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MODEL OF CONSTRUCTION SUBCONTRACTORS SELECTION WITH TIME WINDOWS FOR THEIR AVAILABILITY

S. BIRUK[1], P. JASKOWSKI[2], M. KRZEMIŃSKI[3]

Abstract. Most construction projects involve subcontracting some work packages. A subcontractor is employed on the basis of their bid as well as according to their availability. A viable schedule must account for resource availability constraints. These resources (e.g. crews, subcontractors) engage in many projects, so they become at the disposal for a new project only in certain periods. One of the key tasks of a planner is thus synchronizing the work of resources between concurrent projects. The paper presents a mathematical model of the problem of selecting subcontractors or general contractor's crews for a time-constrained project that accounts for the availability of contractors, as well as for the cost of subcontracting works. The proposed mixed integer-binary linear programming model enables the user to perform the time/cost trade-off analysis.

Keywords: construction project, project scheduling, subcontractor selection, discrete time/cost trade-off problem

1. INTRODUCTION

Most of the research work in the field of scheduling focuses on modeling projects and searching for accurate or heuristic methods of model solving aimed at constructing optimal (or suboptimal) schedules. The baseline schedule of a project is the basis for negotiations with subcontractors and

[1] DSc.,PhD., Eng., Lublin University of Technology, Faculty of Civil Engineering and Architecture, Nadbystrzycka str. 40, 20-618 Lublin, Poland, e-mail: s.biruk@pollub.pl, https://orcid.org/0000-0003-4392-8426
[2] DSc., PhD., Eng., Lublin University of Technology, Faculty of Civil Engineering and Architecture, Nadbystrzycka str. 40, 20-618 Lublin, Poland, e-mail: p.jaskowski@pollub.pl, https://orcid.org/0000-0003-1661-3373
[3] DSc., PhD., Eng., Warsaw University of Technology, Faculty of Civil Engineering, Armii Ludowej str. 16, 00-637 Warsaw, Poland, e-mail: m.krzeminski@il.pw.edu.pl, https://orcid.org/0000-0002-6352-5942

determining the dates of their employment. Typically, the planners rely on two criteria of schedule optimization: time and cost, considering them jointly or one at a time [15, 16]. Many authors strive to maximize economical efficiency measured by the net present value of the project [1, 7, 19, 24].

Many mathematical methods and models have been developed to balance the demand for renewable and non-renewable resources and to schedule projects under resource availability constraints. To capture them, the scheduler can assume that, due to limited resource availability, certain processes may take place only at specific periods (time-window constraints) or at directive times (time-schedule constraints) [8].

The ability to deliver a project in a short time may give a contractor a competitive advantage. However, reducing the project duration involves, apart from more effort in planning, some additional cost, such as overtime work or hiring additional equipment and machines. For this reason, the planner needs to conduct a time and cost analysis of the project [12]. The literature puts forward a number of approaches to such analysis. These are based on a utility function to solve a bi-criterion (time-cost) optimization problem [14, 15] or on one of the numerous methods of the multi-criteria analysis [17, 21].

The organizational structure of a construction project comprises the in-house resources of the general contractor as well as teams that come from cooperating construction companies. The contractor often has to decide on subcontracting already at the stage of bid preparation. The general contractor relies on the bid prices submitted by the subcontractors to estimate the final bid sum for the project. The decision made at this stage also influences the project's schedule and duration. The selection of reliable contractors to deliver each work package becomes a key factor for the success of the whole project.

Managing a large number of partners (later referred to as subcontractors) is a challenge for a general contractor. It is particularly difficult to fit their schedules into the project schedule so that the contractual deadline is met [25]. Each project is different (unique scope and specifications, effect of local conditions, changing economic conditions etc.) and there exists no standard set of criteria for the assessment of the members of the project team to assure a good choice [1, 20, 22]. However, the contracting authority should always take into account several basic criteria when selecting potential subcontractors to be invited to submit tenders: the quality of the work, efficiency, capacity (availability of qualified personnel and appropriate equipment), as well as the possibility of undertaking the work within a specified period of time [6, 18]. The most important factors influencing the choice of subcontractors may be determined by means of questionnaire surveys [18, 20, 23]. The selection of the best subcontractor can be made by using multiple criteria decision making methods [3, 4, 5]. This issue reduces the impact of the manager's intuition on the choice of subcontractor, while taking into account many factors, but does not take into consideration the impact of the decision on the schedule of the construction project.

The problem of selecting subcontractors should be considered together with the scheduling of construction projects. At the planning stage, the use of the contractor's own potential, the scope and cost of the contracted work should be taken into account. The problem of contracting works must take into account the primary objectives of the main contractor: meeting the deadline date agreed with the investor, not to overrun the investment budget and ensuring a high level of use of own resources (working teams, construction machinery and equipment etc.). The planning of a construction project must therefore include different, sometimes contradictory objectives, e.g minimizing project duration, cost, and project total interruption time [9].

Several developed models of construction projects allow to perform time-cost trade-off analyses. Jaśkowski [13] presented the triple-criteria schedule optimization problem (minimizing the project's duration and cost, and reduction of the cost of contracted work) solving using metaheuristic algorithm. The model of Hegazy and Wassef [10] allows to perform time-cost analyses at the determined date for various variants of work execution differing in time and cost of execution. Hyari and El-Rayes [11] presented the model for repetitive construction project which minimizing project duration and maximizing work continuity at the same time.

The paper is organized as follows: Section 2 defines the decision problem and presents its mathematical formulation. Section 3 presents an example of an application of the model for selection of subcontractors for a relatively simple construction project. Section 4 concludes the paper summarizing the merits of the proposed approach and pointing to the directions of further research.

2. MATHEMATICAL MODEL

Let us assume that the project consists in the execution of n construction processes repeated on w work zones (units, objects). The scope of work and the precedence relations among the processes on each zone are modeled using a directed, acyclic and consistent unigraph $G = \langle V, E \rangle$ with no loops, with a single start and a single finish node. $V = \{1,\ 2, ..., n\}$ is a set of the graph's nodes (vertices) that represent construction processes. $E \subset V \times V$ is a relation defining the precedence between processes represented as the graph's edges. Each process i $(i = 1, 2, ..., n)$ can be delivered by a different subcontractor or general contractor's crew. The number of options of delivering a process i, m_i, equals the number of the process' potential providers: the general contractor's crew plus the potential subcontractors who submitted bids for the work package containing this process. Subcontractors for the work package (process) i form a set S_i. Each executor (GC's crew or subcontractor) j who presents a bid for particular process i is required to declare the earliest ($s^0_{i,j}$) and the latest ($s^1_{i,j}$) date of commencement with this process considering all their other assignments, as well as the durations of the process $t_{i,j,z}$ on each work zone z and its price $k_{i,j}$ (on all zones $z = 1, 2, ..., w$). It is assumed that each process will be carried out without interruptions, therefore each crew or subcontractor after the completion of the process on a given work zone will start its implementation on another zone without idle time. The order in which the work zones are realised is established in accordance with their numbering.

Variables $s_{i,z}$ and $f_{i,z}$ represent, respectively, the start and finish dates of the process i on the work zone z. Binary variables $\delta_{i,j}$ model decisions about the selection of the process executor (they take the value of 1 when the process i will be executed by the executor j or the value 0 in otherwise).

The problem consists in such a selection of subcontractors (or GC's crews) and determining the dates of process execution so that the total duration of the project does not exceed the directive time (contractual date of completion) T_d and the cost of subcontracted work is not greater than K_S, moreover the total cost of the project, K, (being the sum of costs of all processes) is minimal. The problem can be formulated as follows:

(2.1)
$$\min K: \; K = \sum_{i=1}^{n} \sum_{j=1}^{m_i} k_{i,j} \cdot \delta_{i,j}$$

(2.2)
$$f_{n,w} \le T_d$$

(2.3)
$$\sum_{i=1}^{n} \sum_{j \in S_i} k_{i,j} \cdot \delta_{i,j} \le K_S$$

(2.4)
$$s_{i,1} \ge \sum_{j=1}^{m_i} s^0_{i,j} \cdot \delta_{i,j}, \; i = 1, 2, ..., n$$

(2.5)
$$s_{i,1} \le \sum_{j=1}^{m_i} s^1_{i,j} \cdot \delta_{i,j}, \; i = 1, 2, ..., n$$

(2.6) $$t_{i,z} = \sum_{j=1}^{m} t_{i,j,z} \cdot \delta_{i,j},\ i = 1, 2, ..., n,\ z = 1, 2, ..., w$$

(2.7) $$f_{i,z} = s_{i,z} + t_{i,z},\ i = 1, 2, ..., n,\ z = 1, 2, ..., w$$

(2.8) $$s_{i,z} \geq f_{r,z},\ \forall (i, r) \in E,\ z = 1, 2, ..., w$$

(2.9) $$s_{i,z+1} = f_{i,z},\ i = 1, 2, ..., n,\ z = 1, 2, ..., w-1$$

(2.10) $$\sum_{j=1}^{m_i} \delta_{i,j} = 1,\ i = 1, 2, ..., n$$

(2.11) $$\delta_{i,j} \in \{0, 1\},\ i = 1, 2, ..., n,\ j = 1, 2, ..., m_i$$

Condition (2.2) assures that the project is completed no later than the contractual date of completion and condition (2.3) that the cost of subcontracted work is not greater than K_S. Conditions (2.4) and (2.5) impose that a process is started within the time window of its subcontractor's availability (as specified by the subcontractor in their bid). Formula (2.6) enables the calculation of the process execution time on each work zone by a selected contractor. Equations (2.7) – (2.9) are used to calculate the start and finish dates of processes taking into account precedence relations. According to relation (2.9), executors realize processes with no idle times. Relation (2.10) ensures that only one subcontractor is selected for each activity.

3. EXAMPLE

An example project involves the construction of three buildings with different surface areas and cubic capacity. Fig. 1 presents the graph representing the precedence relations among construction processes that results from the logic of works. Each of its processes can be delivered by one GC's crew (option 1) or one of four potential subcontractors (options 2 – 5). Thus, there exist five options for each process, differing in the delivery time and cost and restricted in time by the availability of the subcontractor defined by them in their bids in the form of time-windows (or by general contractor for his own crews).

Table 1 and Table 2 list, respectively, the early and the late starts of processes according to each option. Table 3 lists the process durations on each work zone (building) as declared by the subcontractors in their bids or established by general contractor for his own crews. Table 4 lists corresponding prices. Subcontractors whose bids are dominated (in terms of time and cost) by other bidders are not eliminated as their availability may be better than that of other subcontractors. The example was solved by means of Lingo 14.0 solver.

Table 1. Early starts of processes in each option expressed by a number of a working day since the project start [days]

i	Process	Option				
		1	2	3	4	5
1	Earthworks	0	0	5	10	15
2	Structural works	5	10	25	35	25
3	Roof structure	360	370	370	380	350
4	Roof cladding	400	390	405	410	400
5	Facade works	500	480	490	505	505
6	Partitions	380	350	360	370	360
7	Internal plastering	405	410	420	400	410
8	Screeds	410	420	430	410	420
9	Painting	470	500	480	490	500
10	Floors	520	530	510	520	500
11	Installation of doors and windows	440	430	420	435	440
12	Tests on completion	no restrictions				

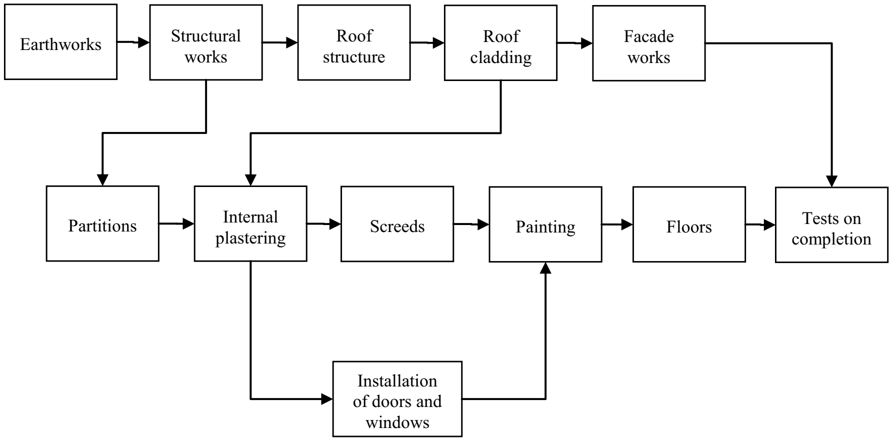

Fig. 1. Precedence relations among processes on each work zone (building) for the example

Table 2. Late starts of processes in each option expressed by a number of a working day since the project start [days]

i	Process	Option				
		1	2	3	4	5
1	Earthworks	10	20	25	30	30
2	Structural works	20	30	50	50	40
3	Roof structure	400	420	400	450	400
4	Roof cladding	430	420	430	450	430
5	Facade works	530	520	560	550	530
6	Partitions	420	400	380	390	380
7	Internal plastering	440	440	430	450	440
8	Screeds	430	450	480	460	450
9	Painting	495	550	550	600	580
10	Floors	590	590	600	600	580
11	Installation of doors and windows	500	520	500	500	550
12	Tests on completion	no restrictions				

Table 3. Process durations (for building I/II/III respectively) declared by the subcontractors and established by general contractor for option 1 [days]

i	Process	Option				
		1	2	3	4	5
1	Earthworks	6/7/8	5/6/7	7/8/9	6/7/8	10/10/11
2	Structural works	130/135/140	140/150/155	160/170/175	140/145/150	140/150/150
3	Roof structure	15/17/20	20/22/25	15/16/18	10/12/15	15/16/18
4	Roof cladding	15/17/19	15/17/20	20/22/25	19/20/22	17/19/21
5	Facade works	30/33/36	30/32/34	35/37/40	33/35/39	32/35/40
6	Partitions	20/22/24	30/34/36	25/27/30	25/26/29	28/30/32
7	Internal plastering	15/16/18	20/22/25	17/19/22	16/18/20	19/22/24
8	Screeds	30/32/34	31/33/35	32/35/37	35/37/40	30/33/35
9	Painting	20/22/24	25/26/28	30/32/35	29/33/35	28/30/32
10	Floors	20/23/26	25/26/28	24/26/29	23/24/25	22/25/27
11	Installation of doors and windows	30/30/31	25/26/27	40/40/42	38/39/40	36/37/38
12	Tests on completion	1				

Table 4. Cost of processes (subcontractors' bid prices and general contactor's estimation for option 1) (for all buildings) [thousand EUR]

i	Process	Option				
		1	2	3	4	5
1	Earthworks	150	135	120	112.5	105
2	Structural works	8250	7125	6750	6750	6375
3	Roof structure	105	97.5	90	82.5	75
4	Roof cladding	131.25	127.5	123.75	120	116.25
5	Facade works	123.75	112.5	105	97.5	93.75
6	Partitions	255	240	236.25	232.5	228.75
7	Internal plastering	127.5	120	112.5	116.25	112.5
8	Screeds	240	225	217.5	213.75	210
9	Painting	172.5	150	135	131.25	127.5
10	Floors	60	52.5	45	45	41.25
11	Installation of doors and windows	375	300	285	277.5	262.5
12	Tests on completion	0				

The results of the time-cost analysis (for nondominated solutions) on the assumption that the cost of subcontracted works is not limited are presented in Table 5. The shortest duration of the project is 579 working days (expressed by a number of a working day since the date 0); the corresponding cost is EUR 9,795,000 and cost of subcontracted works is EUR 1,132,500.

The project duration of 618 days can be achieved at a minimal cost of EUR 9,630,000 (with cost of subcontracted works of EUR 1,380,000). Allowing the project to take longer does not reduce the cost.

Analysing the results presented in Table 5, it should be noted that the highest required cost of subcontracted works is achieved with a project duration of 603 days.

Let us assume that the general contractor allowed the project to be completed within a maximum of 605 days and limited the value of the subcontracted work to the amount of EUR 1,300,000. Under these assumptions, the project duration will be 605 days at a minimum cost of EUR 9,701,250 and the cost of subcontracted works will be EUR 1,196,250. In this solution, the general contractor will execute structural works and partition walls with its own resources, the remaining works will be subcontracted. The project schedule for this solution is shown in Fig. 2. It should be noted that the project will start 5 days after the planned date due to the fact that the earthmoving subcontractor (option 3) is available at the earliest after that date.

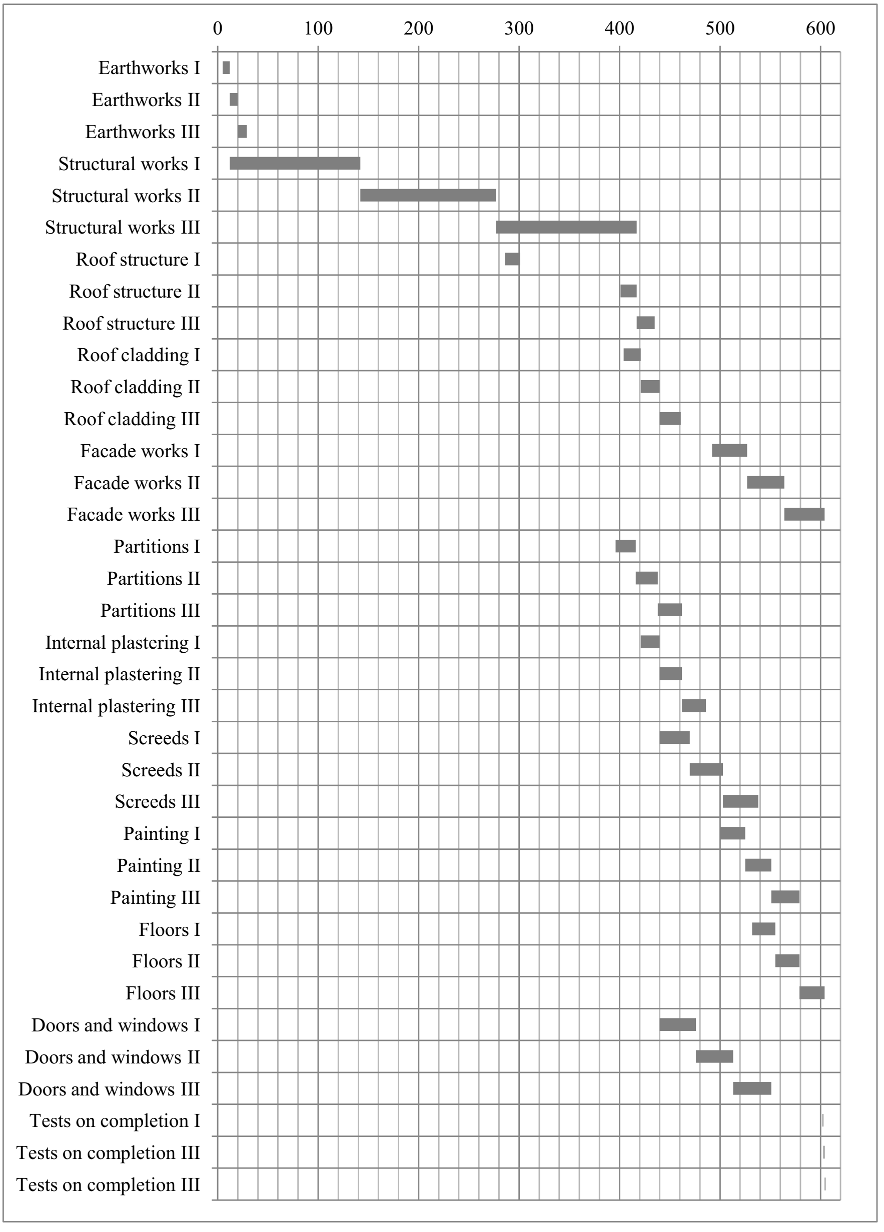

Fig. 2. The optimal schedule with project duration of 605 days with minimal project cost of EUR 9,701,250 and the cost of subcontracted works of EUR 1,196,250

Table 5. The time-cost relationship for the example (cost of subcontracted works not limited)

Project duration, days	Project cost, EUR tho.	Cost of subcontr. works, EUR tho.	Selected option for process *i*:										
			1	2	3	4	5	6	7	8	9	10	11
579	9795	1132.5	2	1	5	2	2	5	5	1	1	5	2
581	9765	1342.5	2	1	5	2	2	5	5	5	1	5	2
587	9753.75	1331.25	2	1	5	5	2	5	5	5	1	5	2
588	9738.75	1316.25	3	1	5	5	2	5	5	5	1	5	2
603	9690	1440	4	1	5	5	3	5	5	5	3	4	2
605	9675	1425	3	1	5	5	3	5	5	5	2	4	5
606	9667.5	1417.5	4	1	5	5	3	5	5	5	2	4	5
608	9663.75	1413.75	4	1	5	5	3	5	5	5	2	5	5
612	9660	1410	3	1	5	5	3	5	5	5	3	4	5
613	9637.5	1387.5	4	1	5	5	5	5	5	5	4	4	5
615	9633.75	1383.75	4	1	5	5	5	5	5	5	4	5	5
618	9630	1380	4	1	5	5	5	5	5	5	5	5	5

4. SUMMARY AND CONCLUSIONS

The ability to account for organizational constraints in the process of scheduling construction projects and the skill to solve the time-cost trade-off problems may be one of the key factors to increase the project efficiency.

The proposed method may be helpful in selecting the optimal set of subcontractors out of a large pool of those willing to participate in the project on the basis of their declared availability, their prices, and time for completion of the work packages they bid for. It also supports the decision on the profitability of employing own GC's crews or subcontractors.

Analyzing the project with account to the capacities of cooperating companies allows the planner to reconcile the objectives of all parties, which in the future may lead to increased confidence and the creation of lasting relationships in the business network.

Further research is going to be focused on developing an algorithm based on the branch and bound method to solve the presented scheduling problem, and to evaluate its efficiency and computational complexity. The direction of further work will also be the verification of the possibility of using the method in practice for the scheduling of construction projects.

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MODEL DECYZYJNY WYBORU PODWYKONAWCÓW BUDOWLANYCH PRZY UWZGLĘDNIENIU ICH OGRANICZONEJ DOSTĘPNOŚCI W CZASIE

Słowa kluczowe: przedsięwzięcie budowlane, harmonogramowanie przedsięwzięć, wybór podwykonawców, dyskretny problem optymalizacji czasowo-kosztowej harmonogramów

STRESZCZENIE

W strukturze organizacji realizującej przedsięwzięcia budowlanego można wyróżnić zasoby własne generalnego wykonawcy (jeżeli taki podmiot jest obecny w systemie realizacji projektu) oraz zasoby podwykonawców − współpracujących przedsiębiorstw budowlanych. Obecnie przedsiębiorstwa skupiają się na swoich podstawowych kompetencjach a przedsięwzięcia budowlane są coraz częściej realizowane w systemie generalnego lub częściowego wykonawstwa, bądź są na podstawie umowy o zarządzanie (contracting management lub construction management), gdzie rola kierownika projektu polega na synchronizacji prac dużej liczby wyspecjalizowanych wykonawców. Wybór wiarygodnych podwykonawców lub niezależnych wykonawców staje się kluczowym czynnikiem sukcesu całego przedsięwzięcia, a zarządzanie dużą liczbą podmiotów zaangażowanych w proces inwestycyjno-budowlany (projektantów, podwykonawców wielu branż, dostawców materiałów budowlanych) stanowi wyzwanie dla kierownika projektu czy generalnego wykonawcy.

Każde przedsięwzięcie budowlane jest niepowtarzalne (różny zakres prac, odmienne otoczenie zewnętrzne i wewnętrzne) i jest realizowane przez tymczasową organizację, powoływaną na okres jego wykonania, której skład zalezy od czynników specyficznych dla danego przedsięwzięcia. Z drugiej strony od sprawności i efektywności pracy uczestników procesu budowy zależy, jak będą kształtować się uzyskiwane wyniki (w jakim terminie przedsiewziecie zostanie zakończone i jakim kosztem zrealizowane). Dlatego problem wyboru podwykonawców budowlanych należy łączyć z harmonogramowaniem przedsięwzięć budowlanych oraz szacowaniem kosztów ich realizacji. Na etapie planowania należy uwzględnić wykorzystanie własnego potencjału generalnego wykonawcy oraz ustalić zakres zleconych prac, oferty cenowe potencjalnych podwykonawców oraz ich dostępność w czasie.

Planowanie przedsięwzięcia musi uwzględniać zwykle sprzeczne cele, np. minimalizację czasu trwania i kosztów przedsięwzięcia oraz maksymalizację wykorzystania potencjału własnego generalnego wykonawcy (zespoły robocze, maszyny i urządzenia budowlane itp.).

W artykule przedstawiono model matematyczny problemu wyboru podwykonawców lub brygad roboczych generalnego wykonawcy przy założeniu ograniczonej w czasie (poprzez okna czasowe) dostępności wykonawców robót budowlanych. Proponowany model matematyczny (mieszany, binarny model programowania liniowego) umożliwia przeprowadzenie analizy czasowo-kosztowej przedsięwzięcia budowlanego. Uwzględnienie na etapie planowania rzeczywistych terminów dostępności zasobów podwykonawców oraz ich ofert cenowych, które mają wpływ na koszt i czas trwania przedsięwzięcia, może dać wykonawcy przewagę konkurencyjną na rynku usług budowlanych.

Dalsze badania autorów będą się koncentrowały na opracowaniu algorytmu opartego na metodzie podziału i ograniczeń dedykowanego do rozwiązywania prezentowanego problemu harmonogramowania przedsięwzięć budowlanych i oceny jego efektywności oraz złożoności obliczeniowej.

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