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PLANNING REPETITIVE CONSTRUCTION PROCESSES TO IMPROVE ROBUSTNESS OF SCHEDULES IN RISK ENVIRONMENT

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Most scheduling methods used in the construction industry to plan repetitive projects assume that process durations are deterministic. This assumption is acceptable if actions are taken to reduce the impact of random phenomena or if the impact is low. However, construction projects at large are notorious for their susceptibility to the naturally volatile conditions of their implementation. It is unwise to ignore this fact while preparing construction schedules. Repetitive scheduling methods developed so far do respond to many construction-specific needs, e.g. of smooth resource flow (continuity of work of construction crews) and the continuity of works. The main focus of schedule optimization is minimizing the total time to complete. This means reducing idle time, but idle time may serve as a buffer in case of disruptions. Disruptions just happen and make optimized schedules expire. As process durations are random, the project may be delayed and the crews' workflow may be severely affected to the detriment of the project budget and profits. For this reason, the authors put forward a novel approach to scheduling repetitive processes. It aims to reduce the probability of missing the deadline and, at the same time, to reduce resource idle time. Discrete simulation is applied to evaluate feasible solutions (sequence of units) in terms of schedule robustness.

Keywords: project scheduling, repetitive construction processes, proactive scheduling, risk management in construction, simulation method

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1. INTRODUCTION

All project participants benefit from a quick, timely, and efficient delivery of construction projects. However, construction activities are conducted in a risky environment. As the list of potential obstacles is long and their occurrence hard to predict at the planning stage, construction projects frequently miss their deadlines. It is advisable to conduct a detailed risk analysis to identify the factors of the greatest impact and probability of occurrence, to estimate losses due to anticipated delays for both the client and the contractor. From the point of the client, any extension of construction time puts back the operating phase and increases the project payback time. In case of delays, the contractor must reckon with penalties, binding more capital in works in progress, and binding resources needed for other projects [20, 42].

Researchers worldwide strive to identify key factors that affect the duration of capital projects, works conducted by a particular contractor, or particular construction operations (Turkey [5], Indonesia [4, 30], Poland [26, 44], the United States of America [46], Hong Kong [2, 49], Kuwait [31], Malaysia [29], Singapore [33], Gaza Strip [12], the Republic of South Africa [35], United Arab Emirates [14], Saudi Arabia [3], Lebanon [36], and Ghana [17]). Lists of risk factors, considered to be the most important in particular countries, can be found, among others, in [6, 43].

Judging by the literature on the subject, the researchers cannot find consensus on the key risks and terminology related to risk factors [9, 16]: the same factors are described in different words, and the same names are given to different notions. The authors conducted own survey on factors affecting the time of construction processes in Polish conditions [26, 27]. The ones deemed most important were: adverse weather (cold, rain), propagation of schedule disturbances (one delayed work implies changes in the consecutive ones), scarcity of qualified personnel, design errors, incomplete design, the client's failure to make decisions in time, extensions and changes of the scope of works (design variations), and no incentive pay system.

The literature is rich in models that facilitate predicting project or process duration on the basis of key independent variables, determined by forecasting the project conditions or risk factors. The most popular techniques to build them are statistical regression [10, 38], neural networks [1, 13, 32, 50], Bayesian networks, as well as mathematical modelling (simple analytical models) and expert systems based on fuzzy logic [15, 18, 37].

The project risk management process is expected to produce a strategy to counteract the negative effects of random impacts and variable conditions, and the necessary actions should be taken

already at the stage of project planning and scheduling. The risk can be managed, minimized, shared, transferred or accepted. However, it cannot be ignored [47]. Extending the project delivery time increases the cost [45, 51].

The paper presents a method of selecting such variant of the schedule of repetitive processes that proves its highest robustness against risks. An original way of testing the schedule robustness is proposed: it accounts for the scale of project delay, protraction of works in particular units (locations/sections/buildings) and extension of the engagement of resources.

2. METHODS OF REPETITIVE SCHEDULING IN CONSTRUCTION: DETERMINISTIC AND RISK-BASED APPROACHES

Projects that involve repetitive processes are common in construction and civil engineering (housing estates, buildings composed of similar sections, tall buildings, roads, tunnels, pipelines, etc.). To enable scheduling for minimised construction time, these facilities are divided into units where similar sets of processes are to be conducted by specialised crews that do the same type of work moving from one unit to the other. Many dedicated methods have been developed to schedule them in deterministic conditions. They are often based on graphical models or mathematical optimization algorithms. They account for relationships between the work of crews in consecutive units and usually aim to ensure the continuity of their work and short project completion time. These methods include the "Line of Balance" [8, 41], "Vertical Production Method" [34], "Horizontal and vertical logic scheduling for multi-storey projects" [48], "Linear scheduling method" [28] and "Repetitive scheduling method" [21]. However, most methods were created with the thought of identical units [40]. If the units differ in the scale of workload, and if there exists no fixed proportion between the workload related with all process types, the sequence of units has a profound impact on project duration and resource continuity. The use of BIM models in the scheduling of construction processes can improve construction management through improved information flow between the project participants. Updating BIM data at the implementation stage allows for updating the life cycle cost value [7].

The problem of selecting the best sequence of units is the object of analysis in the manufacturing industry (job-shop system) as well as in construction. An example of a workflow organisation of construction operations that aim at minimising the time of project implementation is the time couplings method [22] with extra relationships between processes. However, introducing more

constraints (like resource continuity or continuity of work in units) typically makes projects take more time.

Methods of “risk-aware” scheduling have been developed for some time. Unfortunately, most of the established methods were designed for non-repetitive projects unique processes or for industrial production. There exist three strategies to account for uncertainty in project planning: reactive, stochastic, and proactive scheduling. Reactive scheduling consists in revising the schedule in response to disruptions, where the planner strives to meet the completion date defined by the baseline schedule [11, 24]. In stochastic project scheduling, no baseline schedule is created. Subsequent activities are added to a previously agreed partial schedule according to a certain scheduling policy that, at each decision point, adds new activities on the basis of work logic and resource constraints. The scheduling policy may use the information contained in the network, information on the uncertainty of activity durations, information on partial order created until the decision point, or information on activities’ resource requirements. With the proactive approach, a schedule is created to be robust against possible disruptions. A common method to make the schedule robust is adding time buffers [19, 23, 27, 39].

Herroelen and Leus [25] defined two types of robustness: quality robustness understood as the insensitivity of the project completion date (or other optimization criteria) to disruptions, and solution robustness (or schedule stability) where completion dates of particular processes are insensitive to disruptions. The measures of robustness can be derived from simulations. An example of such a measure is the probability of completing the project on time.

Simulation has been used to describe, plan, and study complex construction projects for several decades. The main advantage of simulation models is the lack of limitations to the complexity of the object of testing, the possibility to analyse the impact of multiple random factors, and the possibility to account for stochastic processes.

3. PROPOSED APPROACH TO REPETITIVE CONSTRUCTION PROCESSES SCHEDULING IN RISK ENVIRONMENT

3.1. ASSUMPTIONS

The project comprises n processes to be conducted in a fixed sequence in each of m units (e.g. separate buildings or building segments). The units differ shapes and sizes, and there is no fixed proportion between the amount of work (and thus duration) related to processes in different units.

Such projects are referred to as non-typical repetitive. The proposed approach assumes that process durations are random variables and their probability distributions types and parameters are known. Each process is entrusted to an individual crew. Each crew, on completion of their work in a unit, start the same activity in the next unit, and the unit they leave is taken over by the next crew to conduct the consecutive process. The baseline duration of process $i, i = 1, 2, \dots, n$, conducted by crew i in unit $j, j = 1, 2, \dots, m$, is $\bar{t}_{i,j}$. The project is expected to be completed by the predefined deadline T_d and failing to meet the deadline means contractual penalties to be paid. The penalty amount is proportional to the scale of delay.

The project is modelled according to the Time Coupling Method III [22], which considers couplings only between the units and resources. In deterministic conditions, this method aims to minimize the project duration, and additional constraints causing its extension are less important. If project duration is reduced, the project's time buffer increases – thus increasing the reliability of meeting the deadline and the value of expected delay [27]. The quality of the schedule depends on the sequence in that the crews move from unit to unit, and the sequence is the same for all crews. Therefore, the project duration is a function of the permutation of units, P_k :

$$(3.1) \quad T = f_T(P_k), \quad k = 1, 2, \dots, m! .$$

To boost the reliability of meeting the project due date T_d , all processes are scheduled to start as soon as possible.

One of the basic functions of the scheduling process is to find hidden time reserves. They exist if the works are not sufficiently harmonized. Thus, scheduling is expected to minimize idle time. Schedules are a tool to harmonize work and thus should ensure better use of working time of resources involved in the implementation of projects, by reducing time loss and unnecessary downtime.

Striving for reduced project duration fosters maximizing resource utilization rates, but does not assure continuity of work of particular crews as well as continuity of work in units. The focus is on completing the whole project as soon as possible, not on the quick completion of particular units. The decision-maker, while approving a schedule for implementation, considers additional costs resulting from the idle time of individual crews and fragmentation of works in particular units, often taking them into account in calculating the bid price or expected profit. However, in the risky environment, these costs may increase, and the project's economic efficiency may suffer.

For these reasons, the problem of scheduling repetitive processes with risk can be formulated as a multi-criteria optimization problem with three objective functions:

$$(3.2) \quad \min T_1 : T_1 = E(T(P_k) - T_d), k = 1, 2, \dots, m!$$

$$(3.3) \quad \min T_2 : T_2 = \sum_{i=1}^n E(C_i(P_k) - C_i(P_k)), k = 1, 2, \dots, m!$$

$$(3.4) \quad \min T_3 : T_3 = \sum_{j=1}^m E(O_j(P_k) - O_j(P_k)), k = 1, 2, \dots, m!$$

or with one objective function being their equivalent:

$$(3.5) \quad \min z : z = w_1 T_1 + w_2 T_2 + w_3 T_3,$$

where:

T_1 – the expected value of project delay (delay is measured as the difference between the simulated completion and the contractual due date T_d),

T_2 – the expected value of the total extension of the crews' employment periods in relation to the periods resulting from the schedule with baseline process durations,

T_3 – the expected value of the total extension of the completion time of individual units in relation to the times specified in the schedule with baseline process durations,

w_1, w_2, w_3 – arbitrary weights of criteria corresponding to the unit cost of delays or time extensions,

T – the project duration (random variable),

C_i – the period of employment of crew i with the project (random value); it start is always defined according to the schedule with baseline process durations,

O_j – the completion time of unit j ,

C_i – the baseline value the period of employment of crew i with the project (according to the schedule with baseline process durations),

O_j – the baseline completion time of unit j (according to the schedule with baseline process durations).

3.2. MATHEMATICAL MODEL

The problem consists in finding the optimal permutation of units $P_k = \{1, 2, \dots, r, \dots, m\}$, where the optimal means of minimal value of the objective function. The sequence r of unit j at permutation

P_k is $r = P_k(j)$. For each permutation $P_k, k = 1, 2, \dots, m!$, and each occurrence $t_{i,j}$ of random values $t_{i,j}$ of process durations $i, i = 1, 2, \dots, n$, in units $j, j = 1, 2, \dots, m$ (or for baseline durations), the earliest possible start dates $s_{i,j}$ of processes i in units j can be found by solving the following linear programming problem:

$$(3.6) \quad \min s : s = \sum_{i=1}^n \sum_{j=1}^m s_{i,j}(P_k)$$

$$(3.7) \quad s_{1,j}(P_k) = 0, j : P_k(j) = 1$$

$$(3.8) \quad s_{i,j}(P_k) + t_{i,j} \leq s_{i,l}(P_k), \forall i = 1, 2, \dots, n, \forall (j, l) : P_k(l) = P_k(j) + 1$$

$$(3.9) \quad s_{i,j}(P_k) + t_{i,j} \leq s_{i+1,j}(P_k), \forall i = 1, 2, \dots, n-1, \forall j = 1, 2, \dots, m$$

$$(3.10) \quad s_{n,j}(P_k) \leq T_d, j : P_k(j) = m$$

The objective function (Eq. (3.6)) serves to define the earliest possible start dated of processes in units.

At permutation P_k , the first process in the first unit starts at 0 (Eq. (3.7)).

Conditions (3.8) – (3.9) model the sequence of processes. The project is to be completed by the due date (Eq. (3.10)).

3.3. PROCEDURE FOR SELECTING THE OPTIMAL SCHEDULE

Because of the probabilistic nature of the parameters, this problem is suggested to be solved by means of computer simulation and metaheuristic algorithms or, in simple cases (small number of units) by reviewing the complete set of acceptable solutions.

The procedure comprises three steps:

- 1) generating permutations – acceptable schedules based on deterministic durations of processes,
- 2) Monte Carlo simulations for these schedules where process durations are random values of predefined distribution types and parameters,
- 3) evaluating solutions using the multi-criteria objective function.

In the case of the complete review method, for each permutation of units and the baseline process durations, the early starts of processes in units are defined by solving the problem described by Eq. (3.6) – Eq. (3.10).

On this basis, the baseline schedule is created for each permutation, and related project duration, crew's employment periods, and unit completion times are calculated.

Some permutations may imply contradictions in the linear programming problem (project completion date misses the deadline). These permutations should be excluded. The acceptable permutations are used in the next stage of the problem-solving procedure.

They are evaluated according to criterion (3.5) and used to generate the realization of variable random times of processes in the course of simulations. The permutation with the lowest value of the objective function is considered optimal, and the corresponding schedule is recommended for implementation.

If metaheuristic algorithms are used, a sample of permutations is generated (a population of initial solutions). Its elements are evaluated according to criterion (3.5) and simulations. In subsequent iterations of the algorithm, new populations of solutions are generated in search of better ones, until the stopping condition of the algorithm is met.

4. APPLICATION OF THE PROCEDURE FOR SELECTING THE OPTIMAL SCHEDULE: AN ILLUSTRATIVE EXAMPLE

The proposed procedure, based on a complete review of acceptable solutions, was used to create a schedule for a case presented in [22]. This project involves the construction of four buildings A, B, C, D, each of them constituting a separate unit. The scope of works comprises seven processes. It was assumed that process durations in units are random variables of a triangular distribution. The processes' baseline durations were assumed to be equal to be their means. Table 1 lists the values distribution parameters according to a process and a unit. The project's time for completion was set at 205 days from the start.

Among the total of 24 permutations of units, only 6 were producing acceptable baseline schedules (i.e. the not exceeding project's time for completion). They are listed in Table 2. Corresponding simulation models were constructed with GPSS World (General-Purpose Simulation System) by Minuteman Software. The results of simulation experiments are listed in Tables 3 and 4.

As in the case of non-repetitive construction projects [27] that involve unique processes, the size of the project buffer, i.e. the difference between the project deadline and the as-planned completion date, has a significant impact on the probability of meeting the deadline and on the expected value of the delay. However, as prompted by the results of the example, it is difficult to indicate a clear relationship: permutations may be of the same mean duration but of different mean delays.

Theoretically, a permutation of minimum baseline duration may prove less robust than a permutation with a greater baseline duration.

Table 1. Input – process duration parameters per unit

Process no. i	Description	Unit j	Parameters of the triangular distribution of process durations t_{ij}			
			minimum	maximum	mode	mean $E(t_{ij})$
1	Earth work	A	2	7	3	4
		B	3	10	5	6
		C	1	6	2	3
		D	2	4	3	3
2	Foundation work	A	1	3	2	2
		B	1	3	2	2
		C	2	7	3	4
		D	3	5	4	4
3	Masonry work	A	18	36	24	26
		B	9	27	15	17
		C	16	44	27	29
		D	15	27	18	20
4	Concreting work	A	16	32	21	23
		B	2	9	4	5
		C	15	30	21	22
		D	9	19	11	13
5	Roofing work	A	9	16	11	12
		B	3	8	4	5
		C	1	6	2	3
		D	5	18	10	11
6	Plaster work	A	4	13	7	8
		B	6	16	8	10
		C	9	32	16	19
		D	9	18	12	13
7	Finishing work	A	25	41	30	32
		B	25	52	34	37
		C	28	53	36	39
		D	24	47	31	34

Table 2. Acceptable permutations of units

k	Permutation P_k	Baseline duration [dni]
1	{B, D, A, C}	187
2	{B, D, C, A}	189
3	{B, A, C, D}	199
4	{B, A, D, C}	199
5	{B, C, A, D}	203
6	{B, C, D, A}	203

Table 3. Simulation results for acceptable solutions

k	Permutation P_k	the expected value of the total extension of the crews' employment periods, days						the expected value of the total extension of the completion time of individual units, days				
		1	2	3	4	5	6	7	A	B	C	D
1	{B, D, A, C}	0.882	1.087	3.726	4.118	4.146	4.667	8.519	4.192	6.124	6.363	8.519
2	{B, D, C, A}	0.890	1.098	3.731	4.228	4.283	4.365	7.096	4.195	6.128	7.592	7.820
3	{B, A, C, D}	0.885	1.054	3.728	4.457	4.622	5.569	6.493	4.194	3.553	6.045	6.493
4	{B, A, D, C}	0.887	0.997	3.730	3.957	3.983	4.507	4.864	4.196	3.553	4.149	4.864
5	{B, C, A, D}	0.886	1.060	3.729	4.424	4.860	5.008	5.895	4.193	4.645	4.914	5.344
6	{B, C, D, A}	0.881	1.112	3.729	4.012	4.066	4.144	5.282	4.194	4.644	5.091	5.282

Table 4. Results of simulation studies of the project implementation schedules for the permissible permutations of the P_k facilities - summary of the results according to particular criteria

k	Permutation P_k	Expected value of project delay, days	Expected value of total extension of the crews' employment periods, days	the expected value of the total extension of the completion time of individual units	Objective function value (3.5) at $w_1=0.80, w_2=0.05, w_3=0.15$
1	{B, D, A, C}	0.63719	27.145	25.198	5.647
2	{B, D, C, A}	0.86927	25.691	25.735	5.840
3	{B, A, C, D}	3.31123	26.808	20.285	7.032
4	{B, A, D, C}	2.24348	22.925	16.762	5.455
5	{B, C, A, D}	4.34237	25.862	19.096	7.631
6	{B, C, D, A}	4.29351	23.226	19.211	7.478

Judging by the expected values of extensions of crew employment time and unit completion time, the permutations of longer baseline durations are not “worse”: their extension values are in some cases lower, but this is not a rule. The source of this phenomenon are larger process floats that anticipate random disturbances, with the float sizes being determined by the differences in the baseline values of process durations in units and the sequence of their execution.

For the assumed criteria weights (quoted in Table 4), the following permutation of units proved the best: {B, A, D, C} of 199 days of baseline project duration. Though its expected value of project delay was not the smallest, the expected extensions of the crew’s employment time and the extensions of unit execution times were smaller than those of all competing solutions.

5. CONCLUSIONS

The common phenomenon of construction project delays has its source not in the limited access to resources, but primarily in the exposure of construction production to risk. According to the risk management methodology, risks need to be identified early. Their impact needs to be assessed and actions taken to prevent or reduce them.

The effects of the risks materializing may be expressed with a variety of measures. From the point of contractors or other commercial organizations, the key measure may be the cost of risk or financial losses. This approach was adopted by the authors: the problem of optimizing the schedule of a repetitive project used the objective function that minimised the combined financial losses due to: missing the project deadline, prolonging the period of employment of crews, and extending the completion time of individual units as a result of downtime caused by random phenomena.

The proposed approach to scheduling accounts for the particular character of linear projects or repetitive construction and civil engineering projects. It helps improve the efficiency of project management only through organizational improvements. It is achieved by changing the sequence of works without violating the logic of the works, without engaging additional resources, and at no additional cost.

The paper focuses on only one type of workflow organization method, where the constraints on resource continuity and continuity of works in units were relaxed. The results prompt that the pursuit of reducing project duration leads to large (compared with the expected values of project delays) interruptions in the resource work and in the delivery of units and, as a result, to a significant destabilization of the schedule.

In their further research, the authors intend to develop their scheduling method not only to improve the reliability of the project completion time but also to protect the dates of engaging the crews and durations of works in units against disruptions.

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LIST OF FIGURES AND TABLES:

Tab. 1. Input – process duration parameters per unit

Tab. 1. Dane – parametry rozkładu czasu realizacji procesów na obiektach

Tab. 2. Acceptable permutations of units

Tab. 2. Dopuszczalne permutacje obiektów

Tab. 3. Simulation results for acceptable solutions

Tab. 3. Wyniki badań symulacyjnych dla rozwiązań dopuszczalnych

Tab. 4. Results of simulation studies of the project implementation schedules for the permissible permutations of the P_k facilities - summary of the results according to particular criteria

Tab. 4. Wyniki badań symulacyjnych harmonogramów realizacji przedsięwzięcia dla dopuszczalnych permutacji P_k obiektów – zestawienie wyników ocen wg poszczególnych kryteriów

METODA HARMONOGRAMOWANIE POWTARZALNYCH PROCESÓW BUDOWLANYCH ZWIĘKSZAJĄCA ODPORNOŚĆ HARMONOGRAMÓW W WARUNKACH RYZYKA

Słowa kluczowe: harmonogramowanie przedsięwzięć budowlanych, harmonogramowanie procesów powtarzalnych, harmonogramowanie proaktywne, zarządzanie ryzykiem w budownictwie, metoda symulacji

STRESZCZENIE

Terminowa i sprawna realizacja przedsięwzięć budowlanych oraz redukcja czasu ich wykonania wpływają na efektywność ekonomiczną inwestycji i działalności gospodarczej wielu podmiotów zaangażowanych w proces inwestycyjny. Cechą specyficzną produkcji budowlanej jest znaczna podatność na oddziaływanie zmiennych warunków realizacji, dlatego też przy harmonogramowaniu nie powinno się pomijać wpływu oddziaływania czynników ryzyka.

Wiele przedsięwzięć budowlanych składa się z powtarzalnych procesów, są to m.in. budowy osiedli domów mieszkalnych, budowy obiektów wysokich i wielosekcyjnych, dróg, tuneli, instalacji itd. W celu redukcji czasu ich wykonania obiekty te dzieli się na działki robocze, na których powtarzane jest wykonywanie procesów przez brygady robocze o odpowiednich kwalifikacjach. W przypadku, gdy działki różnią się wielkością i nie występuje zależność wprost proporcjonalna pomiędzy ich wielkością i pracochłonnością robót (jednakowa dla każdego ich asortymentu), na czas realizacji przedsięwzięcia oraz na inne parametry wpływa kolejność zajmowania działek przez brygady.

W artykule została przedstawiona metoda wyboru optymalnego harmonogramu robót powtarzalnych realizowanych na działkach niejednorodnych w warunkach ryzyka i optymalnej permutacji działek roboczych. Analizowany problem opisano za pomocą modelu programowania stochastycznego z funkcją celu minimalizującą łączne straty finansowe spowodowane niedotrzymaniem terminu dyrektywnego przedsięwzięcia, wydłużeniem okresu zatrudnienia brygad i czasu realizacji poszczególnych obiektów, na skutek przestoju spowodowanych zjawiskami losowymi. Ze względu na probabilistyczny charakter parametrów rozpatrywanego problemu do jego rozwiązania zaproponowano procedurę bazującą na zastosowaniu metody symulacji komputerowej oraz algorytmów metaheurystycznych lub – w przypadku problemów o małej złożoności z niewielką liczbą działek roboczych – metody przeglądu zupełnego zbioru rozwiązań dopuszczalnych. Krok pierwszy proponowanej procedury polega na znalezieniu w warunkach deterministycznych dopuszczalnych uszeregowania działek roboczych, którym odpowiadają harmonogramy z terminem realizacji przedsięwzięcia krótszym od założonego terminu dyrektywnego. W kroku drugim założono, że czasy realizacji procesów są zmiennymi losowymi o znanych rozkładach prawdopodobieństwa. Rozwiązania dopuszczalne są analizowane metodą symulacji komputerowej w celu ustalenia wartości oczekiwanej opóźnienia terminu zakończenia przedsięwzięcia w stosunku do terminu dyrektywnego, wartości oczekiwanej łącznego wydłużenia okresów zatrudnienia brygad oraz wartości oczekiwanej łącznego wydłużenia czasu realizacji poszczególnych obiektów w stosunku do okresów wynikających z harmonogramów opracowanych w warunkach deterministycznych. W kroku trzecim wybór rozwiązania optymalnego jest sformułowany jako zadanie optymalizacji wielokryterialnej z trzema funkcjami celu.

Proponowaną procedurę zastosowano do wyboru harmonogramu optymalnego dla przykładowego przedsięwzięcia obejmującego realizację czterech budynków, każdy z nich stanowi odrębną działkę roboczą. Proces budowy podzielono na 7 procesów i do ich realizacji zorganizowano 7 odrębnych brygad branżowych. Przyjęto, że procesy są rozpoczynane w terminach najwcześniejszych z możliwych (bezpośrednio po zakończeniu procesu poprzedzającego na tej działce oraz wykonaniu przez brygadę robót na działce poprzedzającej). Modele symulacyjne harmonogramów dopuszczalnych

były opracowane w języku symulacyjnym ogólnego przeznaczenia GPSS (General-Purpose Simulation System) w wersji opracowanej przez Minuteman Software – GPSS World.

Przeprowadzone badania wykazały, że teoretycznie lepszym rozwiązaniem z punktu widzenia odporności terminu dyrektywnego zakończenia przedsięwzięcia może okazać się permutacja obiektów (działek roboczych), której odpowiada harmonogram zaprojektowany dla warunków deterministycznych z większym niż minimalnym czasem realizacji przedsięwzięcia. Wpływ na prawdopodobieństwo dotrzymania terminu dyrektywnego zakończenia przedsięwzięcia oraz wartość oczekiwaną opóźnienia jego zakończenia ma wielkość buforu projektu, czyli różnica terminów dyrektywnego i planowanego zakończenia. Źródłem tego zjawiska są większe zapasy czasu procesów w harmonogramach dopuszczalnych, które antycypują zakłócenia losowe, przy czym ich wielkość jest zależna od kolejności realizacji obiektów (działek roboczych).

Na podstawie analizy uzyskiwanych wyników można stwierdzić, że dążenie do skrócenia czasu realizacji przedsięwzięcia może prowadzić jednak do niewspółmiernie dużych, w porównaniu do przeciętnych wielkości opóźnień, przerw w zatrudnieniu brygad i w realizacji obiektów oraz w efekcie do znacznej destabilizacji harmonogramu. Proponowana ujęcie może być stosowane do analizy przedsięwzięć budowlanych harmonogramowanych różnymi wariantami metody sprzężeń czasowych, nie tylko z uwzględnieniem sprzężeń pomiędzy frontami robót i środkami realizacji. Kierunkiem dalszych badań autorów będzie zatem rozwijanie proponowanej metody, w celu poprawy nie tylko odporności terminu zakończenia przedsięwzięcia na zakłócenia, ale również terminów zatrudnienia brygad i realizacji poszczególnych obiektów.

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