Article

Optimization of Ecological and Economic Aspects of the Construction Schedule with the Use of Metaheuristic Algorithms and Artificial Intelligence

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Abstract: Construction projects play a vital role in shaping the built environment and have a significant impact on the natural environment and economies around the world. The decisions made during the planning and execution stages of a project can have long-lasting implications for its environmental and economic performance. It is, therefore, essential to consider these factors carefully and make informed decisions that align with sustainable development goals. One way to achieve this is by using metaheuristic algorithms and artificial intelligence tools to optimize and reconcile sustainable development and economic parameters in construction project scheduling. By doing so, one can improve the overall efficiency and effectiveness of the construction process, while also contributing to the well-being of the communities in which these projects are located. In this article, authors propose a new ecological indicator that can be used to evaluate the sustainability of construction projects and provide a case study to illustrate its application. The authors' findings and conclusions highlight the importance of using advanced analytical techniques to optimize the sustainability and economic performance of construction projects and suggest potential avenues for future research.

Keywords: scheduling; construction projects; optimization; value engineering; metaheuristic algorithms; artificial intelligence

1. Introduction

Construction projects are very often complex, and their lifespan is exceptionally long compared to the projects of most other industries [1–7]. If one adds to this the amount of resources they consume and the CO_2 they produce [8], a picture emerges of a project type which has a huge impact on its stakeholders (including clients). Moreover, this influence will be exerted for decades. That is why it is so important to meet the conditions of sustainable development when designing construction processes.

Decisions made at the stage of planning construction projects are very important because it is at this stage that there are the greatest opportunities to introduce savings and carry out optimization processes. Such actions can either significantly reduce costs or construction time or increase the functional potential or value of the facility. There are several key parameters that must be considered during the lifecycle of a construction project, including structural safety, fire safety, usability, acoustic comfort, visual comfort, durability, energy efficiency, and sustainability. All of these factors are important in ensuring the overall success and performance of the project [9–11]. Yet, they are not considered in most studies.

One of the crucial tools that helps in building a construction project optimization model is a construction schedule. It serves not only the purpose of planning and controlling the construction process (by presenting the relationships between activities and their durations) but also allows for balancing resources, cash flow analysis, or preparation of various variants subject to optimization [12–14].

Optimizing construction schedules can be challenging due to the complexity of the problem, which belongs to the class of NP-difficult problems. This means that the time required to find a solution increases exponentially as the size of the problem increases [12,14–16]. In the face of such a problem, many scientific works and analyzes focus on researching and proposing methods for solving such tasks. Most of these articles state that metaheuristic algorithms are the most suitable tools for dealing with scheduling problems. However, in order to use such methods, it is necessary to build a correct model that represents real-life projects in the best possible way. The most common scheduling problems include RCPSP (Resource-Constrained Project Scheduling Problem) and its variations [14,16–19]. However, there are not enough solutions that take into account aspects such as value, functionality, or other requirements expected by clients. This article presents an approach to eliminate the above shortcomings.

The presented research addresses the issue of optimizing construction schedules while considering multiple factors that are crucial for the success and performance of a construction project. These factors are often not considered in traditional optimization methods, but the proposed approach in the study incorporates them in order to create a more comprehensive and realistic model of construction projects. The new approach—the use of metaheuristic algorithms and artificial intelligence tools—also allows for a more efficient and effective solution to the complex problem of scheduling construction projects, which can significantly improve the outcomes of these projects. Additionally, the proposed approach includes a novel sustainable ecological indicator that allows for the selection of a schedule that meets both the requirements of clients and the requirements of sustainable development. The flexibility of the proposed solution also allows for the potential use of various algorithms and calculation tools in the future, further expanding its scope and applicability. Overall, this study is important as it offers a new and improved approach to optimizing construction schedules that can lead to better and more sustainable outcomes for these projects.

2. Materials and Methods
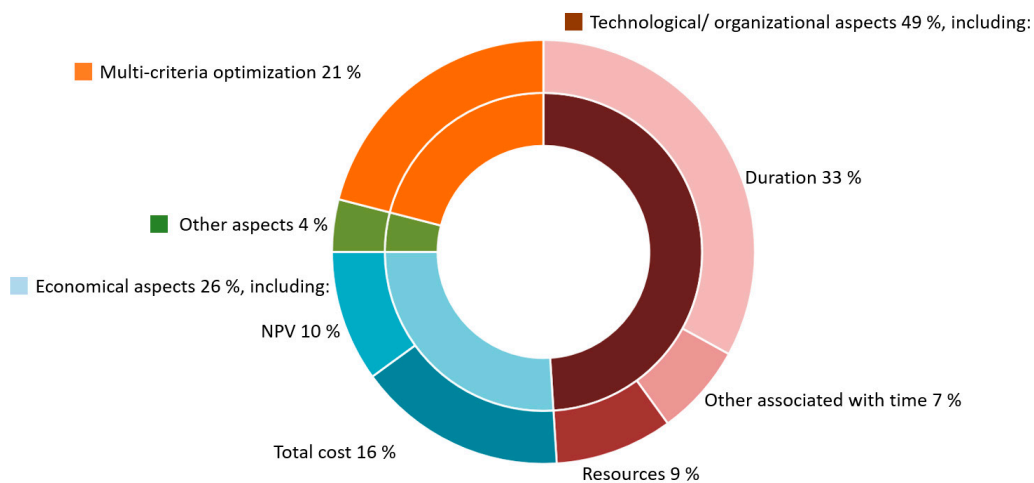
2.1. Schedule Optimization Models

In the literature, authors often use a descriptive scheme classifying scheduling problems. They are divided according to the type of constraints taken into account and the scope of decisions made. One can distinguish here [14,16]:

- the problem of project scheduling without taking into account resource constraints (Unconstrained Project Scheduling Problem, UPSP),
- problem of project scheduling taking into account resource constraints (Resource-Constrained Project Scheduling Problem, RCPSP),
- the problem of project scheduling, taking into account resource constraints and different modes (variants/ways) of performing activities (Multi-Mode Resource Constrained Project Scheduling Problem, MMRCPSP, or MRCPSP).

The extensive studies on optimization models can be found in [14–20].

According to the studies on RCPSP [20], it was noted that in the 216 papers devoted to this type of problem, as many as 33% of them focused on minimizing the duration. The detailed percentage of the optimization criteria is shown in Figure 1.

According to the analysis carried out by the authors (106 articles dated from 1982 to 2019), this distribution for MRCPSP looks as follows—Figure 2. The dominance of the project duration criterion is even more visible—57% of works.

Figure 1. Approximate frequency of schedule optimization according to criteria—RCPSP—modified on a base of [20].
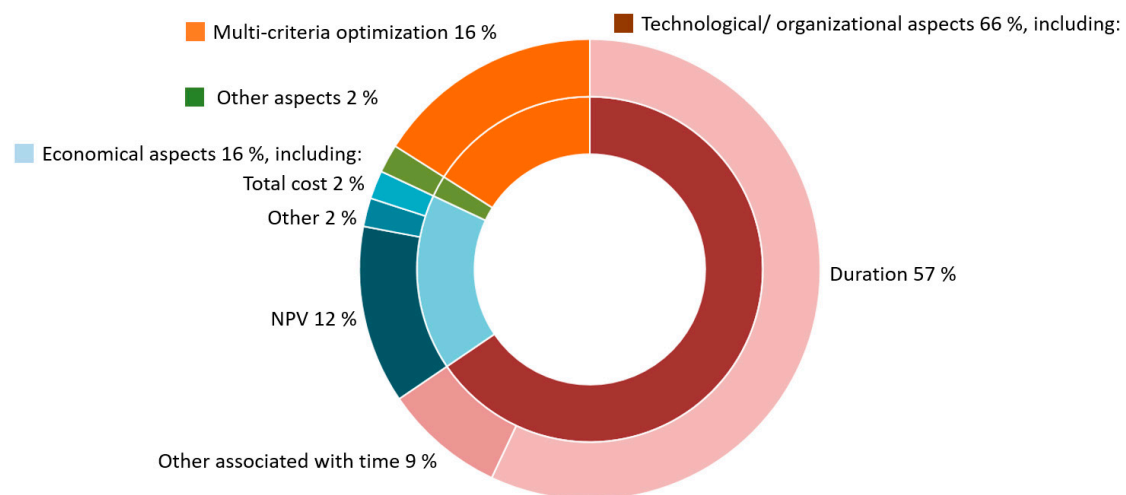
Figure 2. Approximate frequency of schedule optimization according to criteria—MRCPSP.

As can be seen in Figures 1 and 2, most of the articles are focused on the approach of optimizing the duration of projects. However, according to the authors, such an approach does not reflect the needs of construction companies. This phenomenon may be related to the fact that a relatively small percentage of research is focused on the construction industry—only about 16% of the examined papers (however, it should be noted that efforts were made to find as many works related to construction as possible, so if one would analyze all the works on the subject of MRCPSP, this result would be much lower; additionally, it is worth emphasizing that some of these works refer to construction only in the title or a laconic statement that their results can be used in the construction industry).

Another reason behind this phenomenon might be that the cited studies often use popular databases (e.g., PSPLIB [21], or MMLIB [22]), which do not take into account aspects specific to construction projects (since their primary goal is to compare the effectiveness of algorithms).

2.2. Sustainability Value Index

Sustainable indicators in the construction industry refer to metrics and measures that are used to assess the environmental, social, and economic impacts of a construction project. These indicators help to ensure that the project is aligned with principles of sustainable development, which prioritize meeting the needs of the present without compromising the ability of future generations to meet their own needs. Sustainable indicators in the

construction industry can include metrics such as energy and water efficiency, greenhouse gas emissions, materials reuse and recycling, and impacts on local communities. The use of sustainable indicators can help construction companies to make more informed decisions about the design and execution of their projects and can also help to improve the overall sustainability performance of the industry as a whole [23–25].

There are many sustainability indices and indicators. State of the art articles on this topic include [26,27], but none of them have been used so far in creating construction schedules. The combination of the value profile methodology [15,28] with the focus on ecological issues allows for a new approach to construction project scheduling.

The Sustainability Value Index (SVI) is a proprietary indicator developed by the authors based on previous research [15,28]. It is based on the concept of value management [29] and popular factors proposed by renowned organizations (i.e., the European Economic Community (EEC), Conseil International du Bâtiment (CIB), the International Organization for Standardization (ISO), and the United Nations (UN)) [28] with the emphasis put on the sustainability factors of the construction objects' elements/actions/works. Unlike the previously used sets of factors, SVI puts emphasis on aspects strictly related to sustainability (e.g., energy saving, greenhouse gas emissions, the economics of operating costs, and recycling potential), and users' health and comfort. The basic SVI factors and sub-factors are listed below in Table 1. However, the list can be modified by users in order to best satisfy their needs.

Table 1. Sustainability value index—factors and sub-factors.

	1.1. Recycling and utilization
	1.2. Greenhouse gas emissions
1. Sustainability	1.3. Economics (operational costs)
	1.4. Energy saving
	1.5. Durability
	2.1. Air quality
2. User health and safety	2.2. Water supply and other utilities
	2.3. Waste disposal
	3.1. Acoustic comfort
3. User comfort	3.2. Lighting (visual comfort)
	3.3. Hygrothermal comfort
	3.4. Serviceability

SVI values can be obtained based on experts' opinions, and almost any method of multi-criteria assessment of variants. In this case, the authors used previously proposed method described in [15].

According to the method, in the first step, experts evaluate individual criteria or factors. The results of the analysis are normalized by ensuring that the sum of the weights is equal to 1. It is worth emphasizing that not every element/activity must be assessed in terms of each sub-factor. For example, structural elements covered with plaster and paint at a later stage of construction should not be assessed in terms of appearance because they are not visible after the completion of the works. However, for the validity of the method, all sub-factors within the sustainability factors category must be assessed.

The normalization results in creation of a vector **Q** (the weights of the individual factors used in the calculation of the SVI) (Equation (1)) [15]:

$$Q = [q_j] \qquad \sum_{j=1}^{n} q_j = 1. \qquad (1)$$

All criteria rated above 0 are then evaluated by experts. It is crucial to properly quantify the results (if there is such a need). The matrix **P** is formed, which is later normalized $\overline{\mathbf{P}}$ according to the equation (19) [15]:

$$\overline{p}_{ij} = \frac{p_{ij}}{\sqrt{\sum_{i=1}^{m} p_{ij}^2}} \qquad i = \overline{1,m}, \qquad j = \overline{1,n}, \qquad (2)$$

where the number of criteria (sub-factors) is represented by n, and the number of evaluated variants of construction solutions is represented by m.

In order to proceed, a normalized **SVI** rating matrix is calculated. This step ensures that the importance of individual sub-factors is taken into account [15]:

$$SVI_{ij} = \overline{p}_{ij} \cdot q_j \qquad i = \overline{1,m}, \qquad j = \overline{1,n}. \qquad (3)$$

The sustainability value index score of the individual variants SVI_i is calculated by summing up components in each row of the matrix:

$$SVI_i = \sum_{j=1}^{n} SVI_{ij} \qquad i = \overline{1,m}, \qquad j = \overline{1,n}. \qquad (4)$$

The linear maximum standardization is used to calculate the *SVI* values for all variants of all analyzed activities in the schedule. This means that the value for the best variant of a given activity is equal to 1. The procedure for this is described in more detail in the case study, which can be found in Section 3 of this paper.

2.3. Optimization Model

As described in the previous sections, for a construction project to be successful, appropriate analyzes must be undertaken. The authors believe that it is important to analyze all of the factors that contribute to the success of a project at the same time. Such factors include, among others, the uniqueness of the construction market, the method of organization and management of works, contractual issues, local conditions, technological and organizational dependencies, materials and solutions used, etc.

The authors have already presented the appropriate models and tools in their previous works [12,15,28]. In this article, the tools and models used for construction project analysis have been modified to incorporate sustainable development requirements and the needs of construction companies. The modified model uses tried-and-tested indicators for evaluating construction projects: Net Present Value (NPV), limiting maximum monthly cash flow (CF) [4,12,14,28].

The model used for optimization is common for the MRCPS problems (Multi-Mode Resource-Constrained Project Scheduling Problem) [28,30–32]. However, in this article, authors introduce some changes in order to better suit the sustainable construction projects. The R^{ρ} and R^{ν} are sets of (respectively) r^{ρ} renewable, and r^{ν} non-renewable resource types. And their availability is defined as a_k^{ρ}, $k \in R^{\rho}$ and a_l^{ν}, $l \in R^{\nu}$. If used, each activity of the construction schedule j consumes r_{jkt}^{ρ} renewable resources and r_{jlt}^{ν} non-renewable resources on every working day t.

What is characteristic of MRCPS are modes M_j (alternative variants of scheduled activities) in which an activity j, $m \in M_j = \{1, \ldots, |M_j|\}$ can be performed. The duration of activity j performed in the m_j mode is equal to d_{jm}. Each of the m variants requires r_{jmk}^{ρ} renewable and r_{jml}^{ν} non-renewable resources. The model also includes a binary variable x_{jmt}, taking the value 1, if the activity j performed in the mode $m \in M_j = \{1, \ldots, |M_j|\}$ it is finished at the end of the t period of time. Otherwise $x_{jmt} = 0$. EF_j and LF_j are respectively the earliest (early) and late dates for completing the activity j [28].

The proprietary, modified objective function (O_F) includes daily penalties for delay of construction works and is designed to maximize parameters such as Net Present Value (NPV) and Sustainability Value Index (SVI)—Equation (5). With $NPV_r\, o_1 + SVI_r\, o_2$ serving as an objective part of the function and $-CF\, p_1 - R\, p_2 - T\, p_3 - dur\, p_4$ as constraints (penalties). $\sum_1^n o_i = 1$, while p_i values (penalty weights) are set significantly higher to ensure that any solution that does not meet the restrictions is eliminated. As NPV and SVI values are hard to compare, both were normalized using weights o_i and the calculation of relative values.

$$\max O_F:$$

$$O_F = NPV_r\, o_1 + SVI_r\, o_2 - CF\, p_1 - R\, p_2 - T\, p_3 - dur\, p_4 \tag{5}$$

$$NPV_r = \frac{\left(\begin{array}{c} \sum_{h=1}^{H+\Delta} \frac{P_h - IC_h}{(1+\alpha)^{h\,TI}} - \sum_{t'=dur_{pen}+1}^{LF_j} \frac{pen_{dur}}{(1+\alpha)^{t'}} - \\ - \sum_{h=1}^{H} \sum_{m=1}^{|M_j|} \sum_{j=1}^{n} \sum_{q=\max\{t,EF_j\}}^{\min\{t+d_{jm}-1,LF_j\}} \frac{CF_{jm}}{d_{jm}\,(1+\alpha)^t}\, x_{jmq} \end{array} \right) - NPV_{min}}{NPV_{max} - NPV_{min}} \tag{6}$$

$$H = \left\lceil \frac{LF_j}{TI} \right\rceil, \quad t = 1, \dots, H$$

$$SVI_r = \frac{\left(\sum_{m=1}^{|M_j|} \sum_{j=1}^{n} \sum_{t=EF_j}^{LF_j} \frac{f_{jm}\, x_{jmt}}{J} \right) - SVI_{min}}{SVI_{max} - SVI_{min}} \tag{7}$$

$$CF = \begin{cases} 1 \text{ if } \max_t \left\{ \sum_{m=1}^{|M_j|} \sum_{j=1}^{n} \sum_{q=\max\{t,EF_j\}}^{\min\{t+d_{jm}-1,LF_j\}} \frac{CF_{jm}}{d_{jm}\,(1+\alpha)^t}\, x_{jmq} \right\} > CF_{max} \\ 0 \text{ in other cases} \end{cases} \tag{8}$$

$$R = \begin{cases} 0 \text{ if } \sum_{j=1}^{n} \sum_{m=1}^{|M_j|} \sum_{q=\max\{t,EF_j\}}^{\min\{t+d_{jm}-1,LF_j\}} r_{jmk}^{\rho}\, x_{jmq} \leq a_k^{\rho} \\ \quad \text{ and } \sum_{j=1}^{n} \sum_{m=1}^{|M_j|} \sum_{t=EF_j}^{LF_j} r_{jml}^{v}\, x_{jmt} \leq a_l^{v} \\ 1 \text{ in other cases} \end{cases} \tag{9}$$

$$k = 1, \dots, r^{\rho}; \quad l = 1, \dots, r^{v}; \quad t = 1, \dots, H$$

$$T = \begin{cases} 0 \text{ if variants are consistent} \\ 1 \text{ in other cases} \end{cases} \tag{10}$$

$$dur = \begin{cases} 0 \text{ if } \sum_{t=EF_j}^{LF_{n+1}} t\, x_{n+1,m,t} \leq D \\ 1 \text{ in other cases} \end{cases} \tag{11}$$

$$j = 0, \dots, n+1$$

$$\sum_{m=1}^{|M_j|} \sum_{t=EF_j}^{LF_j} x_{jmt} = 1, \quad j = 0, \dots, n+1 \tag{12}$$

$$\sum_{m=1}^{|M_j|} \sum_{t=EF_i}^{LF_i} t\, x_{imt} \leq \sum_{m=1}^{|M_j|} \sum_{t=EF_j}^{LF_j} x_{jmt}\,(t - d_{jm}), \quad \forall (i,j) \in P \tag{13}$$

$$x_{jmt} \in \{0,1\}, \quad j = 0, \dots, n+1, \quad m \in M_j, \quad t = EF_j, \dots, LF_j \tag{14}$$

where:

- Equation (6)—this part of the objective function is focused on optimizing the relative NPV value, with NPV_{max} and NPV_{min} being (respectively) the maximum and minimum NPV values found during UPS phase. The NPV is a measure of the profitability of the project, taking into account the time value of money. By optimizing this value, the objective function aims to improve the financial performance of the project.

- P_h represents the profits for the period ending on h, $h = 1, 2, \ldots, H$.
- IC_h represents the indirect costs for the same period h, $h = 1, 2, \ldots, H$.
- *TI* is a fixed time interval, in this case, one working month expressed in days.
- Δ is a variable used to model payment delays expressed in working days ε, and calculated as $\Delta = \lceil \varepsilon / TI \rceil$.
- CF_{jm} is cash flow of activity j when performed in mode m.
- α is the interest rate (used for NPV calculation).
- dur_{pen} represents a date after which contractual penalties pen_{dur} are being charged.
- Equation (7)—this part of the objective function is focused on optimizing the relative SVI value, with SVI_{max} and SVI_{min} being (respectively) the maximum and minimum SVI values found during the UPS phase. The SVI is a measure of the sustainability of a construction project, taking into account various factors such as energy efficiency, durability, and environmental impact.
- f_{jm} is the SVI value for activity j performed in mode m.
- Equation (8) is the penalty component ensuring that each month the cash flow does not exceed the set limit CF_{max}.
- Equation (9) is the penalty component corresponding to the limits of renewable and non-renewable (and also doubly constrained) resources.
- Equation (10) introduces a binary variable, T, which ensures that the construction is carried out in a technologically consistent manner. This means that the selection of a particular mode for some activities may exclude certain modes for other activities.
- Equation (11) introduces a deadline for construction completion D, $dur_{pen} \leq D$.
- Equation (12) requires that each activity is completed only once and in a single defined mode.
- Equation (13) describes the relations between tasks.
- Equation (14) models binary decision variables.

2.4. Optimization Procedure

The optimization procedure uses a metaheuristic algorithm (tabu search) and artificial intelligence (AI). The AMTANN (Approach for MRCPSP Transformation with the use of Artificial Neural Networks) procedure [16,28] has been adapted and modified in order to get the best results in terms of NPV and SVI. The modified procedure for optimizing construction schedules is presented in a visual diagram, known as a block diagram. This diagram, referred to as Figure 3, illustrates the various steps involved in the process, including the input of data, the application of algorithms and models, and the output of the optimized schedule. By following this procedure, it is possible to identify the most efficient and sustainable options for completing a construction project, taking into account various factors such as profitability, environmental impact, and technological constraints. The AMTANN principles are described in the authors' previous papers [16,28].

In the first step of the procedure, the input construction schedule is introduced. Then, the original versions of the activities and the schedule are analyzed in terms of SVI. At this stage, alternative variants of activities in the schedule are created, which are then examined and assessed by experts in order to determine the duration, costs, and SVI grades.

After introducing additional variants to the model along with their parameters, the multi-mode version of the schedule is prepared. This version is optimized without restrictions (UPS—Unconstrained Project Scheduling). The extreme values of NPV and SVI parameters (min and max) are examined. This step is crucial to determine the relative values of these parameters (Equations (6) and (7)).
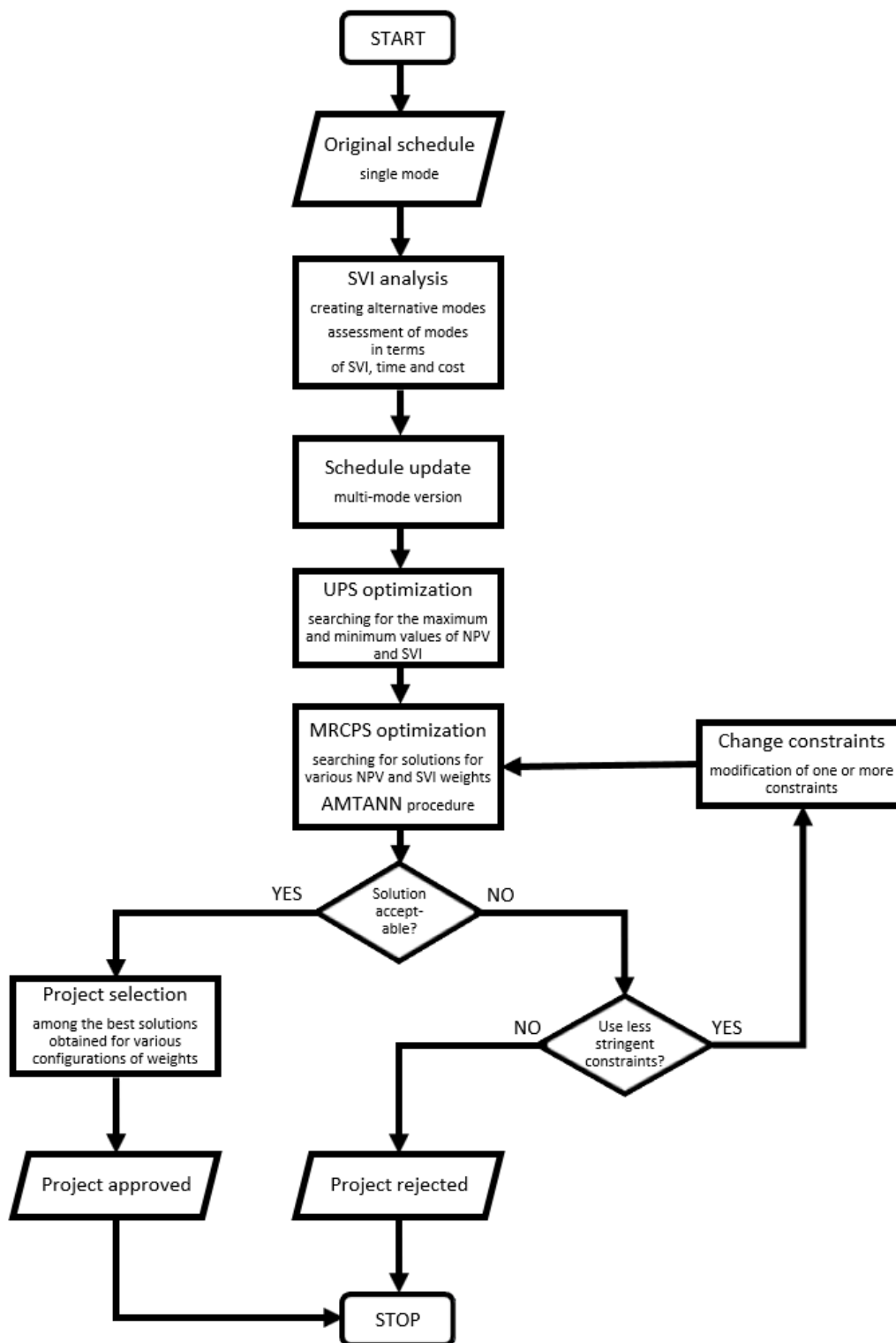
Figure 3. A diagram illustrating the steps involved in the optimization procedure.

After meeting all the above requirements, MRCPS optimization is performed. It is recommended to explore solutions using the AMTANN procedure for different sets of weights. The obtained solutions are later analyzed.

If the calculated results do not meet the requirements of the decision makers, it is possible to relax the requirements and repeat the MRCPS optimization. In extreme cases, a decision should be made to completely reject the project, as it may not meet the requirements of sustainable development or the economic needs of the client. By following

this approach, it is possible to minimize losses for the enterprise that may result from the implementation of a wrong project [28].

If the results of the optimization are satisfactory, the final variant of the schedule can be selected. If acceptable solutions are obtained for different configurations of o_i weights, it is necessary to choose only one of these solutions. One way to do this is to consider only Pareto optimal solutions, which are solutions that cannot be improved in one aspect without worsening another aspect. The final decision can be supported by using a multi-criteria decision-making method such as AHP (Analytic Hierarchy Process), ELECTRE (ELimination Et Choix Traduisant la REalité), or TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) [33].

The detailed steps of the procedure are demonstrated with a real-life example in Section 3.

3. Results

3.1. Case Study

3.1.1. Basic Information

The example shows a simple project. The analyzed object is a typical single-family house. It is based on the model object 1110-103 (1155) (including variants) published in the Bulletins of Building Prices (BCO) in Poland [34]. It is a detached single-family house with the following approximate parameters:

- building area: 160.60 m^2,
- usable area: 153.20 m^2,
- area of the garage and utility part: 38.80 m^2,
- net area: 220.00 m^2,
- gross volume: 650.00 m^3,
- number of above-ground levels: 1 + usable attic,
- basement: none,
- heating: local,
- the groundwater level below the foundations.

Utility program: single-family residential building with an attic: 5 rooms + kitchen with dining room + garage + boiler room + terrace.

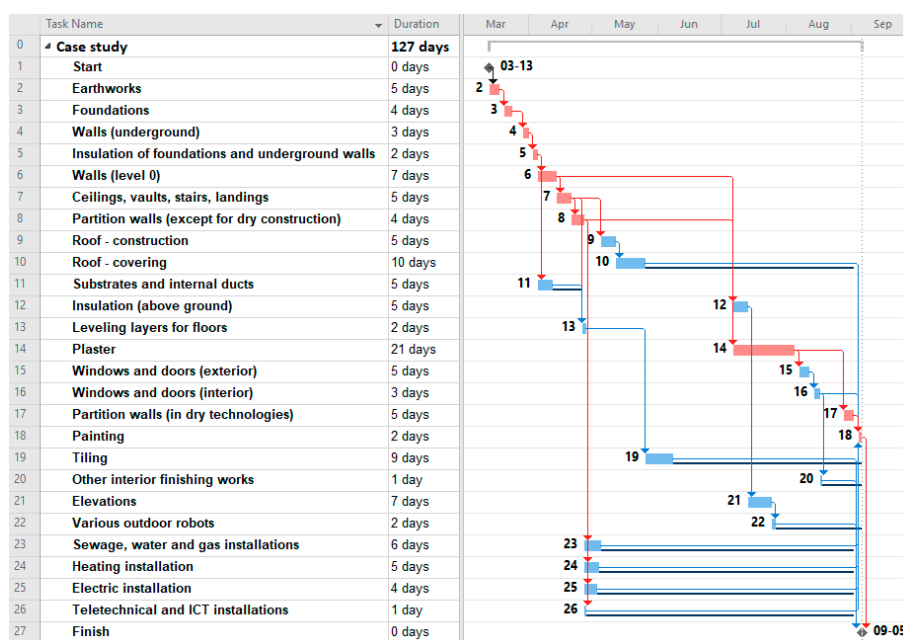The initial schedule is presented in Figure 4.

Figure 4. Construction project—initial schedule (presented in MS Project).

3.1.2. SVI Analysis

To optimize the construction schedule, a table of variants was created that outlines the different methods that were evaluated. This table (referred to as Table 2) was based on the original schedule and the specific parameters of the house being constructed. The planners used historical data to estimate the duration of each activity and the required technological breaks. By comparing the various methods, it is possible to identify the most efficient and sustainable options for completing the construction project. The table of variants provides a clear overview of the different options that were considered and allows for the easy comparison of their performance. It was assumed that the contractor was able to engage one working brigade for the whole period of construction, and subcontractors would be hired for specialist works (gas, electrical installations, etc.). The direct costs related to the implementation of individual activities were determined based on publicly available price catalogs and historical data of the company implementing the project. The SVI values were determined based on the procedure proposed above (below, the value assessment is presented on the example of a floor). The assessment of individual variants is presented in Table 3.

Table 2. A summary of the characteristics of the different variants being evaluated.

	Task	Variant 1	Variant 2	Variant 3	Variant 4	Variant 5
ID	Name	Description	Description	Description	Description	Description
1	Start	-	-	-	-	-
2	Earthworks	excavation (soil category III, groundwater level below the foundation level)	-	-	-	-
3	Foundations	monolithic, reinforced concrete	concrete blocks	brick	-	-
4	Walls (underground)	concrete blocks panels in layers and solid bricks with polystyrene thermal insulation	concrete blocks panels in layers and solid bricks with polystyrene thermal insulation; from the ground level, a pressure layer made of full clinker brick *	lime-sand blocks with thermal insulation made of mineral wool	-	-
5	Insulation of foundations and underground walls	anti-moisture (bitumen)	foil	-	-	-
6	Walls (level 0)	external: layered with checkered and cellular concrete and polystyrene tiles, internal structural: solid brick; binders and columns: monolithic—reinforced concrete	external: layered with checkerboard and polystyrene, with saturated wood filled with full construction brick ("timber framing"); internal structural: full brick; binders and columns: monolithic—reinforced concrete **	external: layered with concrete blocks and polystyrene, with saturated wood filled with full construction brick, ("timber framing"); internal structural: full brick; binders and columns: monolithic—reinforced concrete *	external: SILKA and Styrofoam internal structural: SILKA; binders and columns: monolithic—reinforced concrete	external: Porotherm I Styrofoam internal structural: Porotherm; binders and columns: monolithic—reinforced concrete

Table 2. *Cont.*

	Task	Variant 1	Variant 2	Variant 3	Variant 4	Variant 5
ID	Name	Description	Description	Description	Description	Description
7	Ceilings, vaults, stairs, landings	Teriva ceilings; monolithic reinforced concrete stairs	Smart ceilings; monolithic reinforced concrete stairs	ACKERMAN ceilings; monolithic reinforced concrete stairs	YTONG ceilings; monolithic reinforced concrete stairs	Filigran ceilings; monolithic reinforced concrete stairs
8	Partition walls (except for dry construction)	perforated brick ***	Silka ***	Porotherm ***	solbet (all) ****	ytong (all) ****
9	Roof—construction	wooden truss	-	-	-	-
10	Roof—covering	galvanized trapezoidal sheet; insulation: mineral wool	ceramic tile; insulation: mineral wool	bitumen tile; insulation: mineral wool; sheet metal finishes	-	-
11	Substrates and internal ducts	standard technology	-	-	-	-
12	Insulation (above ground)	Styrofoam	mineral wool	plate polyurethane	-	-
13	Leveling layers for floors	lean concrete	-	-	-	-
14	Plaster	plasters: cat. II (30%) and III (70%); glazed tiles	as in variant 1, but higher standard of materials	-	-	-
15	Windows and doors (exterior)	double-glazed PVC windows, type VEKA (71%); solid board exterior doors (14%); wooden garage doors (15%)	as in variant 1, but higher standard of materials	-	-	-
16	Windows and doors (interior)	full or glazed	as in variant 1, but higher standard of materials	-	-	-
17	Partition walls (in dry technologies)	gypsum boards on a wooden grid ***	none ****	-	-	-
18	Painting	emulsion paint	as in variant 1, but higher standard of materials	as in variant 2, but higher standard of materials	-	-
19	Tiling	ground floor: on a concrete base with terracotta tiles (31%) and oak slats (18%); utility rooms: terrazzo (15%); attic: wooden, varnished (36%)	as in variant 1, but higher standard of materials	-	-	-
20	Other interior finishing works	locksmith and blacksmith elements; balustrades	as in variant 1, but higher standard of materials	-	-	-

Table 2. *Cont.*

	Task	Variant 1	Variant 2	Variant 3	Variant 4	Variant 5
ID	Name	Description	Description	Description	Description	Description
21	Elevations	speckled stucco, plinth faced with clinker tiles	stucco, plinth faced with clinker tiles + wooden structure painted with varnish ("timber framing") **	wooden structure painted with varnish ("timber framing") (here only the painting of the facade and the execution of external balustrades are included *	-	-
22	Various outdoor robots	a band around the building made of concrete paving slabs	as in variant 1, but higher standard of materials	-	-	-
23	Sewage, water and gas installations	plastic water supply and sewage system (polypropylene and PVC) with fittings, accessories and devices. Gas installation made of steel pipes with gas cooker and oven	as in variant 1, but higher standard of materials	-	-	-
24	Heating installation	central heating installation gas boiler, convector heaters	central heating installation local gas boiler, underfloor radiators	-	-	-
25	Electric installation	switchgear with accessories, incandescent luminaires, non-tensioned lightning protection system, earthing system, TN-S electric shock protection (surface-mounted)	-	-	-	-
26	Technical and ICT installations	bell, internet, and telephone installation	as in variant 1, but higher standard of materials	-	-	-
27	Finish	-	-	-	-	-

* Marked variants are consistent (condition T)—"timber framing" with clinker brick, i.e., if a variant marked with * is selected for any of the activities, other variants with the * symbol have to be selected in every other activity (if there is such possibility). ** Marked variants are consistent (condition T)—"timber framing" with full brick. *** Marked variants are consistent (condition T)—partial implementation of the partition walls in dry technologies was assumed. **** Marked variants are consistent (condition T)—construction of partition walls without the use of dry technologies was assumed.

Table 3. Assessment of variants.

ID	Variant 1				Variant 2				Variant 3				Variant 4				Variant 5			
	Cost [1000 USD]	Duration [Days]	SVI	Resources [Working Brigades]	Cost	Dur	SVI	Res	Cost	Dur	SVI	Res	Cost	Dur	SVI	Res	Cost	Dur	SVI	Res
1	0.0	0	1.00	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2	13.4	5	1.00	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3	9.4	4	1.00	1	13.0	3	0.95	1	13.7	3	0.86	1	-	-	-	-	-	-	-	-
4	25.5	3	1.00	1	37.6	4	0.95	1	23.6	4	0.95	1	-	-	-	-	-	-	-	-
5	5.2	2	0.98	1	7.9	3	1.00	1	-	-	-	-	-	-	-	-	-	-	-	-
6	58.3	7	1.00	1	75.9	9	0.72	1	117.1	10	0.70	1	39	5	1.00	1	39	5	0.89	1
7	28.2	5	0.80	1	33.0	1	0.98	1	36.9	8	0.82	1	49.3	1	1.00	1	30.9	2	0.97	1
8	10.8	4	0.55	1	11.6	3	0.60	1	9.6	2	0.62	1	11.9	4	0.89	1	14.4	4	1.00	1
9	30.7	5	1.00	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
10	42.2	10	1.00	1	31.4	6	0.86	1	22.2	4	0.58	1	-	-	-	-	-	-	-	-
11	8.1	5	1.00	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
12	28.7	5	0.74	1	31.3	2	0.98	1	28.7	6	1.00	1	-	-	-	-	-	-	-	-
13	4.6	2	1.00	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
14	26.3	21	0.87	1	38.3	25	1.00	1	-	-	-	-	-	-	-	-	-	-	-	-
15	23.6	5	0.92	1	31.6	5	1.00	1	-	-	-	-	-	-	-	-	-	-	-	-
16	5.9	3	0.86	1	8.1	4	1.00	1	-	-	-	-	-	-	-	-	-	-	-	-
17	7.7	5	1.00 *	1	0.0	0	1.00 *	0	-	-	-	-	-	-	-	-	-	-	-	-
18	3.4	2	0.89	1	5.3	3	0.93	1	8.5	4	1.00	1	-	-	-	-	-	-	-	-
19	31.8	9	0.84	1	46.7	11	1.00	1	-				-	-	-	-	-	-	-	-
20	1.5	1	0.97	1	2.3	1	1.00	1					-	-	-	-	-	-	-	-
21	15.3	7	0.95	1	16.2	8	0.76	1	2.5	1	1.00	1	-	-	-	-	-	-	-	-
22	4.0	2	0.94	1	5.3	2	1.00	1	-	-	-	-	-	-	-	-	-	-	-	-
23	21.0	6	0.72	0	30.0	7	1.00	0	-	-	-	-	-	-	-	-	-	-	-	-
24	39.9	5	0.56	0	71.1	5	1.00	0	-	-	-	-	-	-	-	-	-	-	-	-
25	20.1	4	1.00	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
26	0.4	1	0.93	0	0.9	1	1.00	0	-	-	-	-	-	-	-	-	-	-	-	-
27	0.0	0	1.00	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

* The evaluation of the SVI was carried out for task 8, therefore for task 17 the value of SVI = 1 is used for both cases.

The assessment of the SVI for activity 7 assumed the comparison of the Teriva ceiling (variant 1—V1), Smart (variant 2—V2), Ackerman (variant 3—V3), YTONG (variant 4—V4), and Filigran (variant 5—V5). The SVI calculations along with the assessment of the significance of individual criteria is presented below (Table 4).

Expert teams assessed each variant taking into account each criterion. Some of the criteria could not be assessed (e.g., ceilings will be covered and cannot be assessed in terms of visual comfort). After analyzing and comparing the different variants, the values were normalized to create a vector of weights **Q** (Table 5). Normalization is a mathematical process that scales the values to a specific range, in this case, ensuring that the sum of the weights is equal to 1. The vector of weights, **Q**, represents the relative importance of each variant and is used in the optimization process to identify the most efficient and sustainable options for completing the construction project.

Table 4. Assessment of criteria and variants (evaluation matrix **P**)—task 7-ceilings.

		Criteria Score	V1	V2	V3	V4	V5
1. Sustainability	1.1. Recycling and utilization	2	4	5	4	5	3
	1.2. Greenhouse gas emissions	5	4	5	4	5	5
	1.3. Economics (operational costs)	10	4	5	4	5	5
	1.4. Energy saving	8	3	3	3	5	3
	1.5. Durability	10	4	5	4	5	5
2. User health and safety	2.1. Air quality	2	3	5	3	5	5
	2.2. Water supply and other utilities	n/a	n/a	n/a	n/a	n/a	n/a
	2.3. Waste disposal	n/a	n/a	n/a	n/a	n/a	n/a
3. User comfort	3.1. Acoustic comfort—Rw (dB)	3	48	54	49	40	53
	3.2. Lighting (visual comfort)	n/a	n/a	n/a	n/a	n/a	n/a
	3.3. Hygrothermal comfort	2	3	4	3	3	5
	3.4. Serviceability	2	3	4	5	2	4

Table 5. Vector of weights **Q**—illustrative representation.

Criterion	Weight
1.1 Recycling and utilization	0.045455
1.2 Greenhouse gas emissions	0.113636
1.3 Economics (operational costs)	0.227273
1.4 Energy saving	0.181818
1.5 Durability	0.227273
2.1 Air quality	0.045455
2.2 Water supply and other utilities	0
2.3 Waste disposal	0
3.1 Acoustic comfort	0.068182
3.2 Visual comfort (lighting)	0
3.3 Hygrothermal comfort	0.045455
3.4 Serviceability	0.045455

In the next step a normalized evaluation matrix $\bar{\mathbf{P}}$ with scores is calculated—Table 6.

Table 6. Normalized evaluation matrix $\bar{\mathbf{P}}$—illustrative representation.

	1.1	1.2	1.3	1.4	1.5	2.1	2.2	2.3	3.1	3.2	3.3	3.4
V1	0.419	0.387	0.387	0.384	0.387	0.311	0.447	0.447	0.431	0.447	0.364	0.359
V2	0.524	0.483	0.483	0.384	0.483	0.518	0.447	0.447	0.539	0.447	0.485	0.478
V3	0.419	0.387	0.387	0.384	0.387	0.311	0.447	0.447	0.431	0.447	0.364	0.598
V4	0.524	0.483	0.483	0.64	0.483	0.518	0.447	0.447	0.216	0.447	0.364	0.239
V5	0.314	0.483	0.483	0.384	0.483	0.518	0.447	0.447	0.539	0.447	0.606	0.478

A matrix of normalized **SVI** ratings is calculated, taking into account the relative importance of the individual factors that contribute to the value of the construction project (Table 7).

Table 7. Assessment matrix **SVI**—illustrative representation.

	1.1	1.2	1.3	1.4	1.5	2.1	2.2	2.3	3.1	3.2	3.3	3.4
V1	0.839	1.933	3.867	3.073	3.867	0.622	0	0	1.294	0	0.728	0.717
V2	1.048	2.417	4.834	3.073	4.834	1.037	0	0	1.617	0	0.97	0.956
V3	0.839	1.933	3.867	3.073	3.867	0.622	0	0	1.294	0	0.728	1.195
V4	1.048	2.417	4.834	5.121	4.834	1.037	0	0	0.647	0	0.728	0.478
V5	0.629	2.417	4.834	3.073	4.834	1.037	0	0	1.617	0	1.213	0.956

The final evaluation of each variant in terms of SVI (sustainability value index) was obtained by summing and standardizing the values. The results are presented in Table 8.

Table 8. SVI assessment of ceiling variants for activity 7 of the schedule.

Variant	SVI Score
V1—Teriva	0.801
V2—Smart	0.983
V3—ACKERMAN	0.824
V4—YTONG	1.000
V5—Filigran	0.975

3.1.3. Updating the Schedule

After performing an SVI analysis, the original schedule was updated with additional details such as the durations of each activity, the resources required, and the technological constraints (T). In addition, calculated SVI values were introduced, and the links between tasks were updated so that, depending on the selected mode, the successor starts with the appropriate delay. It was necessary to take into account the appropriate technological breaks, e.g., the execution of block-ribbed ceilings forced a break before commencing the works above them, while the YTONG ceiling did not require such a break. The schedule was also updated with data on the contractual deadline—155 days. The model includes indirect costs. Indirect costs are expenses that are not directly related to the production of goods or services but are still necessary for the operation of a business. In the context of a construction project, indirect costs may include things like rent, insurance, utilities, and administrative expenses. These costs are typically not directly associated with any specific activity or task but are still important to consider when evaluating the overall profitability of the project. By including indirect costs in the analysis, it is possible to get a more accurate picture of the financial performance of the project and make informed decisions about its success [16].

3.1.4. UPS Optimization

The UPS optimization was performed with the use of a metaheuristic algorithm included in commercial software (OptQuest® Engine, OptTek Systems, Inc.'s). Maximum and minimum values of *NPV* and *SVI* were calculated: NPV_{max}, NPV_{min}, SVI_{max}, and SVI_{min}. The results of the analysis are presented in Table 9. The variables analyzed in this table are the different modes of execution of the works (ranging from 1 to 5 possible options), additional links between tasks (binary variables), allowing for a different ordering of tasks, and delays for subcontracted works (from 104 to 110 possible options, depending on activities).

Table 9. UPS optimization—extreme values of *NPV*, and *SVI*.

| Indicator	Value
NPV_{max}	32 308 USD
NPV_{min}	20 925 USD
SVI_{max}	1.000
SVI_{min}	0.858

3.1.5. MRCPS Optimization and AMTANN Procedure

Multi-Objective Resource-Constrained Project Scheduling (MRCPS) optimization was carried out using five different sets of weights: $o_1 = 0.8$ and $o_2 = 0.2$, $o_1 = 0.65$ and $o_2 = 0.35$, $o_1 = 0.5$ and $o_2 = 0.5$, $o_1 = 0.35$ and $o_2 = 0.65$, and $o_1 = 0.2$ and $o_2 = 0.8$. The best scores for each set of weights were recorded for comparison with the scores obtained using the AMTANN algorithm (Microsoft$^{®}$ Excel macro-enabled workbook with Office Visual Basic for Applications was used for calculations in this case study). These results, together with random suboptimal solutions, were used as a sample for training, validation, and testing of the artificial neural network (2000 records). As part of the AMTANN procedure, the possibility of reducing the range of variables related to delays in subcontracted works was analyzed; they had from 104 to 110 variants.

The method of selecting variables for possible range reduction is illustrated with an example of activities 25—non-reduced variables (electric installations) and 26—reduced variables (technical and ICT installations). After processing the data through a neural network and determining the weights for each variable, the relationships between the predictors (variables) and outcomes (outputs) were analyzed by examining solution profiles. Another aspect analyzed was interactions between predictors. The impact of each variable on the predicted result was analyzed (for 3 fixed predictor values: minimum, intermediate, and maximum). The solution profiles of the objective function values for the variable modeling the possible delay of activity 25: electric installations (in three variants) are shown in Figures 5–7.
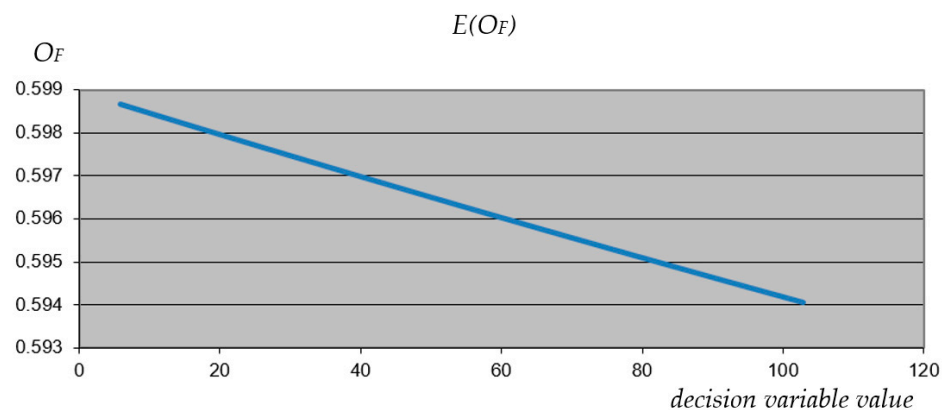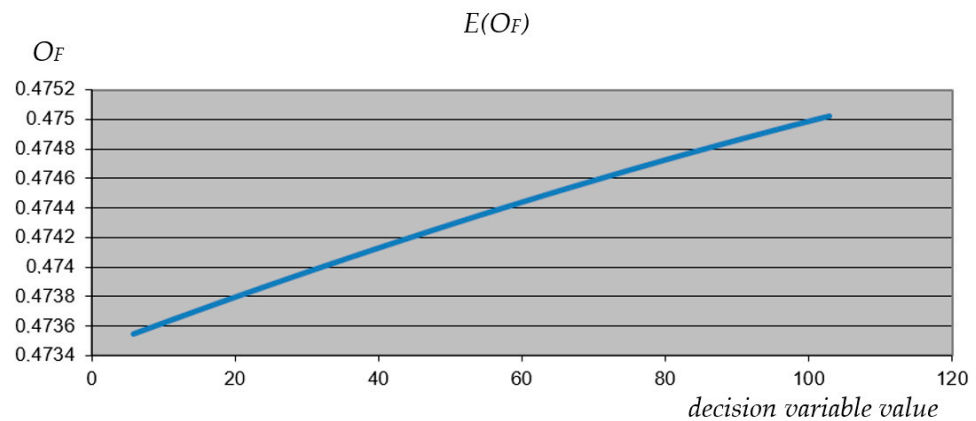

Figure 5. The expected value of the objective function (O_F) plotted as a function of the value of the decision variable being analyzed (activity 25), with the maximum values of the other variables held constant.
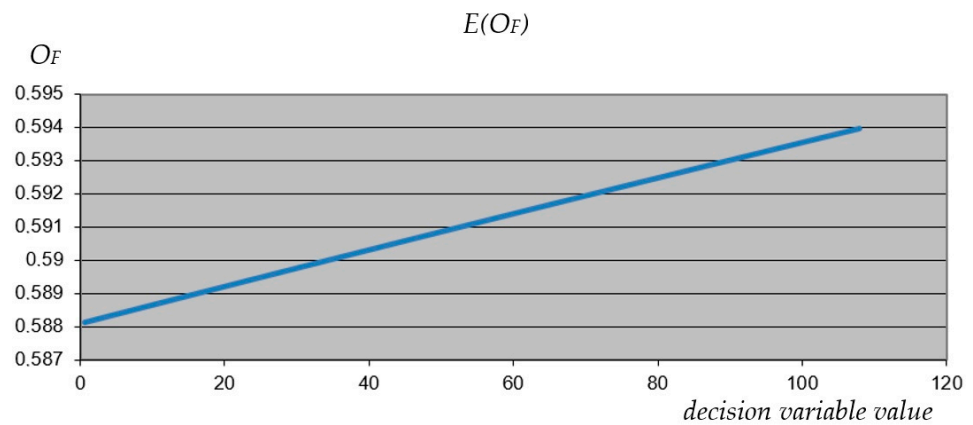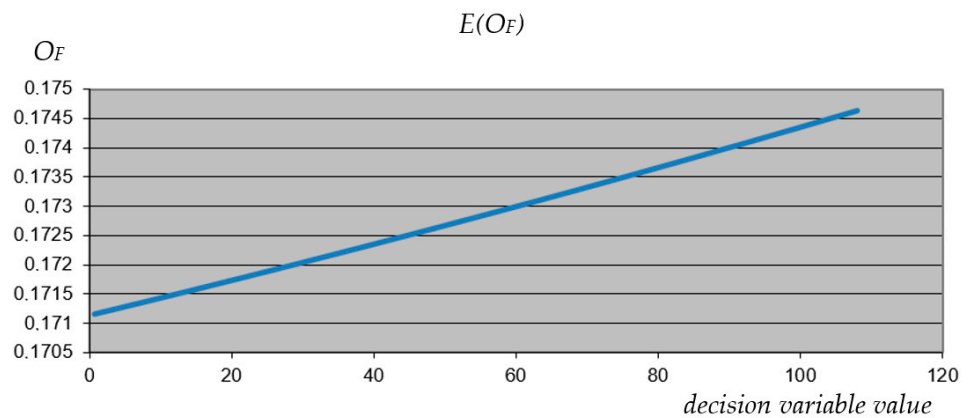
$E(O_F)$

O_F
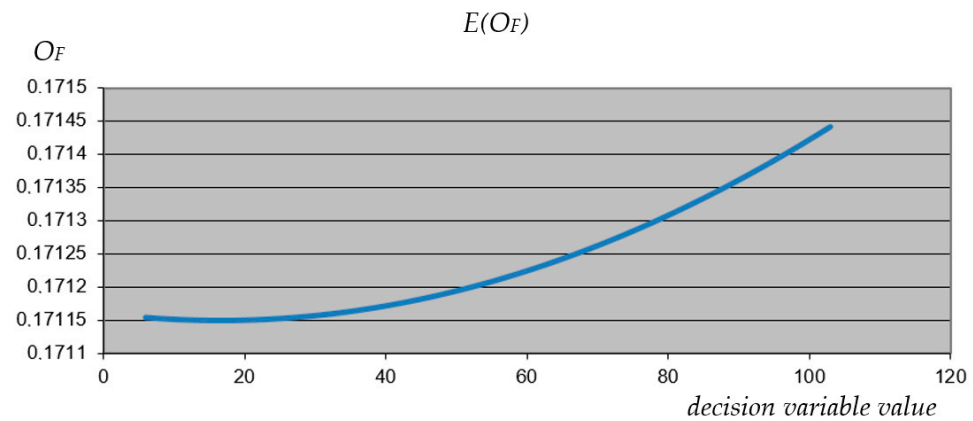
Figure 6. The expected value of the objective function (O_F) plotted as a function of the value of the decision variable being analyzed (activity 25), with the minimum values of the other variables held constant.

$E(O_F)$

O_F

Figure 7. The expected value of the objective function (O_F) plotted as a function of the value of the decision variable being analyzed (activity 25), with the intermediate values of the other variables held constant.

After examining the solution profiles, it was determined that there was inconsistency in the results. As a result, it was decided not to narrow the range of the variable related to the delay of activity 25 (electric installations).

A similar analysis was carried out for the variable corresponding to the delay in the activity: technical and ICT installations (task 26). As one can see in Figures 8–10, the analyzed variable has a consistent impact on the expected result, regardless of the values of the other variables. According to the proposed procedure, such variables should be subjected to a reduction in its range. It was decided to remove the lower half of the variable range.

Figure 8. The expected value of the objective function (O_F) plotted as a function of the value of the decision variable being analyzed (activity 26), with the maximum values of the other variables held constant.


Figure 9. The expected value of the objective function (O_F) plotted as a function of the value of the decision variable being analyzed (activity 26), with the minimum values of the other variables held constant.
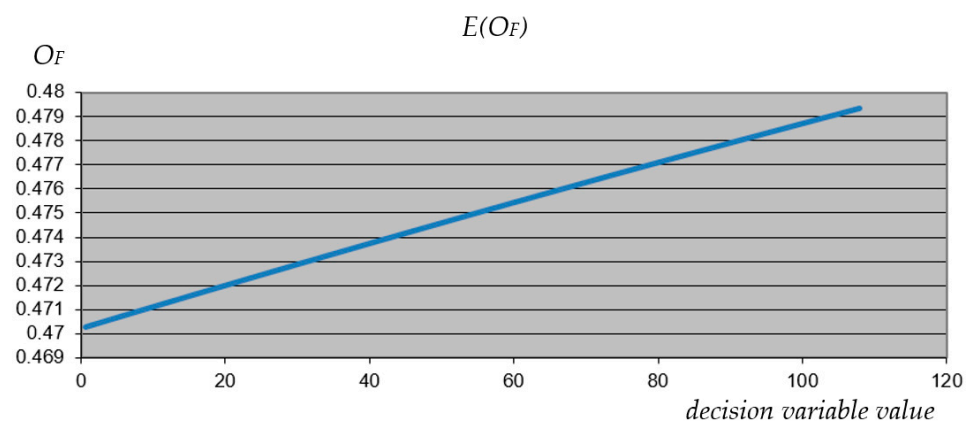
Figure 10. The expected value of the objective function (O_F) plotted as a function of the value of the decision variable being analyzed (activity 26), with the intermediate values of the other variables held constant.

As a result of the procedure, ranges of 3 out of 4 analyzed variables were reduced. This procedure narrowed the range of the solution space. The results calculated before and following the use of AMTANN are presented below in Table 10 and Figure 11.

Table 10. The results of the analysis for different configurations of weights, both before and after using the AMTANN procedure.

o_1 (NPV)	0.8	0.2	0.65	0.35	0.5
o_2 (SVI)	0.2	0.8	0.35	0.65	0.5
Before use of AMTANN					
NPV_r	0.6019	0.6138	0.6788	0.6531	0.5966
SVI_r	0.7353	0.8311	0.8187	0.8421	0.9313
CF_r	0.0684	0.0652	0.0667	0.0672	0.0579
O_F	0.6286	0.7877	0.7277	0.7760	0.7639
Duration [d]	148	144	154	142	149
NPV [USD]	27,683	27,822	28,576	28,278	27,621
SVI	0.9625	0.9761	0.9743	0.9776	0.9903
CF [USD]	99,250	98,344	98,782	98,917	96,273
After use of AMTANN					
NPV_r	0.6714	0.6218	0.6608	0.6325	0.6389
SVI_r	0.7971	0.9362	0.8139	0.8742	0.8684
CF_r	0.0670	0.0704	0.0600	0.0565	0.0634
O_F	0.6966	0.8733	0.7143	0.7896	0.7536
Duration [d]	149	152	149	144	144
NPV [USD]	28,491	27,915	28,367	28,038	28,113
SVI	0.9713	0.9910	0.9736	0.9822	0.9814
CF [USD]	98,846	99,821	96,852	95,864	97,826
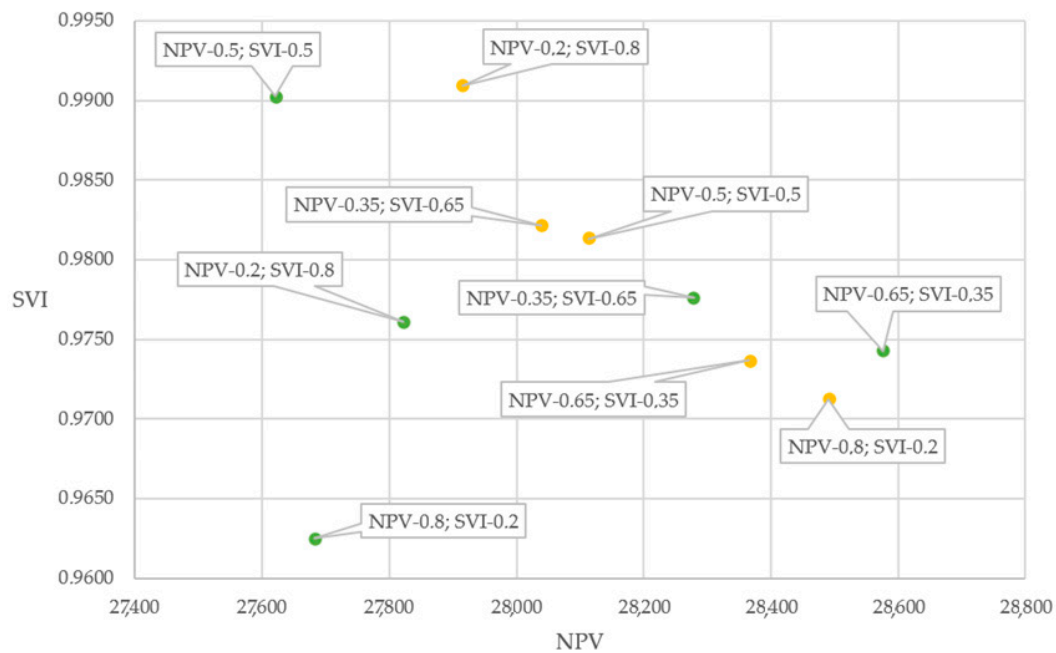
Figure 11. Results before (green) and after (yellow) application of the AMTANN for various configurations of weights of the objective function (NPV and SVI).

As shown in Figure 11, the results obtained after using artificial neural networks (AMTANN) showed less variation and generally had better performance (greater average distance from the center of the coordinate system). It is worth noting that the AMTANN procedure preserves the original results for later comparison with the final results. As a result, the solution with the highest NPV value (obtained for NPV-0.65; SVI-0.35 weights—green in Figure 11) was not lost. The results obtained after applying the ANN form a Pareto front, and the location of individual solutions on the graph (Figure 12) corresponds to the values of weights o_i assumed in the objective function (the same cannot be said about the original solutions). This is typical for common trade-off problems [18].
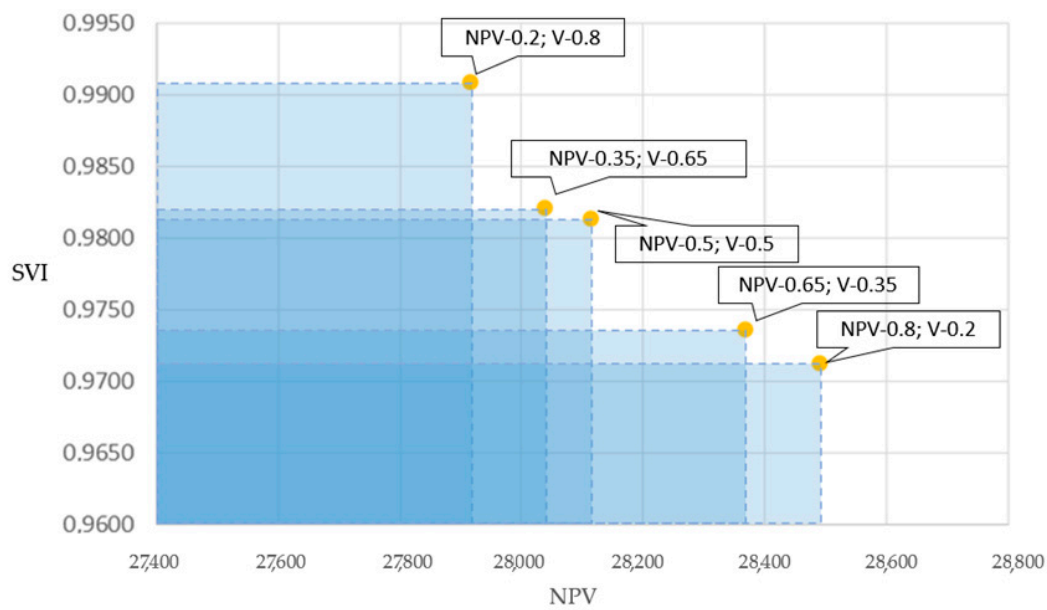
Figure 12. The dominance area of solutions for different configurations of the weights in the objective function (NPV and SVI)—after the use of AMTANN procedure.

3.1.6. Project Selection

In the last step of the procedure, the primary and ANN-modified results were selected in order to form a Pareto front (Figure 13). These results represent a range of possible versions of the project. The decision maker must choose one of these options or decide to abandon the project altogether.
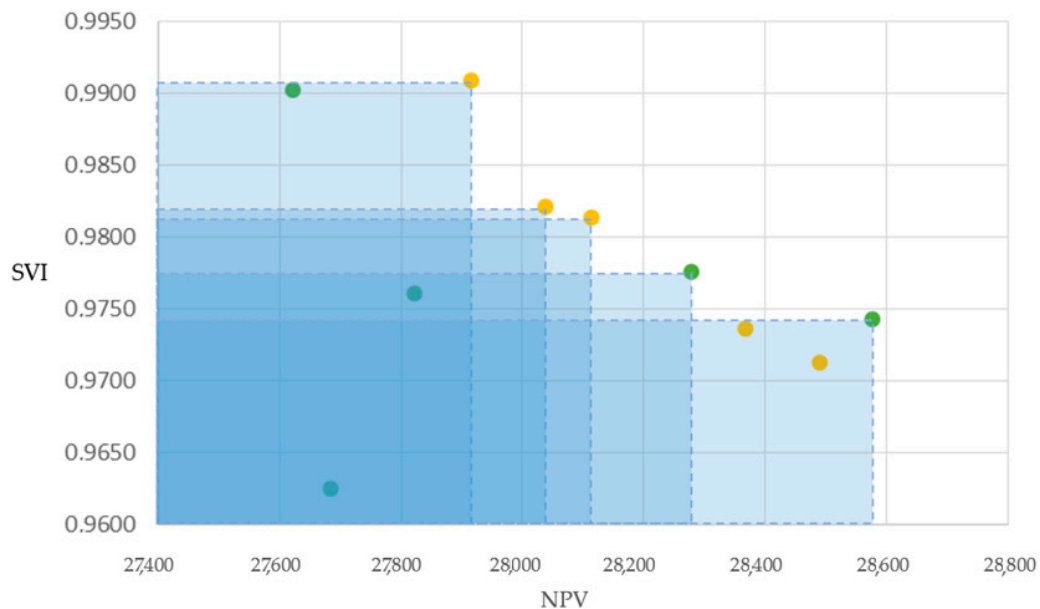
Figure 13. The dominance area of solutions, the Pareto front—results before and after the use of AMTANN.

As previously mentioned, a multi-criteria decision-making method can be used to make the final selection. In this case, the authors chose the most sustainable variant with the highest SVI (accepting the associated NPV value). The schedule for the selected variant is shown in Figure 14, and the selected variants of works are listed in Table 11.

Table 11. Final selection of variants.

ID	Task Name	Selected Variant (Mode)
1	Start	1
2	Earthworks	1
3	Foundations	1
4	Walls (underground)	1
5	Insulation of foundations and underground walls	2
6	Walls (level 0)	1
7	Ceilings, vaults, stairs, landings	2
8	Partition walls (except for dry construction)	5
9	Roof—construction	1
10	Roof—covering	1
11	Substrates and internal ducts	1
12	Insulation (above ground)	2
13	Leveling layers for floors	1
14	Plaster	2
15	Windows and doors (exterior)	1
16	Windows and doors (interior)	2
17	Partition walls (in dry technologies)	2
18	Painting	3
19	Tiling	2
20	Other interior finishing works	2
21	Elevations	1
22	Various outdoor robots	1
23	Sewage, water, and gas installations	2
24	Heating installation	2
25	Electric installation	1
26	Technical and ICT installations	2
27	Finish	1

3.2. Additional Tests

The effectiveness of the AMTANN procedure has been confirmed many times [16,28]. Nevertheless, for the example examined in this article, authors decided to perform additional tests. The averaged results are shown in Figure 15. On average, the results obtained after using artificial neural networks (ANNs) have higher values for NPV (Net Present Value) and SVI (Sustainability Value Index). In addition, they are more systematic, creating a Pareto front consistent with the assigned weights.
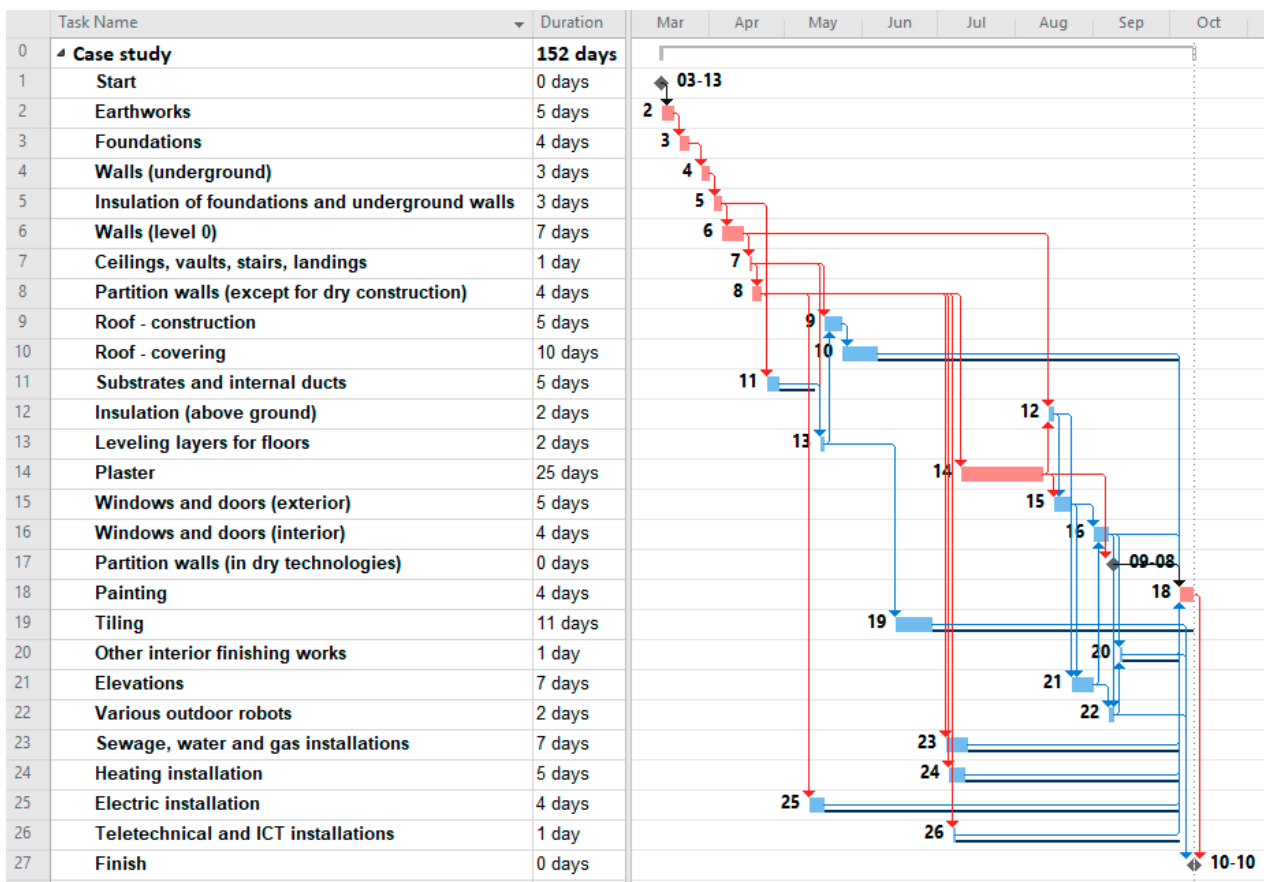
	Task Name	Duration
0	◢ **Case study**	**152 days**
1	Start	0 days
2	Earthworks	5 days
3	Foundations	4 days
4	Walls (underground)	3 days
5	Insulation of foundations and underground walls	3 days
6	Walls (level 0)	7 days
7	Ceilings, vaults, stairs, landings	1 day
8	Partition walls (except for dry construction)	4 days
9	Roof - construction	5 days
10	Roof - covering	10 days
11	Substrates and internal ducts	5 days
12	Insulation (above ground)	2 days
13	Leveling layers for floors	2 days
14	Plaster	25 days
15	Windows and doors (exterior)	5 days
16	Windows and doors (interior)	4 days
17	Partition walls (in dry technologies)	0 days
18	Painting	4 days
19	Tiling	11 days
20	Other interior finishing works	1 day
21	Elevations	7 days
22	Various outdoor robots	2 days
23	Sewage, water and gas installations	7 days
24	Heating installation	5 days
25	Electric installation	4 days
26	Teletechnical and ICT installations	1 day
27	Finish	0 days

Figure 14. Construction project—the final schedule (presented in MS Project).
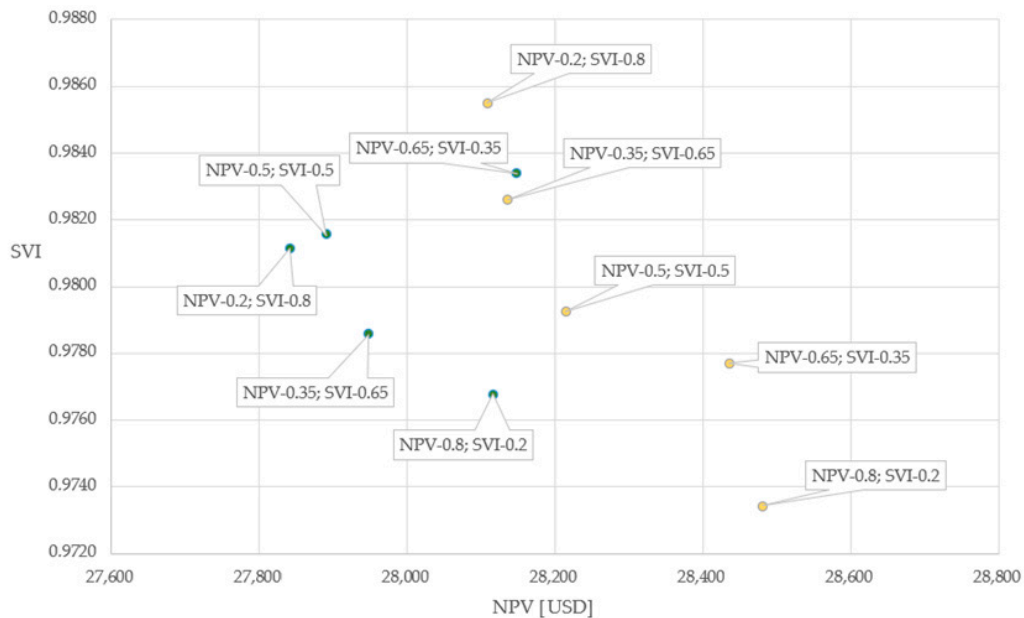
Figure 15. Average results before (green) and after (yellow) application of AMTANN for different configurations of objective function weights (NPV and SVI).

4. Discussion

The case study presented in the article shows how metaheuristic algorithms can be combined with ANNs in order to effectively optimize a construction schedule. What is more, the schedule adheres to the sustainable requirements thanks to the inclusion of the

Sustainability Value Index (SVI). According to the summary of results in Table 12, the initial solution (not feasible) was improved twice. First, by the use of metaheuristic algorithm, and then further (by almost 11%) thanks to the AMTANN procedure.

Table 12. Results summary—comparison.

	Metaheuristic Optimization Results		Initial Solution
	After AMTANN	**Before AMTANN**	
O_F	0.8733	0.7877	not feasible
NPV [USD]	27,915	27,822	23,892
SVI	0.9910	0.9761	0.896
CF [USD]	99,821	98,344	179,177

Importantly, the presented methodology gives decision makers the ability to choose from among the multiple solutions that make up the Pareto front (Figure 13).

The initial solution was not feasible ($CF > CF_{max} = 100,000\ USD$). According to equations (5) and (8), the initial CF value (179,177 USD) led to the activation of p_1 penalty and a negative O_F value.

Not only was there a significant improvement in the objective function and SVI parameter (dominant in the analyzed case), the NPV indicator (crucial from the client's economical point of view) was also improved. This fact shows that environmental and economic aspects can be successfully combined. Furthermore, meeting the conditions for sustainable development does not always have to involve a compromise, sometimes it can also be economically viable.

The presented method is flexible and allows for changes in the list of criteria. Additionally, it can be applied to projects of various sizes. A slight disadvantage may be the fact that the method requires the careful construction of a model. As a result, an experienced consultant/manager must be involved in its use. However, such practices should be common for major projects.

5. Conclusions

The sustainable ecological indicator proposed in the article (SVI) allowed for the selection of a schedule that best meets the requirements of decision makers/clients. At the same time, the economic requirements were met. It is crucial as they have a great influence on decisions made by large construction companies. This was possible thanks to the use of a mix of metaheuristic algorithms and artificial intelligence.

The tests carried out previously, and for the purposes of this article, using the AMTANN procedure, showed its effectiveness. The key to the success of the method is the fact that the algorithm does not cross out the initial solutions but uses them to compare and improve the following solutions. According to the authors, the proposed model reflects the level of complexity of construction processes to a good extent. At the same time, it allows users to be flexible and adapt the model to their own needs.

Based on the research and analyses conducted by the authors, the following conclusions were drawn:

1. It is possible to improve the sustainable parameters of a construction object by using appropriate methods and algorithms.
2. It is possible to model the construction schedule and to select the mode of the project most adequate to the formulated expectations of decision makers.
3. It is possible to reconcile the ecological and economical aspects of construction project optimization with the use of artificial intelligence tools.
4. Artificial neural networks can be effectively utilized to enhance the performance of metaheuristic algorithms and improve the outcomes of construction projects.

It is important that the flexibility of the solution proposed by the authors allows the use of various algorithms and calculation tools.

There are several limitations to the work presented in the article. One limitation is that the proposed model relies on the availability of accurate data and estimates for various parameters, such as durations, resource requirements, and technological constraints. Inaccurate or incomplete data can lead to less reliable results.

There are also limitations to the use of artificial intelligence tools, such as the possibility of bias in the data used to train the models and the need for significant computational resources.

Despite these limitations, the proposed model and its use of artificial intelligence tools offer a promising approach to optimizing construction schedules while considering both sustainable and economic parameters. There is potential for further development and refinement of the model, including the incorporation of additional factors that may impact the success of a construction project. The authors also suggest testing and comparing the performance of different optimization algorithms and AI tools in future work.

Abbreviations

List of abbreviations used in the article (in alphabetical order).

AMTANN	Approach for MRCPSP Transformation with the use of Artificial Neural Networks
ANN	Artificial Neural Networks
CIB	Conseil International du Bâtiment, ang. International Council for Building
CIOB	Chartered Institute of Building
ICC	International Code Council
ISO	International Organization for Standardization
LCC	Life Cycle Cost
MRCPSP/MMRCPSP	Multi-Mode Resource-Constrained Project Scheduling Problem
MRCPSPDCF	MRCPSP with Discounted Cash Flows
MRC-TCT/RC-TCT/TCT	Multi-Mode Resource-Constrained Time—Cost Trade-off
NPV	Net Present Value
RCPS	Resource-Constrained Project Scheduling
RCPSP	Resource-Constrained Project Scheduling Problem
SVI	Sustainable Value Index
TCT	Time—Cost Trade-off
TS	Tabu Search
UPS	Unconstrained Project Scheduling
UPSP	Unconstrained Project Scheduling Problem
VE	Value Engineering
VM	Value Management

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