WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2023.147677

ARCHIVES OF CIVIL ENGINEERING

Vol. LXIX ISSUE 4 2023

pp. 573 –589

Research paper

Selection of technological and organizational solutions for construction works with the use of a fuzzy relation of preferences

Nabi Ibadov[1], Sahib Farzaliyev[2], Irene Ladnykh[3]

Abstract: The main idea of this article is the necessity to take into account the multi-variant technological and organizational solutions of individual construction works in order to ensure rational planning for the implementation of construction projects. In practice, selection of construction works most often limited to the evaluation of technological and organizational solutions on the basis of time and cost criteria. However, it should be remembered that construction projects usually have a complex technological and organizational structure. This fact may increase the durations and costs of individual works in relation to their planned durations and costs. Therefore, the authors propose to take into account the criterion of technological and organizational complexity of the assessed construction work. The article describes the procedure for the technological and organizational optimization of construction works. A numerical example of the method of selecting technological and organizational solutions with the use of a fuzzy relation of preferences is also presented. The article also proposes to combine the computational selection model with the network planning model in a graphic form. This approach expands the computational and decision-making possibilities of network models in the practice of planning construction projects.

Keywords: technological and organizational solution, selection of construction works, construction implementation planning, fuzzy relation of preferences, fuzzy decision node

[1]Assoc Prof., DSc., PhD., Eng., Warsaw University of Technology, Faculty of Civil Engineering, Al. Armii Ludowej 16, 00-637 Warsaw, Poland, e-mail: nabi.ibadov@pw.edu.pl, ORCID: 0000-0003-3588-9551
[2]Assoc Prof., PhD., Eng., Azerbaijan University of Architecture and Construction, Faculty of Construction, Ayna Sultanova 11, Baku, Azerbaijan, e-mail: sferzeli@gmail.com, ORCID: 0000-0002-9241-4424
[3]PhD student., MSc., Eng., Warsaw University of Technology, Faculty of Civil Engineering, Al. Armii Ludowej 16, 00-637 Warsaw, Poland, e-mail: irene.ladnykh.dokt@pw.edu.pl, ORCID: 0000-0002-3322-0064

1. Introduction

One of the key issues in the planning of a construction project and the detailed design is the stage of forming technological and organizational solutions (TOS) for the execution of construction works (processes). The final effect of a construction project depends on a correctly selected TOS [1].

In essence, construction production is multi-variant [2, 3], which means that each construction work (or construction process) can be performed in several ways, both from the point of view of technology and organization of its implementation [4]. In this context, the analysis and examination of various execution (implementation) possibilities is aimed at multi-variant technological and organizational designing of works during the preparation of construction production. This means that useful TOS variants for the execution of construction works should be subject to a preliminary analysis, from which the most rational variant under the conditions under consideration should be selected. In practice, this choice is most often limited to the assessment of technological and organizational solutions based on the criteria of time and cost. In this respect, the optimal technological and organizational solution is sometimes the one that is characterized by the most favorable cost and implementation time ratio [5, 6]. The adoption of these two criteria is understandable because the lower the labor intensity, the faster it is possible to perform and start other new tasks, while low costs of execution mean higher profits.

In order to get the best results of a construction project, different authors propose different approaches. Some optimize the execution schedule in terms of time risk [8–11], others optimize the schedule taking into account the limitation of resource availability [12]. Noteworthy is also the cost approach, where the cost risk of the project is also analyzed [13–17]. In this respect, a developed mathematical tool in the field of probability theory, fuzzy sets theory [17, 18] and multi-criteria decision making are used [19]. Meanwhile, it should be emphasized that the basis of any optimization is a specific technological and organizational solution (TOS). It is the selected technology and organization of construction works that determine the amount of time and costs. In this context, the works [20–22] in the field of technology selection using artificial intelligence [20] and multi-criteria analysis [22], deserve attention. A simulation approach containing information on the dates of commencement of individual construction works is also proposed [23]. However, it should be remembered that construction projects usually have a complex technological and organizational structure. During the implementation of a construction project, the technological and organizational complexity of individual works may cause disturbing factors in the synchronization of works of particular specialties, hinder the smooth organization of works, etc. This fact may extend the planned time of execution of individual works and increase the costs of the facility. These may be, for example, such factors as: technological difficulty of carrying out individual works or the difficulty of organizing individual works due to the limited construction site; etc. The degrees of occurrence of these factors create technological and organizational risk. Therefore, when choosing TOS, apart from the time and cost criteria, one should also take into account the technological and organizational complexity of the construction work (process). For this purpose, a TOS selection model for

the execution of construction works was developed in the article, where fuzzy preference relation and linguistic variables were used to describe and model the evaluation criteria.

As a consequence of the developed method, a number of preferential TOS variants for the execution of works are obtained, from among which the most preferred variant for a given decision situation can be selected. This allows us to conclude that in order to implement a construction project without disruptions and achieve the goal with the smallest possible deviation from the designed (planned) parameters at the pre-design stage and planning the implementation of a construction project, it is necessary to take into account the multivariate technological and organizational solutions, both for individual works and the entire project. . This will ensure the rationality of the selection with correctly defined evaluation criteria.

In this article, the authors also propose a TOS selection model to combine with network planning in the form of a decision node.

2. Relevant information on technology and organization of construction works

The current level of technology and organization of construction works is very diverse due to the possibility of using various technical and technological solutions and the corresponding different methods of work organization. Such a state requires deep thought and the best selection of both technologies and methods of organizing individual construction works, both in designing and planning the implementation of construction processes. In this matter, the technological process is of primary importance, which can be selected in various ways of organization. Therefore, it is reasonable to analyze the technological process along with the elements, influencing factors and rules that should be followed during the implementation. The conceptual model of the technological process is shown in Fig. 1.

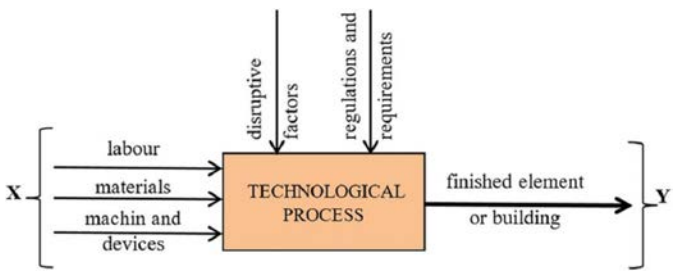

Fig. 1. Conceptual model of the technological process

When analyzing the technological process, it can be noticed that one should look for a solution that would meet the basic equation of technology Eq. (2.1):

$$Y = f(X) \tag{2.1}$$

where: Y – the output vector, X – the input vector.

Achieving the optimal output vector requires:

– Optimal shaping of the input vector by appropriate qualitative and quantitative selection and coordination of labor, items and means of work in all their components;
– Optimal planning of the production process in all its parameters;
– Organizing the optimal method and conditions for carrying out the works, which would facilitate its course by preventing any disruptions, taking into account the relevant quality and other requirements.

The optimization of technological and organizational solutions is also made difficult by the lack of an appropriate database, which is necessary for optimization. In order to optimize the construction process, it is first necessary to carefully analyze it in order to detect all its indivisible components, connections with the environment and dependence of effects on expenditure. And be able to answer the question of whether it is impossible to achieve the goal in a different, better way. This means that in order to obtain the best effect, in addition to the above-mentioned aspects, various variants of the works execution should be taken into account, both in terms of technology and organization methods. The following describes the optimization of TOS in the context of the scheme of conduct, taking into account alternative variants of the execution of works.

3. Optimization of technological and organizational solutions for construction works

Optimization of technological and organizational solutions for the performance of construction works is aimed at selecting a variant in which, taking into account local conditions, the maximum reduction of working time is ensured with the effective use of material and technical resources. The optimal solutions are revealed on the basis of a multivariant design of construction works and a comprehensive analysis of the compared variants of works. The essence of optimization search is to divide the design process into stages. This allows at every stage to analyze the technological and organizational connections between individual elements and to compare the variants with each other or with the basic (analog) variant.

The logical diagram of TOS optimization of construction works (processes) is shown in Fig. 2.

According to the diagram, in each block (D_i; P_i), a series of sequential computational and logical operations are performed, the content of which is as follows:

Block D_1 concentrates information on the object (building or structure) and the types and methods of execution of construction works, design and technological documentation regarding spatial planning and construction solutions, the size of works, conditions and limitations of their execution.

In block D_2, the analysis of the output data and design documentation of the facility is performed; determines the range of mechanization measures that can be used under given conditions; the possibility of using various methods of carrying out works, the technological sequence of their implementation; the possibility of concentration of material and technical

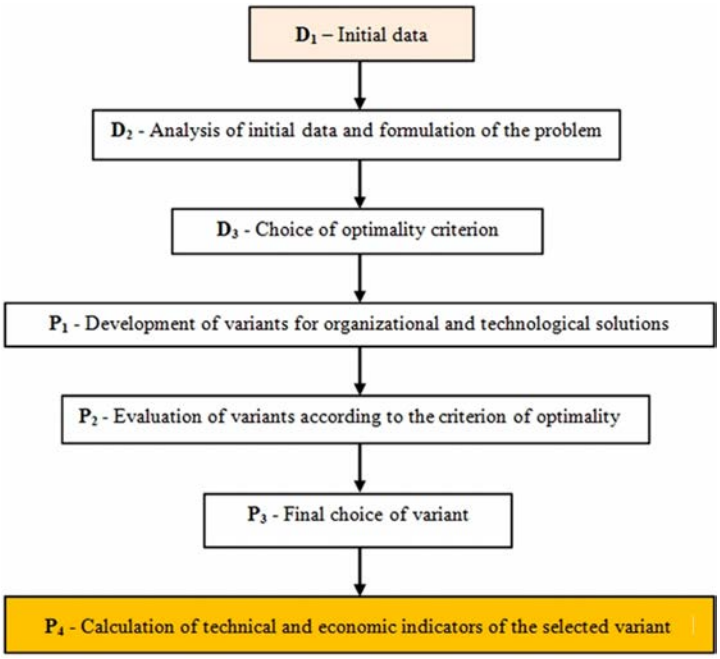

Fig. 2. Logical diagram of TOS optimization of construction

resources and human resources, methods of intensifying the conduct of certain types of single works and groups of works.

An important assessment of the possibilities of technological and organizational solutions is the justification and selection of the optimality criterion (or criteria) considered in block D_3. As such criteria, for example, the minimum duration of the construction works and/or the minimum labor costs can be used. In addition to the selected optimality criterion, it is also necessary to use other indicators characterizing the effectiveness of construction and assembly works. These indicators may include: the time period for carrying out the works, the level of concentration and use of material and technical resources and labor. The choice of one or another optimality criterion usually depends on the specific conditions for carrying out (execution) works, the size and planned dates of works.

The activities performed in block $P = (P_1, P_2, P_3, P_4)$ come down to the development (selection) of possible variants of technological and organizational solutions, taking into account the limitations of working areas and other limitations resulting from the conditions of work and types of works. At the same time, they justify and specify: the size of the sites needed to carry out the works (for example, assembly and disassembly works), the order of their inclusion in the execution of the works, the methods of leading construction works (or processes); select machines and mechanisms on the basis of technical parameters, determine their operational efficiency, the degree of connection (linkage) and the intensity of construction and assembly works. Along with this, work patterns are justified, labor costs

are determined, machine time costs are determined, and the calculation and formation of units and teams of workers is carried out.

When developing variants of technological and organizational solutions, basic work patterns are drawn up. These diagrams reflect the main methods of implementation of construction works (or processes), the location of machines and mechanisms, the sequence of their movement along the facility, etc. The developed diagrams and the technological and organizational solutions adopted in them are the basis for calculating the technical and economic indicators of the variant under consideration in block P_4.

In block P_2, operations of technical and economic evaluation of each variant are performed in terms of methods and means of mechanization of construction works, the use of material and technical resources and labor, as well as work times (sometimes and work schedule). When comparing the variants, the index adopted in block D_3 as the main optimality criterion is used as the basis for the comparison. Due to the fact that the volume, structure and labor intensity of the work will be different, in the final selection of the variant (block P_3), first of all, decisions should be made that will ensure the shortening of the work time with the minimum costs of material, technical and labor resources.

The presented diagram of the procedure in Fig. 2 together with the description of individual blocks helps in organizing knowledge and creating a sequence of logical procedures and calculations in order to obtain (select) the optimal TOS.

It should be emphasized that in construction practice, technology is largely selected based on experience, intuition or on the basis of the "fashion" of building [4], with almost no analysis of various variants of execution. This means that the selection of the appropriate technology and construction methods is often poorly organized and carried out. Meanwhile, this is critical to the success of your construction project. Unfortunately, the exact consequences of different execution methods depend on a number of factors, information about which may be sketchy, incomplete and imprecise in the implementation planning phase. The consequence of this is to a large extent the situation that the comparative analyzes omit a very important criterion of evaluation in terms of the broadly understood technological and organizational complexity (difficulties) of the chosen method of implementation. The proposed criterion of technological and organizational complexity allows to take into account possible threats in the process of execution of works. These can be aspects such as: the degree of difficulty of the execution of works in a given technology, the availability of materials used in a given technology, the availability of qualified specialists in the field of the selected technology, the availability of necessary machines and devices in a given technology, the degree of difficulty in organizing works in a given technology, difficulties in the field of synchronization of robots of individual specialties, etc.

Therefore, it is justified to take into account, apart from the time-cost characteristics of the TOS under consideration, an additional criterion of "the degree of technological and organizational complexity", taking into account the priorities of a given decision-making situation as much as possible, and the use of a mathematical tool that allows a comparative analysis to be carried out when the assessment criteria are different in nature and can be determined using linguistic variables. To this end, the article proposes the use of fuzzy preference relations. Selected elements of the fuzzy set theory are presented below.

4. Basic information on the used elements of the fuzzy sets theory

Due to the nature of the issue under consideration, the article uses the following essential elements of the fuzzy set theory: linguistic variables and fuzzy relation of preferences [24–28].

Linguistic variables can be used to model both qualitative and quantitative criteria. It also provides the opportunity to offer some kind of preliminary data formalization and decision making that allows the comparison of alternatives by computing numerical values for preferences and creating a preferential series. This approach is justified by the fact that at the planning stage, the data needed to make decisions are in most cases inaccurate and of a fuzzy nature, which is reflected in qualitative assessments expressed in natural language. For example, the technological and organizational complexity of alternative construction solutions can be assessed with the help of a linguistic variable like "low", "average", "high", etc. Also the mentioned linguistic variables can be transformed into a more reliable baseline evaluation scale and described by membership functions. In Fig. 3, the conceptual model of the linguistic evaluation of alternative construction works according to the degree of technological and organizational complexity (TOC). Where μ is the degree of membership in the fuzzy set, x is the numerical value from the base scale according to the considered criterion.

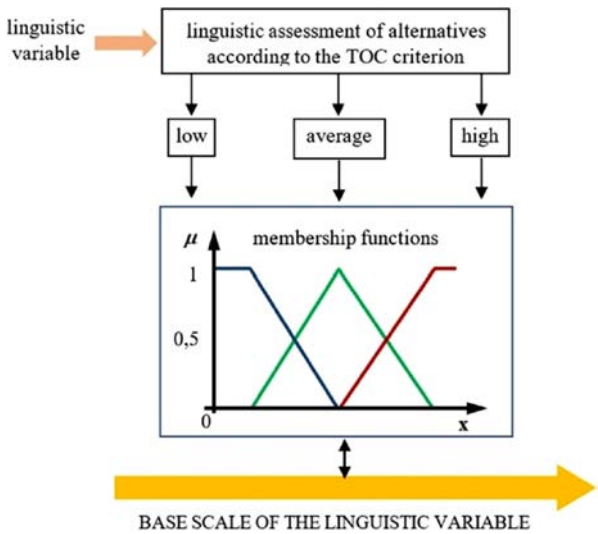

Fig. 3. Conceptual model of fuzzy linguistic evaluation of works according to the degree of TOC

Calculation of the membership function "low", "average", "high" presented in Fig. 4 using the Eq. (4.1)–(4.3), [1–4].

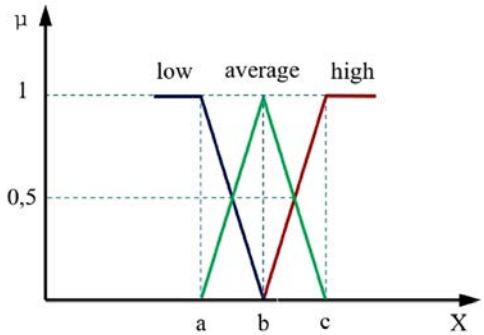

Fig. 4. Low, average and high class membership functions

Low class function is described by the Eq. (4.1):

$$\text{Low} = (x; a, b) = \begin{cases} 1 & \text{for } x \le a \\ \dfrac{b-x}{b-a} & \text{for } a \le x \le b \\ 0 & \text{for } x \ge b \end{cases} \tag{4.1}$$

Average class function is described by the Eq. (4.2):

$$\text{Average} = (x; a, b, c) = \begin{cases} 0 & \text{for } x \le a \\ \dfrac{x-a}{b-a} & \text{for } a \le x \le b \\ \dfrac{c-x}{c-b} & \text{for } b \le x \le c \\ 0 & \text{for } x \ge c \end{cases} \tag{4.2}$$

High class function is described by the Eq. (4.3):

$$\text{High} = (x, a, b) = \begin{cases} 0 & \text{for } x \le b \\ \dfrac{x-b}{c-b} & \text{for } b \le x \le c \\ 1 & \text{for } x \ge c \end{cases} \tag{4.3}$$

As for the use of a fuzzy relation of preferences, it consists in determining such a relation (degree of preferences) in the set of alternatives to the evaluation criteria. On the other hand, in the situation of making a decision, which alternative is the best from the decision- maker's point of view, has ceased to exist. Such alternatives are called non-dominant. In a short form, selecting the best alternative using a fuzzy relation of preferences can be described as follows. Assume that X is a set of alternative construction works characterized by several criteria (both qualitative – e.g. time and cost, and quantitative – e.g. technological and organizational complexity) with the index $j = 1, \ldots, m$. The pairwise comparison information for each criterion is presented as a fuzzy preference relation R_j. In this way, n

preference relations R_j are obtained on the set X. One should choose the best alternative from the set $\{X, R_1, \ldots, R_m\}$.

The membership function of the fuzzy preference relation on the set X consisting of the elements x_i, where $(i = 1, 2, \ldots, k)$, is calculated as follows Eq. (4.4):

$$\mu_R(x_i, x_j) = \begin{cases} \mu_R(x_i, x_j) - \mu_R(x_j, x_i) & \text{if } \mu_R(x_i, x_j) \geq \mu_R(x_j, x_i) \\ 0 & \text{if } \mu_R(x_i, x_j) < \mu_R(x_j, x_i) \end{cases} \tag{4.4}$$

Based on the established values of fuzzy preference relations μ_R on the set X, one can calculate a subset of non-dominated alternatives using the membership function Eq. (4.5):

$$\mu_R^{nd} = 1 - \sup_{x_i \in X} \left(\mu_R(x_j, x_i) - \mu_R(x_i, x_j)\right) \tag{4.5}$$

where: μ_R^{nd} – the degree of the non-dominated alternative x_i. The higher the degree of non-dominance, the more preferred the alternative.

The application of such an approach and the algorithms of conduct were presented in the selection of technological and organizational solutions for the execution of construction works, presented on the basis of a numerical example.

5. Numerical example

Let's assume that at the stage of planning the implementation of construction works (processes) for a given job, 3 technological and organizational solutions are possible. Individual solutions will be assessed using the criteria: cost of completing the entire work K_1 in PLN, time to complete the entire work K_2 in days and the degree of technological and organizational complexity K_3. These evaluation criteria can be described with the respective membership functions presented in Fig. 3, according to the values from the base scale for each criterion. The base scale for the criterion of technological and organizational complexity was adopted in the range of (0–10). The higher the value, the technological and organizational solution is more complex, i.e. less preferred. Table 1 presents the values of individual criteria.

Table 1. Values of the evaluation criteria

Alternative TOS of construction work	Cost of execution PLN/ entire work K_1	Duration Day/ entire work K_2	The degree of TOC [0–10] K_3
x_1	30000	8	6
x_2	40000	6	7
x_3	27000	10	5

Choose the most appropriate TOS. The fuzzy relation of preferences is obtained by comparing individual alternative TOS with respect to the evaluation criteria $K = (K_1, K_2, K_3)$.

Let's assume that the membership functions of alternative TOS taking into account their values (Table 1) according to particular criteria are described by the Eq. (5.1):

$$\begin{aligned} \mu_{K_1} &= 0.5/30000 + 0.3/40000 + 0.6/27000 \\ \mu_{K_2} &= 0.4/8 + 0.6/6 + 0.2/10 \\ \mu_{K_3} &= 0.4/6 + 0.3/7 + 0.5/5 \end{aligned} \tag{5.1}$$

The information about the alternatives compared to each criterion of K_k is presented in the form of a fuzzy relation of preferences R_k. The fuzzy relation of preferences on the set X is calculated by the Eq. (5.2):

$$R_k = \begin{matrix} \mu_R(x_1,x_1) & \mu_R(x_1,x_2) & \mu_R(x_1,x_3) \\ \mu_R(x_2,x_1) & \mu_R(x_2,x_2) & \mu_R(x_2,x_3) \\ \mu_R(x_3,x_1) & \mu_R(x_3,x_2) & \mu_R(x_3,x_3) \end{matrix} \tag{5.2}$$

Hence, the fuzzy relations according to individual criteria (relations according to the cost criterion R_1, relations according to the criterion of duration R_2 and relations according to the TOC criterion R_3) are as follows Eq. (5.3), (5.4), (5.5):

The calculated fuzzy relations according to the cost criterion are presented in the Eq. (5.3):

$$\mu_{R_1} = \begin{matrix} 1 & 0.2 & 0 \\ 0 & 1 & 0 \\ 0.1 & 0.3 & 1 \end{matrix} \tag{5.3}$$

The calculated fuzzy relations according to the duration criterion are presented in the Eq. (5.4):

$$\mu_{R_2} = \begin{matrix} 1 & 0 & 0.2 \\ 0.2 & 1 & 0.4 \\ 0 & 0 & 1 \end{matrix} \tag{5.4}$$

The calculated fuzzy relations according to the TOC criterion are presented in the Eq. (5.5):

$$\mu_{R_3} = \begin{matrix} 1 & 0.1 & 0 \\ 0 & 1 & 0 \\ 0.1 & 0.2 & 1 \end{matrix} \tag{5.5}$$

Then the intersection of the three relations $D_1 = R_1 \cap R_2 \cap R_3$ is determined using the Eq. (5.6):

$$\mu_{D_1} = \min_k(\mu_{R_k}(x_i, x_j)), \qquad k = 1, \ldots, 3 \tag{5.6}$$

Hence, Eq. (5.7):

$$\mu_{D_1}(x_i, x_j) = \begin{matrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{matrix} \tag{5.7}$$

Then one need to find a subset of the non-dominated alternatives x_i in the set $\{X, \mu_{D_1}\}$ for each i and j, where $(i \neq j)$ according to the Eq. (4.5). The individual values of $\mu^{nd}_{D_1}(x_i)$ are Eq. (5.8):

$$\begin{aligned} \mu^{nd}_{D_1}(x_1) &= 1 \\ \mu^{nd}_{D_1}(x_2) &= 1 \\ \mu^{nd}_{D_1}(x_3) &= 1 \end{aligned} \tag{5.8}$$

Hence, the computed values of the subset of the non-dominated alternative TOS values are Eq. (5.9):

$$\mu^{nd}_{D_1} = big[1,\ 1,\ 1] \tag{5.9}$$

In the next step, the weights $w_k = \{w_1, w_2, w_3\}$ of the individual criteria of K_k are determined. Let us assume that for the considered decision situation, the planner sets weights $w_1 = 0.3$, $w_2 = 0.3$, $w_3 = 0.4$ for the criteria K_1, K_2 and K_3, respectively. Taking into account the individual values of the criteria weights, the fuzzy relation D_2 is calculated using the Eq. (5.10):

$$\mu_{D_2}(x_i, x_j) = \sum_{k=1}^{3} w_k \cdot \mu_{R_k} \tag{5.10}$$

Hence, the individual values of $\mu_{D_2}(x_i, x_j)$ are Eq. (5.11):

$$\begin{aligned} \mu_{D_2}(x_1, x_2) &= 0.3 \times 0.2 + 0.3 \times 0 + 0.4 \times 0.1 = 0.1 \\ \mu_{D_2}(x_1, x_3) &= 0.3 \times 0 + 0.3 \times 0.2 + 0.4 \times 0 = 0.06 \\ \mu_{D_2}(x_2, x_1) &= 0.3 \times 0 + 0.3 \times 0.2 + 0.4 \times 0 = 0.06 \\ \mu_{D_2}(x_2, x_3) &= 0.3 \times 0 + 0.3 \times 0.4 + 0.4 \times 0 = 0.12 \\ \mu_{D_2}(x_3, x_1) &= 0.3 \times 0.2 + 0.3 \times 0 + 0.4 \times 0.1 = 0.07 \\ \mu_{D_2}(x_3, x_2) &= 0.3 \times 0.3 + 0.3 \times 0 + 0.4 \times 0.2 = 0.17 \end{aligned} \tag{5.11}$$

Taking into account that the values $\mu_{D_2}(x_1, x_1)$, $\mu_{D_2}(x_2, x_2)$, $\mu_{D_2}(x_3, x_3)$ are equal to 1, $n \times n$ dimensional matrix of the fuzzy relation $\mu_{D_2}(x_i, x_j)$ has the following form Eq. (5.12):

$$\mu_{D_2}(x_i, x_j) = \begin{matrix} 1 & 0.1 & 0.06 \\ 0.06 & 1 & 0.12 \\ 0.07 & 0.17 & 1 \end{matrix} \tag{5.12}$$

Then one need to find a subset of the non-dominant alternatives x_i in the set $\{X, \mu_{D_1}\}$ for each i and j, where $(i \neq j)$ according to the Eq. (4.5). The individual values of $\mu^{nd}_{D_2}(x_i)$ are as follows Eq. (5.13):

$$\begin{aligned} \mu^{nd}_{D_2}(x_1) &= 1 - \max((0.06 - 0.01), (0.07 - 0.06)) = 0.99 \\ \mu^{nd}_{D_2}(x_2) &= 1 - \max((0.1 - 0.06), (0.17 - 0.12)) = 0.95 \\ \mu^{nd}_{D_2}(x_3) &= 1 - \max((0.06 - 0.07), (0.12 - 0.17)) = 1 \end{aligned} \tag{5.13}$$

Hence, Eq. (5.14):

$$\mu_{D_2}^{nd}(x_i) = \begin{vmatrix} 0.99 & 0.95 & 1 \end{vmatrix} \tag{5.14}$$

Finally, in order to find the best TOS, one should compute the intersections of the two membership functions μ_{D1}^{nd} and $\mu_{D_2}^{nd}$ for the non-dominated alternatives D_1 and D_2 using Eq. (5.15):

$$\mu^{nd}(x_i) = \mu_{D_1}^{nd} \cap \mu_{D_2}^{nd} = \left(\frac{0.99}{x_1}; \ \frac{0.95}{x_2}; \ \frac{1}{x_3} \right) \tag{5.15}$$

According to the calculation, the best TOS is x_3.

6. Discussion

It should be emphasized that the calculation was carried out assuming that the cost of execution and duration are equally important ($w_1 = w_2 = 0.3$), but the most important is the technological and organizational complexity ($w_3 = 0.4$). With the established values of the criteria weights, it should be considered that the best TOS is x_3, which is characterized by both the lowest cost of execution and the lowest technological and organizational complexity, however, it has the longest duration.

Due to the fact that for a given decision-making situation, the criterion of technological and organizational complexity was the most important than the other criteria, the choice of the x_3 alternative may be most justified from a practical point of view, especially since it has the lowest cost of implementation.

If, however, for various reasons, the planner would like to shorten the duration at the expense of additional expenses, the second better solution is x_1, which is characterized by average values in relation to all criteria, especially since the solution x_1 is almost comparable to the solution x_3.

The worst solution is x_2, which is characterized by the highest cost of execution as well as technological and organizational complexity. In turn, this solution has the shortest duration. When choosing such a solution – in order to significantly shorten the duration compared to the x_3 solution, however, one should be aware of a significant increase in costs and implementation difficulties due to technological and organizational complexity.

As for the application of the proposed TOS selection method for construction works, the authors propose to combine the selection model (decision model) with the network planning model in planning the implementation of construction projects as well as in the executive design. Such a connection results in a network model with a fuzzy decision node, where alternative variants of works before the decision node are taken into account. The graphical interpretation of the network model is shown in Fig. 5. The mathematical description of such a network based on the theory of graphs was presented by the authors in [2, 3].

Due to the fact that such a network is calculated in the traditional way (taking into account additional alternative activities a_i), the authors do not present the issue of the

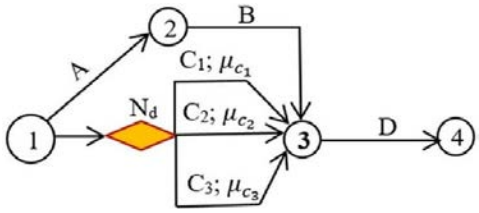

Fig. 5. Graphical interpretation of the use of calculation results in the network model

network calculation in this article. However, it is important to note that the presented calculations of the selection of TOS for the execution of construction works using the fuzzy relation of preferences gives the possibility to mark alternative activities a_i in the network model additionally with their degrees of preference $\mu_{c_1}, \mu_{c_2}, \mu_{c_3}$ which according to the Eq. (5.13), they are respectively: 0.99; 0.95 and 1. Consequently, it indicates which path in the sequence of alternative activities is more preferred.

It should also be emphasized that a solved network with alternative activities gives the possibility of creating a set of acceptable solutions in Fig. 6 with time-cost parameters (t_i, c_i) of each alternative path (including individual alternative activities a_i) in the network model with their respective degrees of technological and organizational complexity, modeled by membership functions (and degrees of preferences μ_i). The graphical interpretation of the set of acceptable solutions as a result of the calculation of the network with alternative activities (limited solutions $a_1(t_1, c_1)$ and $a_2(t_2, c_2)$) with their respective TOC membership functions is shown in Fig. 6.

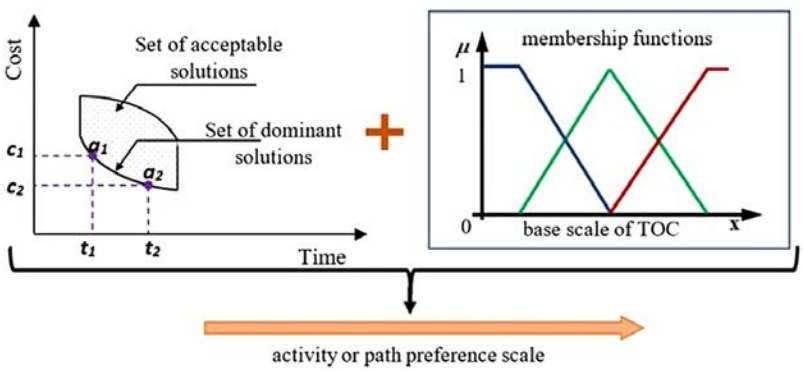

Fig. 6. Graphical interpretation of the computational result of an alternative network with a fuzzy decision node

The presented method of using the results of the TOS selection is the basis for further in-depth analysis of various network models with alternative activities in construction planning, which the authors will describe in their future research.

7. Conclusions

Based on the described methodology, numerical example and the proposed use of the results in planning construction processes (works), the following conclusions can be drawn:

- The solved calculation example shows the operation of the proposed approach. Thus, justifying the practical usefulness and inclining to take into account an additional criterion when selecting TOS "the degree of technological and organizational complexity" of construction works;
- Taking into account an additional criterion also has a practical justification, because usually during the execution of construction processes, due to technological and organizational complexity, difficulties arise in the synchronization of works of individual specialties, difficulties in the smooth organization of works, etc.;
- The developed approach also makes it possible to take into account and better formalize the assessment criteria in relation to the classic methods of multi-criteria assessment, especially in terms of quality criteria;
- Another important element of the proposed approach is that at the design stage, due to high uncertainty, the decision-maker has big problems in defining preferences as to TOS In such a situation, using a fuzzy relation of preference to select TOS variants is a better way to formalize and describe the decision situation;
- Creating a fuzzy relation of preferences also allows all TOS to be ranked according to their degree of preferences. It also allows for a detailed view of the entire set of alternatives considered;
- The method of using the results from the numerical example in planning the implementation of construction processes is also an important element. The combination of the proposed computational (decision-making) model with the network model allows for a comprehensive analysis of the network model with the possibility of taking into account alternative works and choosing the implementation in one planning model.

It should be emphasized that the elements listed above constitute the strength and novelty of this article. In turn, according to the authors, the conceptual model of combining the TOS selection model with network planning with a fuzzy decision node, proposed in the article, deserves special attention. Compared to known planning methods, the proposed method broadens the scope of analysis, improves the computational and decision-making capabilities of network models.

The decision node, in turn, gives the planner the opportunity to choose (decision making) the most appropriate variant at each planning stage, taking into account both planning decisions and uncertain technical, technological and organizational conditions for carrying out construction works. This is of great importance in the practical planning of construction projects.

This approach can be used for scheduling construction projects both in the classical and probabilistic-fuzzy approach, which the authors plan to deal with in their future research. Nevertheless, the authors are aware that taking into account the multi-variant nature of technological and organizational solutions for each construction work in one network

increases the topological variants of the network, but limiting the multi-variant nature to the so-called critical works and using a computer calculation, such a limitation can be circumvented.

References

[1] N. Ibadov, "Selection of construction project taking into account technological and organizational risk", *Acta Physica Polonica A*, vol. 132, no. 3-II, pp. 974–977, 2017, doi: 10.12693/APhysPolA.132.974.

[2] N. Ibadov, "The alternative net model with the fuzzy decision node for the construction projects planning", *Archives of Civil Engineering*, vol. 64, no. 2, pp. 3–20, 2018, doi: 10.2478/ace-2018-0013.

[3] N. Ibadov and J. Kulejewski, "Construction projects planning using network model with the fuzzy decision node", *International Journal of Environmental Science and Technology*, vol. 16, pp. 4347–4354, 2019, doi: 10.1007/s13762-019-02259-w.

[4] N. Ibadova and J. Rosłon, "Technology selection for construction project, with the use of fuzzy preference relation", *Archives of Civil Engineering*, vol. 61, no. 3, pp. 105–118, 2015, doi: 10.1515/ace-2015-0028.

[5] J. Sobieraj, D. Metelski, and P. Nowak, "PMBoK vs. PRINCE2 in the context of Polish construction projects: Structural Equation Modelling approach", *Archives of Civil Engineering,* vol. 67, no. 2, pp. 551–579, 2021, doi: 10.24425/ace.2021.137185.

[6] P. Jaśkowski, S. Biruk, and M. Krzemiński, "Proactive scheduling of repetitive construction processes to reduce crews idle times and delays", *Archives of Civil Engineering*, vol. 67, no. 4, pp. 287–302, 2021, doi: 10.24425/ ace.2021.138500.

[7] P. Jaśkowski, S. Biruk, and M. Krzemiński, "Modeling the problem of sequencing projects in the contractor's portfolio of orders", *Archives of Civil Engineering*, vol. 68, no. 3, pp. 307–322, 2022, doi: 10.24425/ace.2022.141887.

[8] N. Ibadov, "Construction project planning under fuzzy time constraint", *International Journal of Environmental Science and Technology*, vol. 16, pp. 4999–5006, 2019, doi: 10.1007/s13762-018-1695-x.

[9] S. Biruk and P. Jaśkowski, "Selection of the optimal actions for crashing processes duration to increase the robustness of construction schedules", *Applied Science*, vol. 10, no. 22, art. no. 8028, 2020, doi: 10.3390/app10228028.

[10] P. Jaśkowski and S. Biruk, "Analiza czynników ryzyka czasu realizacji przedsięwzięć budowlanych", *Czasopismo Techniczne, Budownictwo*, vol. 2, no. 1-B, pp. 157–166, 2010. [Online]. Available: http://repozytorium.biblos.pk.edu.pl/resources/35434. [Accessed: 20. Jul. 2023].

[11] P. Jaśkowski and S. Biruk, "Minimizing the duration of repetitive construction processes with work continuity constraints", *Computation*, vol. 7, no. 1, art. no. 14, 2019, doi: 10.3390/computation7010014.

[12] J.H. Rosłon and J. Kulejewski, "A hybrid approach for solving multi-mode resource-constrained project scheduling problem in construction", *Open Engineering*, vol. 9, no. 1, pp. 7–13, 2019, doi: 10.1515/eng-2019-0006.

[13] A. Leśniak and K. Zima, "Cost calculation of construction projects including sustainability factors using the Case Based Reasoning (CBR) method", *Sustainability*, vol. 10, no. 5, art. no. 1608, 2018, doi: 10.3390/su10051608.

[14] E. Plebankiewicz and J. Gracki, "Analysis of the impact of input data on the planned costs of building maintenance", *Sustainability*, vol. 13, no. 21, art. no. 12220, 2021, doi: 10.3390/su132112220.

[15] E. Plebankiewicz, A. Lesniak, E. Vitkova, and V. Hromadka, "Models for estimating costs of public buildings maintaining – Review and assessment", *Archives of Civil Engineering*, vol. 68, no. 1, pp. 335–351, 2022, doi: 10.24425/ace.2022.140171.

[16] E. Plebankiewicz and D. Wieczorek, "Prediction of cost overrun risk in construction projects", *Sustainability*, vol. 12, no. 22, pp. 1–15, 2020, doi: 10.3390/su12229341.

[17] E. Plebankiewicz, K. Zima, and D. Wieczorek, "Modelling of time, cost and risk of construction with using fuzzy logic", *Journal of Civil Engineering and Management*, vol. 27, no. 6, pp. 412–426, 2021, doi: 10.3846/ jcem.2021.15255.

[18] E. Plebankiewicz, W. Meszek, K. Zima, and D. Wieczorek, "Probabilistic and fuzzy approaches for estimating the life cycle costs of buildings under conditions of exposure to risk", *Sustainability*, vol. 12, no. 1, 2020, doi: 10.3390/su12010226.

[19] H. Anysz, A. Nicał, Z. Stević, M. Grzegorzewski, and K. Sikora, "Pareto optimal decisions in multi-criteria decision making explained with construction cost cases", *Symmetry*, vol. 13, no. 1, art. no. 46, 2021, doi: 10.3390/sym13010046.

[20] J. Rosłon, "Materials and technology selection for construction projects supported with the use of artificial intelligence", *Materials*, vol. 15, no. 4, art. no. 1282, 2022, doi: 10.3390/ma15041282.

[21] E. Radziszewska-Zielina, E. Kania, and G. Śladowski, "Problems of the selection of construction technology for structures of urban aglomerations", *Archives of Civil Engineering*, vol. 64, no. 1, pp. 55–71, 2018, doi: 10.2478/ace-2018-0004.

[22] E. Szafranko, "The choice of variant technologies and materials supported by multicriteria methods and an assessment of variants with graphic profiles of criteria", *Materials Today Proceedings*, vol. 5, no. 1, part 1, pp. 2002–2009, 2018, doi: 10.1016/j.matpr.2017.11.305.

[23] S. Biruk and Ł. Rzepecki, "A simulation model of construction projects executed in random conditions with the overlapping construction works", *Sustainability*, vol. 13, no. 11, art. no. 5795, 2021, doi: 10.3390/su13115795.

[24] B. Sunita, B. Srijit, and S.K. Singh, "Selection of most economical green building out of n-alternatives: approach of vague fuzzy logic", *International Journal of Research in Engineering and Technology*, vol. 4, n. 2, pp. 164–168, 2015, doi: 10.15623/ijret.2015.0402020.

[25] B. Sunita, B. Srijit, and S.K. Singh, "Approach of fuzzy logic for evaluation of green building rating system", *International Journal of Innovative Research in Advanced Engineering*, vol. 2, no. 3, pp. 35–39, 2015. [Online]. Available: https://www.ijirae.com/archivesid=115. [Accessed: 20. Jul. 2023].

[26] L.O. Ugur and U.N. Baykan, "Fuzzy sets applications in civil engineering basic areas", *Düzce University Journal of Science & Technology*, vol. 4, pp. 176–206, 2016. [Online]. Available: https://dergipark.org.tr/en/download/article-file/224911. [Accessed: 20. Jul. 2023].

[27] L.A. Zadeh, "Fuzzy sets as a basis for a theory of possibility", *Fuzzy Sets and Systems*, vol. 100, suppl. 1, pp. 9–34, 1999, doi: 10.1016/S0165-0114(99)80004-9.

[28] E. Radziszewska-Zielina and G. Śladowski, "Proposal of the use of a fuzzy stochastic network for the preliminary evaluation of the feasibility of the process of the adaptation of a historical building to a particular form of use", in *IOP Conf. Series: Materials Science and Engineering*, vol. 245, no. 7, art. no. 072029, 2017, doi: 10.1088/1757-899X/245/7/072029.

Wybór rozwiązań technologiczno-organizacyjnych robót budowlanych z wykorzystaniem rozmytej relacji preferencji

Słowa kluczowe: rozwiązanie technologiczno-organizacyjne, wybór robót budowlanych, planowanie budowy, rozmyta relacja preferencji, rozmyty węzeł decyzyjny

Streszczenie:

Główną ideą artykułu jest konieczność uwzględniania wielowariantowości rozwiązań technologiczno-organizacyjnych poszczególnych robót budowlanych w celu zapewnienia racjonalnego planowania realizacji przedsięwzięć budowlanych. W tym kontekście, cele artykułu obejmują wykazanie znaczenia wielowariantowości robót budowlanych oraz przedstawienie metody oceny poszczególnych wariantów i koncepcji agregacji modelu obliczeniowego z modelem planowania sieciowego.

Wielowariantowe projektowanie technologiczno-organizacyjne wykonania robót w trakcie przygotowania produkcji budowlanej polega na analizie i zbadaniu różnych możliwych sposobów ich wykonania w celu wyboru wariantu najbardziej racjonalnego w danych warunkach realizacji przedsięwzięcia. W praktyce, wybór ten najczęściej ogranicza się do oceny rozwiązań technologicznych

i organizacyjnych na postawie kryteriów czasu i kosztu. Należy jednak pamiętać, że przedsięwzięcia budowlane mają zazwyczaj złożoną strukturę technologiczno-organizacyjną. W trakcie realizacji przedsięwzięcia budowlanego, złożoność technologiczna i organizacyjna może generować czynniki zakłócające synchronizację robot poszczególnych specjalności, utrudniające płynną organizację robót, itp. Fakt ten może powodować wydłużenie czasów realizacji poszczególnych robot i zwiększenie kosztów realizacji obiektu w stosunku do ich planowanych czasów i kosztów realizacji. Dlatego, oprócz kryteriów czasu i kosztu, podczas podejmowania decyzji o wyborze wariantu realizacji robót budowlanych należy uwzględnić także złożoność technologiczno-organizacyjną danej roboty budowlanej lub procesu budowlanego. W artykule opisano procedurę optymalizacji technologiczno-organizacyjnej robót budowlanych. Przedstawiono również przykład obliczeniowy metody doboru rozwiązań technologiczno-organizacyjnych z wykorzystaniem rozmytej relacji preferencji.

W celu realizacji przedsięwzięcia budowlanego bez zakłóceń i z jak najmniejszym odchyleniem jego parametrów uzyskanych od planowanych w artykule przedstawiono koncepcję połączenia decyzyjnego modelu obliczeniowego z modelem sieciowym w postaci alternatywnego modelu sieciowego z rozmytym węzłem decyzyjnym w formie opisowo-graficznej. Takie podejście rozszerza możliwości obliczeniowe i decyzyjne modeli sieciowych w praktyce planowania projektów budowlanych.

Received: 2023-08-08, Revised: 2023-09-05