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|
| \( i \) | 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 |

Sequence variants \( v_{a,h} \)

\( h = 1 \) | x | x | x | x | x | x | x | x |
\( h = 2 \) | x | x | x | x | x | x | x | x | x |
\( h = 3 \) | x | x | x | x | x | x | x | x | x | x |
\( h = 4 \) | x | x | x | x | x | x | x | x | x |
\( h = 5 \) | x | x | x | x | x | x | x | x | x |

The variant selection process is coded in the form of a matrix of constraints, \( G = \{ g_{a,h,i} \}_{A \times H \times U} \). At any stage of repair/modernization planning horizon, as in a unit of time \( u \), one can select no more than one variant of each sequence \( a \). In the next iteration of the algorithm, meant for the next unit of time \( (u + 1) \), the activities that belonged to the previously selected variant are removed from the remaining variants, so activities already completed will not be repeated if the sequence is decided to be continued. These constraints for the analyzed example and the first unit of time, are presented in Table 6.

The whole planning horizon is composed of 5 periods (years)—a relatively short time to keep the numerical example concise. At each period, the optimization algorithm helps select variants that ensure the greatest increase in the building performance ratings, considering the fact that the maximum monthly contribution to the sinking fund, acceptable for the residents, is 8 PLN/m². By setting this sinking fund rate, the housing manager calculates the annual budget to be 187,488 PLN plus funds not consumed in the previous
year. The results of optimization calculations, showing the increase in the value of these criteria for particular stages and the whole renovation period, are presented in Table 7.

Table 6. The matrix of constraints on selection sequence variants $G = [g_{a,h,u}]_{A \times H \times U}$ for the first stage of renovation/modernization ($u = 1$)—the example.

| $a$ (Sequence ID) | $h$ (Variant ID) | 1 | 2 | 3 | 4 | 5 | Condition |
|-------------------|------------------|---|---|---|---|---|-----------|
| 1                 | 1                | 1 | 1 | 1 | 1 | 1 | $\leq 1$ |
| 2                 | 1                | 1 | 1 | 0 | 0 | 0 | $\leq 1$ |
| 3                 | 1                | 1 | 1 | 1 | 0 | 0 | $\leq 1$ |
| 4                 | 1                | 1 | 1 | 0 | 0 | 0 | $\leq 1$ |
| 5                 | 1                | 1 | 1 | 0 | 0 | 0 | $\leq 1$ |
| 6                 | 1                | 1 | 1 | 1 | 1 | 1 | $\leq 1$ |

Table 7. Criteria-wise rating increments in consecutive units of the planning horizon ($P_{j,u}$).

| $j$ | $P_{j,u}$ (Points) | $P_{j}$ (Points) | $P_u$ (points) | $O_u$ (points) | $C_u$ (PLN) | $B_u$ (PLN) | $w_u$ |
|-----|-------------------|------------------|---------------|----------------|------------|------------|------|
| 1   | 0.000             | 0.000            | 1.428         | 3.830          | 187,300    | 187,488    | 7.62 |
| 2   | 0.000             | 0.000            | 0.714         | 4.544          | 181,000    | 187,676    | 3.94 |
| 3   | 0.199             | 0.022            | 0.637         | 5.181          | 171,100    | 194,164    | 3.72 |
| 4   | 0.351             | 0.176            | 0.672         | 5.853          | 207,200    | 210,552    | 3.24 |
| 5   | 0.303             | 0.067            | 0.332         | 6.185          | 165,500    | 190,840    | 2.01 |
| 6   | 0.066             | 0.013            | 0.418         | 6.399          | 0.126      | 0.264      |      |
| 7   | 0.300             | 0.240            | 0.820         | 0.419          | 0.118      | 0.241      |      |
| 8   | 0.000             | 0.118            | 0.540         | 0.639          | 0.000      | 0.241      |      |
| 9   | 0.176             | 0.044            | 0.000         | 1.262          | 0.000      | 0.000      |      |
| 10  | 0.034             | 0.034            | 0.000         | 0.000          | 0.000      | 0.000      |      |

As expected, the year-by-year figures show that the priority is given to the most effective renovation and modernization measures, so the measures that produce the greatest rating increments $P_u$ related to their cost $C_u$. Whether the money available at a particular period is consumed or saved, depends on the set of measures available for selection and their cost. In the later stages of the planning horizon, the choice of measures is reduced, and the utilization of the budget drops. Figure 3 presents allocation of activities to consecutive periods.

To analyze how the availability of funds affects the results of renovation and modernization (with the same pool of activities to select from), calculations were repeated assuming the monthly sinking fund rate per m$^2$ ranging from 5 to 13.1 PLN. The aim of these calculations, summarized in Table 8, was to see the difference in the final increase in the building’s rating, the total cost, as well as the benefit to cost ratio. Such calculations are expected to be useful in negotiations with the condominium members of tenants regarding the amount of the sinking fund (if paying more is likely to increase the benefits to the building’s performance).
To analyze how the availability of funds affects the results of renovation and modernization activities, calculations were repeated with different assumptions on the target rating (options). Target ratings for the renovation and modernization measures in the consecutive periods of the planning horizon were set to be equal, as in Equation (22).

The results are shown in Table 8: the sequence variants selected for each unit of the planning horizon, their cost, increments of the building’s rating, and the benefit to cost ratio. Such analysis would be practical to inform condominium members on the financial consequences of briefer or deeper modernization of the building.

| Option | Sinking Fund Rate s (PLN/m²) | Budget B₀/D (PLN) | Total Rating Increment P Points | Total Cost C (PLN) | Benefit to Cost Ratio w |
|--------|-------------------------------|-------------------|-------------------------------|-------------------|------------------------|
| 1      | 5                             | 117,180/585,900   | 2.737                         | 565,600           | 4.84                   |
| 2      | 7                             | 164,052/820,260   | 3.614                         | 787,100           | 4.59                   |
| 3      | 9                             | 210,924/1,054,620 | 4.324                         | 1,006,600         | 4.30                   |
| 4      | 11                            | 257,796/1,288,980 | 5.249                         | 1,241,600         | 4.23                   |
| 5      | 13.1 *                        | 307,360/1,536,800 | 6.078                         | 1,536,800         | 3.96                   |

* The amount of the sinking fund rate to complete all scheduled activities.

In this particular case, with the predefined set of renovation and modernization activities to choose from, the relative benefits drop with higher spending. This is due to the fact that with the highest budget, the most expensive modernization measures become possible—but they are incommensurably expensive in relation to the obtained increment of the value of the assessment of the building state. Of course, these observations are case-specific.

The second optimization approach was also applied to the example to indicate the cheapest renovation and modernization schedule that ensures reaching the desired building performance rating by the end of the planning horizon. Again, calculations were repeated with different assumptions on the target rating (Z) namely 5, 6, 7 and 8 points (options). Target ratings for the renovation and modernization measures in the consecutive periods of the planning horizon were set to be equal, as in Equation (22).

The results are shown in Table 9: the sequence variants selected for each unit of the planning horizon, their cost, increments of the building’s rating, and the benefit to cost ratio. Such analysis would be practical to inform condominium members on the financial consequences of briefer or deeper modernization of the building.
Table 9. The selection and the total cost of renovation and modernization measures for different targets of building performance rating.

| Option | $u$ = 1 | $u$ = 2 | $u$ = 3 | $u$ = 4 | $u$ = 5 | $P$ (Points) | $C$ (PLN) | $w$ |
|--------|---------|---------|---------|---------|---------|--------------|----------|-----|
| $O_u/Z_4$ (points) | 2.93/2.92 | 3.53/3.44 | 4.09/3.96 | 4.80/4.48 | 5.42/5.00 | 3.01 | 623,900 | 4.83 |
| $q_{a,i}$ | $q_{2,1}, q_{4,1}$ | $q_{2,2}, q_{1,1}, q_{3,2}$ | $q_{2,2}, q_{3,1}, q_{3,2}$ | $q_{1,1}$ | $q_{3,1}$ | $q_{3,1}$ |
| $C_u$ (PLN) | 50,600 | 64,000 | 136,100 | 181,000 | 192,200 | |
| $O_u/Z_4$ (points) | 3.14/3.12 | 3.94/3.84 | 4.80/4.56 | 5.57/5.28 | 6.39/6.00 | 3.99 | 871,600 | 4.58 |
| $q_{a,i}$ | $q_{2,1}, q_{4,2}, q_{3,3}$ | $q_{2,1}, q_{3,1}, q_{3,2}$ | $q_{1,1}, q_{2,2}$ | $q_{3,1}, q_{3,2}$ | $q_{3,1}$ | $q_{3,1}$ |
| $C_u$ (PLN) | 709,000 | 138,300 | 222,500 | 217,700 | 222,200 | |
| $O_u/Z_4$ (points) | 3.34/3.32 | 4.26/4.24 | 5.19/5.16 | 6.12/6.08 | 7.12/7.00 | 4.72 | 1,051,600 | 4.49 |
| $q_{a,i}$ | $q_{2,1}, q_{4,2}, q_{3,3}$ | $q_{2,1}, q_{3,1}, q_{3,2}$ | $q_{1,1}, q_{2,2}, q_{3,2}$ | $q_{1,1}, q_{3,3}$ | $q_{1,1}$ | $q_{1,1}$ |
| $C_u$ (PLN) | 84,600 | 219,600 | 235,000 | 234,200 | 278,200 | |
| $O_u/Z_4$ (points) | 3.53/3.52 | 4.65/4.64 | 5.90/5.76 | 7.08/6.88 | 8.21/8.00 | 5.81 | 1,401,600 | 4.15 |
| $q_{a,i}$ | $q_{2,1}, q_{4,2}, q_{3,3}$ | $q_{1,1}, q_{3,2}$ | $q_{3,3}, q_{3,4}, q_{3,2}$ | $q_{1,1}$ | $q_{3,3}$ | $q_{3,3}$ |
| $C_u$ (PLN) | 114,600 | 275,600 | 330,000 | 317,700 | 363,700 | |

6. Discussion and Conclusions

The proposed approach covers all stages of planning, starting from the performance assessment of the building, through the indication of potential interventions, to the selection and timing of the most advantageous repair, renewal and improvement activities. It addresses the multi-criteria character of building maintenance decisions. The model to select and schedule the activities may serve as a practical (i.e., simple) tool to assist the manager in the long-term maintenance planning for residential buildings in a particular decision environment (optimization of the scope of gradual improvements, spread in small portions over long time for budgetary reasons). It allows the planner to easily experiment with different settings, such as the criteria weights, the length of the planning horizon, or the budget to estimate the costs and benefits of selecting a particular scope of repair, renewal and improvement measures. In particular, such analysis may be crucial for justification for changes of the monthly sinking fund fee to be agreed with the condominium members. Compared with models presented in the literature and devoted to selecting technical measures to improve buildings, its unique feature is the approach to the constraints on sequential relationships between the measures and to their selection: it accounts for interdependence between the interventions to the building’s fabric that arise from their complementary character and the logic of works.

However, the proposed model is still raw and calls for refinement to produce plausible results. First, it was created for a specific situation: planning repair, renovation and improvement activities that can be proposed well ahead and can be spread arbitrarily over the planning horizon. This means it does not directly account for differences in the urgency of the activities. The decision-maker sets targets and a complete list of measures that enable reaching them, and then, using the model, consequently, selects the best measures to be executed year by year, improving the ratings at a steady rate. The only constraints in this selection out of a determined pool of activities are affordability and the logic of works. The first constraint is again specific—the money comes solely from the sinking fund fee accrued month by month in a steady rate agreed at the beginning of the planning horizon. Moreover, the model ignores the possibility to select options of activities (the same effect can be achieved by different technical measures and at different cost). In the future research, the authors intend to expand the model to enable considering activity options as well as different funding patterns, such as using loans for “bigger improvement projects” to be implemented quickly instead of using the painstakingly collected funds to conduct improvements in small steps over many years.
Second, the proposed optimization model is deterministic. It assumes that a complete information on the initial building performance levels is known and stays valid for the whole planning horizon. The optimal selection and schedule of activities assumes that the pool of activities is fixed (no extra activities are proposed after the list is closed). It is also assumed that the activity costs as well as their effects (increase in the building’s performance ratings), both estimated at the beginning of the planning horizon, stay the same regardless of the moment of conducting the activities. This way, the model produces solutions that are not robust against changes, and these are very likely over the long planning horizon of several years. Thus the natural direction of further work is to improve the model’s robustness: directly allow for the uncertainties.

Third, the model is too static: it does not account for deterioration of the building over the planning horizon. As the latter is intended to be long, ignoring deterioration processes is a serious deficiency. Therefore, a deterioration function needs to be introduced into the model, reducing the functional component’s or space’s rating period by period.

The fourth limitation of the model arises from the subjective character of most of the input (criteria weights $w_j$, criteria-wise performance ratings $o_{ij}$, and the expected impact of applying activities on the criteria-wise performance of the building $o_{a,i,j}$). This way, different experts or decision-makers are likely to produce different input for the analysis of the same building. It was decided that the performance criteria can be set at will in terms of their type, number, and relative importance to allow for a particular decision environment. Therefore, the subjectivity of the selection of criteria and their weights was intentional.

As for the measures of criteria values and the impact of the activities, they are proposed to be assessed by an expert in a six-point ordinal scale, and then re-scaled into “points” in a linear manner. Though it would be possible to find objective and exact measures for some criteria (like cubic meters of fresh water consumption per person for “water efficiency”, or the share of energy from renewable sources in the total energy consumption of a building for the criterion of “use of renewable energy sources”), the estimates of such values would be imprecise anyway—due to deciding on a particular measure of a criterion (where a number of measures can be used instead), simplified methods of their calculation (buildings are complex systems), and uncertainties related with the input for such calculations (like user behavior or workmanship errors). Some criteria, like aesthetics, have no precise measure anyway and are subjective by default. Therefore, subjectivity and even vagueness of input is considered inevitable, and this observation is shared by many authors (among others, [16,52,55,67,71,72]). Generalized measures of asset performance, expressed in similar scales, are commonly accepted in business applications for decision-making [73].

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Appendix A. Notations

Table A1. Indices.

| Symbol | Description |
|--------|-------------|
| $a = 1, 2, \ldots, A$ | sequence of activities (addressed for a particular functional component or functional space of the building) |
| $h = 1, 2, \ldots, H_a$ | activity sequence variant |
| $i = 1, 2, \ldots, I_a$ | activity (repair, renovation, or improvement) |
| $j = 1, 2, \ldots, m$ | criterion |
| $u = 1, 2, \ldots, U$ | unit of time (period of the planning horizon) |

Table A2. Sets and their elements.

| Symbol | Description |
|--------|-------------|
| $q_{a,i}$ | an activity addressed for a particular functional component or space of the building ($a$) |
| $v_{a,h}$ | a variant of activity sequence; it comprises $h$ activities addressed for a particular functional component or space of the building ($a$) connected by sequential relationships |
| $V$ | a set of all possible sequence variants of activities addressed for all functional components and functional spaces of the building, $V = V_1 \cup V_2 \ldots V_A$. |
| $V_a$ | a set of sequence variants addressed for a particular functional component or space of the building, $V_a = \{v_{a,1}, v_{a,2}, \ldots, v_{a,H_a}\}$ |
| $V_u$ | set of activity sequence variants available for selection at the unit of time $u$ |

Table A3. Parameters.

| Symbol | Description |
|--------|-------------|
| $B$ | money collected over one full period of the planning horizon |
| $c_{a,i}$ | cost of activity $i$ that belongs to sequence $a$ (value to be defined by an expert who proposes activities) |
| $d$ | usable floor area of apartments |
| $D$ | budget for the whole planning horizon |
| $g_{a,h,u}$ | binary element of the matrix of constraints preventing selection of more than one variant of sequence $a$ at period $u$ of the planning horizon and eliminating selected variants from choice available for the next period |
| $o$ | number of months of $i$th period of the planning horizon |
| $o_j$ | original rating of the building’s performance according to criterion $j$ (values to be defined by an expert) |
| $g_{a,i,j}$ | impact of activity $i$ that belongs to sequence $a$ on the building’s performance according to criterion $j$ (value to be defined by an expert who proposes activities) |
| $O$ | combined rating of the building’s performance (initial state) |
| $p_{a,i,j}$ | increment of the building’s performance rating according to criterion $j$ as the effect of activity $i$ that belongs to sequence $a$ |
| $s$ | fixed monthly rate of the fee towards the sinking fund, expressed in units of currency per unit of usable floor area |
| $w_j$ | weight of criterion $j$ (values to be defined by the decision-maker) |
| $z_j$ | the value of the building’s performance rating according to criterion $j$ on completion of all proposed activities |
| $Z$ | the assumed combined rating of the building’s performance expected to be reached by the end of the planning horizon (to be defined by the expert) |
| $Z_u$ | the assumed lowest acceptable rating of the building to be reached at period $u$ of the planning horizon |
### Table A4. Variables.

| Symbol   | Description                                                                 |
|----------|------------------------------------------------------------------------------|
| $B_u$    | budget available for spending at the beginning of period $u$ except of the first period \((u = 2, 3, \ldots, U)\) (difference between funds collected so far and funds spent on variants selected for previous periods) |
| $c_{a,h}$| cost of variants $h$ of sequence $a$ selected for execution                   |
| $C$      | total cost of all activity sequence variants selected within the whole planning horizon |
| $C_u$    | cost of activity sequence variants selected for execution at period $u$       |
| $O_u$    | combined rating of the building’s performance at period $u$ of the planning horizon (effect of selected activity sequence variants) |
| $p_{a,u,j}$| increment of the building’s performance rating according to criterion $j$ as the effect of selecting variant $h$ of sequence $a$ |
| $P$      | increment of the combined building’s performance rating in the effect of all activity sequence variants selected within the whole planning horizon |
| $P_j$    | increment of the building’s performance rating according to criterion $j$ in the effect of all activity sequence variants selected within the whole planning horizon |
| $P_u$    | increment of the combined building’s performance rating in the effect of all activity sequence variants selected for period $u$ |
| $P_{j,u}$| increment of the building’s performance rating according to criterion $j$ in the effect of activity sequence variants selected for period $u$ |
| $w$      | benefit to cost ratio achieved by the end of the planning horizon (measuring the quality of solution) |
| $w_u$    | benefit to cost ratio achieved at period $u$ (measuring the quality of solution) |
| $x_{a,h,u}$| binary variable modeling the decision on variant selection |

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