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.2023.147649

ARCHIVES OF CIVIL ENGINEERING

Vol. LXIX ISSUE 4 2023

 pp. 89 – 104

Research paper

Proactive-reactive repetitive project scheduling method – the concept of risk consideration at the project planning and execution stage

Piotr Jaśkowski[1], Sławomir Biruk[2], Michał Krzemiński[3]

Abstract: The construction contractor is concerned with reducing the cost of the project, including reducing unnecessary downtime. This is achieved when resources are fully utilized; this means the crews work continuously moving without interruption from one location to the other. However, any disturbance in the optimally scheduled workflow caused by random events is likely to result in delays, interruptions in the crews work, and productivity losses. There is therefore a need for scheduling methods that allow plans to be more resilient to disruptions and ensure a reduction in downtime and implementation costs. The authors put forward a proactive-reactive approach to the schedule risk management. Proposed method makes it possible to protect schedule deadlines from the impact of risk factors by allocating time buffers (proactive approach). It also takes into account the measures that managers take during execution in response to delays that occur, such as changing construction methods, employing extra resources, or working overtime (reactive approach). It combines both ideas and is based on project simulation technique. The merits of the proposed approach are illustrated by a case of a repetitive project to erect a number of buildings. The presented example proves that the proposed method enables the planner to estimate the scale of delays of processes' start and consider the impact of measures to reduce duration of processes in particular locations taken in reaction to delays. Thus, it is possible to determine the optimal schedule, at which the costs of losses associated with delays and downtime are minimal.

Keywords: project risk management, project scheduling, repetitive construction processes, schedule optimization, simulation modeling

[1]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, ORCID: 0000-0003-1661-3373
[2]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, ORCID: 0000-0003-4392-8426
[3]DSc., PhD., Eng., Warsaw University of Technology, Faculty of Civil Engineering, Al. Armii Ludowej 16, 00-637 Warsaw, Poland, e-mail: m.krzeminski@il.pw.edu.pl, ORCID: 0000-0002-6352-5942

1. Introduction

The production and project scheduling literature is rich in optimization methods that allow for a variety of real-life constraints. As the scheduling problems are computationally complex the algorithms are typically of heuristic nature. Whether the best schedule defined by the planner is optimal or only sub-optimal is not important: even a perfectly optimized solution may expire in the face of disruptions in the course of processes. Especially in construction projects, disturbances are common [1]. Occurrences such unexpected local conditions, adverse weather, misunderstandings among the typically numerous project participants, or design inconsistencies, naturally lead to changes in process durations and may spoil even most cleverly devised plans [2]. Even in the times of resource availability (so if the machinery, skilled workforce, or subcontractors can be easily and quickly hired), exceeding project due dates and budgets is common. Besides, any reaction to bring a disrupted project back on tracks assumes spending extra money. For this reason, there is a call for scheduling methods that allow for the natural dynamics of projects in risky or uncertain environment.

The majority of scheduling methods were invented for non-repeatable projects involving one-off processes to be conducted in a predefined sequence modeled by precedence networks. However, the nature of most construction projects is repeatable [3]. The erected structures may be reasonable to divide into units whose delivery involves completing repeatable sequences of processes entrusted to specialized resources (construction crews or machine sets), and the project execution process may be streamlined by enabling the resources to work concurrently in different units. In such cases, network modeling proves inefficient [4].

Similarly, the classic methods of risk-aware scheduling, such as PERT, prove oversimplified [5]. The contemporary scheduling techniques assume a proactive approach to risk and aim at creating schedules robust to some level of disruptions. However, it is not practical to devise schedules that ensure reliability of meeting the completion date by postponing it (i.e. adding generous buffers): in construction, the completion dates and intermediate milestones are typically non-negotiable. If fixed due dates are enforced by the client, the only way to meet them is to anticipate problems and react by speeding up the works when necessary.

The authors propose a predictive-reactive scheduling for projects that include repetitive processes. The method aims at reducing the sum of costs of delay penalties, resource idle time, and actions to reduce deviations from the baseline schedule. The proactive approach consists in constructing a baseline schedule defining start dates for crews delivering repeatable processes. The schedule incorporates time buffers that precede the start of consecutive activity sequences [6]. They anticipate the disturbance and their purpose is to assure resource continuity. The size of buffers is decided according to proposed response to the delays to reduce duration of processes that cannot start as scheduled in the baseline. The quality of schedules is evaluated by simulation.

2. Risk-aware scheduling concepts

The literature presents several approaches to scheduling at risk. Three most frequently referred to are: offline, online, and hybrid scheduling [7].

The offline scheduling involves creating robust baseline schedules that include measures anticipating potential execution disruptions and protecting due dates of processes, milestones, or the entire project. Their use is all the more advisable and important as fixed dates for the execution of processes in the construction schedule make it possible to optimize the logistics behind the on-site activities (auxiliary production, schedules of supplies with materials and equipment, acquisition of human resources, and subcontractors) [8]. Reducing the deviation of scheduled deadlines from the actual ones makes it possible to reduce the costs of exceeding them, including the cost of capital tied up in inventories, cost of resource downtime, delay penalties, etc. [9].

Such robust schedules can be created using robust optimization techniques that focus on generating acceptable solutions, so schedules that meet all constrains. These methods can only be applied to repetitive or routine projects, as they base on reliable historical data to derive probability distributions of process execution times. They can be applied even in the absence of probability distributions of parameters, as long as the ranges of their values are known [10]. However, the approach using robust optimization techniques is judged to be conservative when it leads to an objective value of obtained solutions much worse than expected.

Another type of the offline scheduling approaches is predictive scheduling, where disturbances are anticipated (proactive approach) and the schedule is constructed to be immune to them [11]. It typically consists in distributing time buffers throughout the schedule to protect the process start dates against delays of their predecessors [12] using the redundancy and contingency techniques.

The contingency technique is more traditional and consists in locating buffers at the end of predecessors so that the buffers are treated as the integral part of the duration estimate of a process calculated with an assumed "satisfactory" confidence [8]. As a result, schedules that include processes arranged in series prompt project durations considerably longer than "unbuffered" schedules.

In contrast, the redundancy technique treats buffers as scheduled pauses in the course of works located in a few carefully selected places of the project network. Their usual location is before processes or project milestones that are critical for the timely delivery of the project, and before the project finish [13]. The buffers anticipate disturbances in processes to be delivered in series scheduled to start "as soon as possible" or according to the "railway policy" (as soon as possible but no earlier than on a fixed start date). One of the first methods of redundancy-based robust scheduling that consisted in protecting the key series of processes (the critical chain), was proposed by Goldratt [14]. This method does not enable the planner to set fixed dates of particular processes: just like with PERT, the processes are scheduled "as soon as possible". This focus on protecting the completion date of the whole project is characteristic for most classic methods of scheduling at risk/ uncertainty. The focus on completing "the whole thing" on time is not sufficient. There is a need for precise setting of dates of introducing new resources (subcontractors, crews) to the project, for assuring resource continuity, and for meeting project packages' due dates as, in practice, construction works are paid in stages, per completed package of works.

To apply the proactive scheduling idea to practice, the research and management community search for the best methods to define buffer sizes and locations. Goldratt's proposals in this respect [14] are criticized for the feeding buffers' insufficiency in protecting continuity of the critical chain processes, the project buffer's unnecessary delaying the as-planned project completion date, and the arbitrary halving the estimates of the processes' time for completion [15]. Other ideas are tested by means of simulations and assessed under a variety of schedule quality criteria. The most frequent objective of schedule optimization is minimizing the "schedule instability cost", so the weighted sum of the expected values of costs attributable to process or project stage delays [16].

A characteristic feature of the offline methods is relying on information present before the project starts, so considering only what is known at the moment when the baseline schedule is prepared. This is natural, but the planner admits that their product is based on available, but incomplete and imprecise input. In contrast, the online [17, 18], or dynamic [19] scheduling approach rests upon information that appears in the course of project execution.

With online scheduling, decisions on which process to start at certain moment (or which processes should start in the near future) are made and reviewed as the project progresses. The hallmark of this approach is that no baseline schedule is created. Instead, short-term partial schedules are created. Subsequent activities are added to the previous version of a partial schedule based on the so-called scheduling policy or dispatching rules. Thus, in every decision point, the planner refers to precedence and resource availability constraints, and adds new activities. The scheduling policy can use information contained in the network, information about planned activity durations, the partial schedule created for the decision point, or the activities' resource usage [20]. As there exists no baseline schedule to cover the whole scope of the project over the whole planning horizon, this approach is hard to apply to construction with its one-off supply chains and long negotiation times. However, there are reports on its successful implementation in the production industry environment.

Construction schedules tend to expire even if they are created using proactive methods: construction activity is subject to events with the impact too big to be mitigated by any economically justified buffers set in advance. There is then a need to react – to modify processes to follow to bring the project "back on tracks" and adhere to the baseline schedule logic, or even to schedule remainder of the project anew [21].

Modification (rescheduling) is usually done to ensure the stability of the baseline schedule, i.e. to minimize the changes of dates of processes that have not started yet. This may involve revising process sequences or distributing process floats in a way consistent with the initial planning objectives and constraints. Alternatively, one can reschedule the remainder of the project seeking to optimize the schedule under the original criteria used for the baseline, focus on increasing the resilience of the new schedule, or seek to minimize the cost of corrective actions.

If delays proved considerable, rescheduling may involve increasing availability of resources (working overtime, hiring extra workforce or plant etc.) or changing methods of delivering processes. This way, the processes may stay the same in terms of their material effect, but the mode of delivering them becomes different. The approach of changing the mode of certain activities while considering resource constraints was applied by Deblaere et al. [22], but the effects were assessed only in terms of discrete activity duration disruptions and resource disruptions at randomly selected moments and ignoring the random character of process durations.

Pasławski [23] observed that considering process modes already at the stage of creating the baseline schedule makes the planning process flexible and streamlines schedule updates. Considering multiple process modes is the idea behind the so called conditional scheduling that consists in preparing a number of predictive schedule options to be chosen from at the moment a disturbance occurs [24].

Only few rescheduling methods combine the online and offline approaches: the project is delivered according to the dates set by the baseline schedule, and the updates of the baseline are made on the basis of real-time information on the actual progress. An example of this approach is presented in the paper [9]. The update does not consist in building a new schedule, but on selecting such modes of processes or delay mitigation measures that result in least changes relative to the baseline.

A few methods, drawing from the online approach, rely on predefined policies or strategies of selecting processes for execution. For instance, Van de Vonder et al. [25] put forward two new robust scheduling generation schemes, based on processes priority rules.

Rescheduling procedure may be implemented periodically or in reaction to an unexpected event that causes a serious disruption [26].

It is worth noting that the concepts described above are applied to various types of human activity defined as projects and modeled using network techniques. There are few examples of their tailoring to construction projects. For example, Milat et al [27] proposed surrogate measure that considers appropriate time distribution of floats through the structure of a schedule. Zuo et al. [28] presented a method for allocating the limited risk-related resources as an effective project risk-response strategy. Schatteman et al. [29] worked out a heuristic procedure to develop a stable proactive baseline schedule of network modeled construction projects, while Cao et al. [30] a multiobjective robust optimization model of line-of-balance schedules to minimize the project cost and maximize the schedule robustness. Also, the optimization approach was used by Poshdar et al. [31] in their probabilistic-based buffer allocation method.

There exist a particular research gap in methods intended for repetitive construction projects, with isolated examples of studies focused on dynamic rescheduling [32], or the search for optimal sequencing of work plots to increase schedule stability [33]. As the majority of construction projects involve repetitive processes, and the construction activities are susceptible to the highly volatile execution conditions, there is a call for better scheduling methods, and this paper is attempting to answer this call.

The methods indicated earlier, based on the network technique, can also be used for repetitive projects, but it is inefficient. The main limitation is the difficulty of reflecting the flow of resources and ensuring the continuity of the work of crews.

3. Outline of the proactive-reactive method of scheduling repetitive construction projects

This proposed method is based on the use of simulation techniques. Simulation models have been used to describe, plan, and study complex construction projects. Projects that involve the same sequences of processes conducted in a number of units/locations (often of different sizes) are referred to as repetitive projects [31].

Let us assume that, in each unit, the processes of certain type are to be delivered always by the same specialized resource (subcontractor, crew, or machine set, later referred to as crews). To reduce the project duration, and assuming that composition of each crew is to stay fixed throughout the whole project, the composition of the crew should be set in a way that maximizes the crew's capacity in the least labor-intensive unit they are to work in (this way, the crew can be fully utilized in all units regardless of their size).

Let us assume that a sequence of processes i ($i = 1, 2, \ldots, n$), arranged in series and in a fixed order prompted by the logic of works, is to be conducted in each unit j ($j = 1, 2, \ldots, m$). The duration of process i in unit j is a random variable of a defined distribution type and parameters, and its expected value is $t_{i,j}$. The contractual due date of the project is T_d.

The steps of the proposed proactive-reactive scheduling method are as follows:

1. Create the initial baseline schedule.

This deterministic schedule assumes the following:

– The duration of processes in units equal the expected values $t_{i,j}$;
– The processes are scheduled continuously – the crews are to move from unit to unit always in the same sequence and without any waiting time;
– A successive process in a unit may start no earlier than its predecessor has been completed;
– The start date of the first process in the first unit is set to 0 ($t^s_{1,1} = 0$);
– A crew commences with process $i + 1$ in unit 1 after $d_{i,i+1}$ days from the start of process i in this unit. The start-to-start lag $d_{i,i+1}$ is calculated as follows:

$$d_{i,i+1} = \max \begin{cases} t_{i,1} \\ t_{i,1} + t_{i,2} - t_{i+1,1} \\ \vdots \\ \sum_{j=1}^{m} t_{i,j} - \sum_{j=1}^{m-1} t_{i+1,j} \end{cases} \tag{3.1}$$

The start dates $t^r_{i,j}$ and completion dates $t^f_{i,j}$ of processes are calculated as follows:

$$t^f_{i,j} = t^s_{i,j} + t_{i,j}, \qquad i = 1, 2, \ldots, n, \quad j = 1, 2, \ldots, m, \tag{3.2}$$

$$t^s_{i+1,1} = t^s_{i,1} + d_{i,i+1}, \qquad i = 1, 2, \ldots, n - 1, \tag{3.3}$$

$$t^s_{i,j+1} = t^f_{i,j}, \qquad i = 1, 2, \ldots, n, \quad j = 1, 2, \ldots, m - 1. \tag{3.4}$$

The as-planned project completion date that results from the initial baseline schedule, T, is equal to the completion date of the last process n in the last unit m ($t^f_{n,m}$).

2. Simulate project progress basing on the initial baseline schedule.

At this stage, a simulation model of the project is created. In each simulation run, the execution times of processes in units are generated according to the assumptions on the distribution type and parameters (e.g., using the inverse distribution function). It is assumed that the crews are available (ready to work) at the times resulting from the initial baseline schedule. Simulations help determine the average values of downtime, g_i, for individual crews executing process i ($i = 2, 3, \ldots, n$) and estimate the distribution of project duration.

3. Build the set of buffered baseline schedules.

The initial baseline schedule assumes that processes are started as soon as possible to make the work of the crews continuous. Due to the random character of processes' duration, crew downtime appears (if the predecessor's duration happened to be longer than the expected value, the crew to conduct the successor must wait; if the duration of the predecessor takes less than the expected value, the crew conducting it needs to wait for the next unit to become available). The variability of process durations results also in the project's exceeding the as-planned deadline T, or even the contractual due date T_d.

To reduce propagation of the disturbance, the start dates of consecutive processes in the first unit are proposed to be lagged: this is naturally going to affect the as-planned project completion date T of the initial baseline schedule. Assuming that the resulting new completion date T' is acceptable, the total of these extra lags is $\Delta T = T' - T$.

The distribution of the extra lags $D_{i,i+1}$ in starting the consecutive sequences of processes, added to the lags $d_{i,i+1}$ from the initial baseline schedule, is to be conducted in proportion to the mean crew downtimes (established in the previous steps) and daily costs of crew downtimes.

Let us express the unit downtime cost of crew employed to deliver process ik^c_i. The size of the extra delay is defined by solving the following discrete mathematical problem:

$$\max z: \quad z = \min_{i=1,2,\ldots,n-1} \left\{ \frac{D_{i,i+1}}{k^c_{i+1} \cdot g_{i+1}} \right\} \tag{3.5}$$

$$\sum_{i=1,2,\ldots,n-1} D_{i,i+1} = \Delta T \tag{3.6}$$

$$D_{i,i+1} \in Z, \quad i = 1, 2, \ldots, n-1 \tag{3.7}$$

where: Z is a set of integers.

These delays act as buffers to protect the start dates of process sequences and to prevent crew downtime and delays in the execution of individual processes in units as well as in the entire project. The set of baseline schedules differing in start dates of consecutive process sequences is created for a predefined limited number of ΔT s.

4. Simulate project progress for each baseline schedule.

The set of the buffered schedules needs to be assessed to select the most suitable one. Since the buffers alone are usually insufficient (random variability of process duration generates some downtime and delays anyway), additional measures are considered to reduce the impact of risk and contribute to compressing durations of processes to make up for delays. These measures can be, for instance, working overtime on standard working days, adding extra working day in a week, or hiring additional resources. This results in the possibility of executing each process in each unit in a different (accelerated) mode, having a duration modeled as a random variable of known distribution, and a characteristic extra cost compared with the basic mode in the amount of k_i^m (for each process $i = 1, 2, \ldots, n$) per day.

Let us assume that a penalty for delivering the project later than on the contractual due date is k^p for each day of delay. Simulations enable the planner to define the average values of downtime C_i of crews delivering process $i = 1, 2, \ldots, n$, the average period M_i of implementing a different mode of delivering each process, and the average scale of the project delay P.

Thus, the average total extra cost of implementing a particular buffered baseline schedule is K (penalties, downtime costs, costs of implementing different process modes) calculated as follows:

$$K = P \cdot k^p + \sum_{i=1,2,\ldots,n} \left(C_i \cdot k_i^c + M_i \cdot k_i^m \right) \tag{3.8}$$

The buffered baseline schedule with the lowest K is considered to be the best choice.

4. Example

Application of the method is presented on the example of a project to erect six buildings (structural and envelope works). The scope of the project comprises five processes entrusted to separate crews. These are: 1 – earthworks, 2 – substructure, 3 – superstructure, 4 – roofing, 5 – facade. The execution times of individual processes in each unit (building) are random variables of a triangular distribution; table 1 summarizes the input (minimum duration – $t_{i,j}^a$, most likely duration – $t_{i,j}^m$, maximum duration – $t_{i,j}^b$). For each process, one other mode of its delivery is considered, characterized by a shorter duration (also defined by a triangular random variable) and an extra cost per day. The data on process modes are also listed in Table 1.

The delay penalty is $k^p = 20\,000$ EUR/day. The costs of crew downtime are the same for each crew and equal $k_i^c = 800$ EUR/day. The contractual due date was set to $T_d = 226$ days.

The deterministic initial baseline schedule was prepared according to the expected durations. Its total duration was 212 days. The dates of each crews' starting work to assure continuity of works are: earthworks – 0 (beginning of the first day of the project) substructure – day 22, superstructure – day 44, roofing – day 66, façade – day 89.

The first simulation of the randomized initial baseline schedule assumes that all processes start at dates set in the initial baseline schedule. The simulation was programmed using the General Purpose Simulation System (GPSS World) by Minuteman Software, using the system's default triangular distribution generators. The average duration of the project was found to be 222,897 days.

Table 1. Input for the example: durations of processes in units, the basic and accelerated mode, and the extra per day cost of using the accelerated mode

Process i	Unit (building) j	Basic mode				Accelerated mode			
		$t^a_{i,j}$ [days]	$t^m_{i,j}$ [days]	$t^b_{i,j}$ [days]	$t_{i.j}$ [days]	$t^a_{i,j}$ [days]	$t^m_{i,j}$ [days]	$t^b_{i,j}$ [days]	k^m_i [EUR/day]
1	1	17	19	27	21	–	–	–	300
	2	16	21	32	23	13	17	26	
	3	15	18	27	20	11	15	22	
	4	14	16	24	18	10	11	19	
	5	15	18	30	21	12	25	27	
	6	16	17	27	20	12	13	22	
2	1	17	20	29	22	13	16	25	300
	2	18	20	28	22	15	17	23	
	3	13	15	29	19	10	12	25	
	4	14	18	31	21	11	14	26	
	5	16	18	26	20	11	13	21	
	6	13	17	27	19	10	13	22	
3	1	17	19	30	22	15	17	28	300
	2	18	20	28	22	14	16	22	
	3	12	15	27	18	9	13	24	
	4	19	21	26	22	14	16	21	
	5	15	18	27	20	11	13	22	
	6	15	17	25	19	12	14	23	
4	1	18	20	31	23	14	16	16	300
	2	15	17	25	19	12	14	23	
	3	16	20	27	21	12	16	23	
	4	14	16	27	19	11	13	22	
	5	15	17	25	19	12	14	22	
	6	19	22	28	23	14	16	20	
5	1	17	20	26	21	13	15	21	300
	2	16	18	26	20	14	15	23	
	3	16	18	26	20	12	16	22	
	4	15	17	25	19	13	15	22	
	5	17	19	27	21	13	15	24	
	6	18	21	27	22	15	18	26	

The average values of crew downtimes were 0.000, 3.946, 6.760, 9.503, 10.885 days, respectively (the crew performing the first process never needs to wait for the next unit to be freed by other crews, so it works without interruptions). These average downtimes were the basis for defining the lags $D_{i,i+1}$ in starting the consecutive processes by solving the model described by Equations (3.5)–(3.7). Their values, calculated according to a set of predefined ΔT s, were shown in Table 2.

Table 2. Lags $D_{i,i+1}$ [days] between the starts of processes

Delay	Total lags ΔT [days]								
	2	4	6	8	10	12	14	16	18
$D_{1,2}$	0	1	1	1	2	2	2	2	3
$D_{2,3}$	0	1	1	2	2	3	3	4	4
$D_{3,4}$	0	1	2	2	3	3	4	5	5
$D_{4,5}$	2	1	2	3	3	4	5	5	6

Next, the simulations were repeated for the set of buffered baseline schedules differing in the delays between the starts of consecutive processes listed to Table 2. Results of the simulation research are presented on Fig. 1.

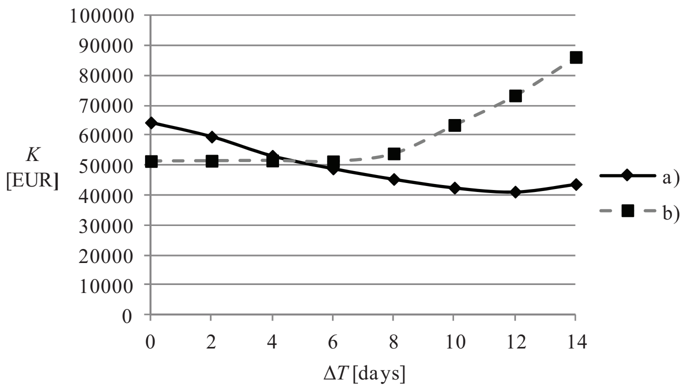

Fig. 1. The effect of the total lags ΔT on the average total cost of delays and delay mitigating measures K: a) with application of accelerated process modes, b) without modification to process modes

Please note that Process 1 in Unit (building) 1 always starts as scheduled in the initial baseline schedule, and is always conducted in its baseline mode. The results (the average crew downtimes, the average delay of project completion, the average duration of processes in accelerated modes) were used to prepare a chart (Fig. 1, solid line) relating the total delay with the extra cost of delays and measures to fight it. The dashed line in the same figure presents this relationship assuming that no other mode but the baseline mode can be applied to execute all processes, and the only way to counteract disturbance consisted in buffering.

In the analyzed case, the lowest average cost of delays and delay mitigating measures was found for the total delay of 12 days and using the option to use accelerated modes of processes. If the idea of using accelerated modes was abandoned (dashed line at $\Delta T = 12$), the costs would grow considerably because of greater exceedance the due date and resulting penalties. This observation is of course case-specific (scale of penalties compared with the cost of implementing accelerated modes and the scale of delays that result in switching to the accelerated modes).

5. Conclusions

Timely completion of a construction project is important for both the client and the contractor. It is important to meet the project due dates as well as not to miss the deadlines set for project stages or work packages, as delay penalties compromise profits. Timely delivery of tasks and projects means less trouble with the project logistics, as re-arranging delivery dates and dates of subcontractors and in-house crew's commencement with works may be difficult, costly or even impossible.

Many methods have been developed to optimize schedules according to a variety criteria, whether cost or time, taking into account various production constraints, and intended for repetitive or non-repetitive projects. However, construction projects involve risk and uncertainty, and schedules deemed optimized may easily expire. Actions taken under operational management to reduce the durations of some processes to make up for delays already incurred may be costly and unreasonable if not analyzed from the point of their impact on the project as a whole. It thus seems reasonable to develop scheduling methods that help the planner analyze effects of potential disruptions before they occur, as well as to map activities and study the effects of project monitoring and control to update plans.

The proposed proactive-reactive approach to scheduling facilitates selecting the optimal measures to reduce the impact of random phenomena on the project development in terms of costs associated with penalties for not meeting the contractual due date, losses resulting from resource downtime, as well as acceleration costs (like compensation for working overtime). The simulation technique helps map and plan policies of selecting and timing the measures taken in response to disturbances in the project progress. In the example presented in the paper, only one variant of time-reducing measures was limited to use. It seems reasonable to develop the method in order to implement and be able to evaluate the effects of multiple variants of measures. The search for optimal decisions in this area may be a direction for further research.

Acknowledgements

This work was funded under the grant "Subvention for Science" (MEiN), project no. FN-06, FN-10, FD-20/IL-4/005, FD-20/IL-4/026.

References

[1] P. Kostrzewa-Demczuk and M. Rogalska, "Planning of construction projects taking into account the design risk", *Archives of Civil Engineering*, vol. 69, no. 1, pp. 613–626, 2023, doi: 10.24425/ace.2023.144191.

[2] P. Jaśkowski and S. Biruk, "The method for improving stability of construction project schedules through buffer allocation", *Technological and Economic Development of Economy*, vol. 17, no. 3, pp. 429–444, 2011, doi: 10.3846/20294913.2011.580587.

[3] 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.

[4] H.R.Z. Dolabi, A. Afshar, and R. Abbasnia, "CPM/LOB scheduling method for project deadline constraint satisfaction", *Automation in Construction*, vol. 48, pp. 107–118, 2014, doi: 10.1016/j.autcon.2014.09.003.

[5] S.E. Elmaghraby, "The estimation of some network parameters in the PERT model of activity networks: Review and critique", in *Studies in Production and Engineering Economics, Advances in Project Scheduling*, R. Słowiński and J. Węglarz, Ed. Elsevier, 1989, pp. 371–432.

[6] W. Herroelen and R. Leus, "The construction of stable project baseline schedules", *European Journal of Operational Research*, vol. 156, no. 3, pp. 550–565, 2004, doi: 10.1016/S0377-2217(03)00130-9.

[7] M. Klimek, "Predictive-reactive production scheduling with resource availability constraints", PhD thesis, AGH University of Science and Technology, Krakow, Poland, 2010, (in Polish).

[8] P. Moonseo and P.-M. Feniosky, "Reliability buffering for construction projects", *Journal of Construction Engineering and Management*, vol. 130, no. 5, pp. 626–637, 2004, doi: 10.1061/(ASCE)0733-9364(2004)130:5(626).

[9] S. Biruk and P. Jaśkowski, "Selection of the optimal actions for crashing processes duration to increase the robustness of construction schedules", *Applied Sciences*, vol. 10, no. 22, pp. 1–14, 2020, doi: 10.3390/app10228028.

[10] N. Balouka and I. Cohen, "A robust optimization approach for the multi-mode resource-constrained project scheduling problem", *European Journal of Operational Research*, vol. 291, no. 2, pp. 457–470, 2021, doi: 10.1016/j.ejor.2019.09.052.

[11] S. Van de Vonder, E. Demeulemeester, and W. Herroelen, "Proactive heuristic procedures for robust project scheduling: An experimental analysis", *European Journal of Operational Research*, vol. 189, no. 3, pp. 723-733, 2008, doi: 10.1016/j.ejor.2006.10.061.

[12] M. Połoński and K. Pruszyński, "Impact of baseline terms on the course of critical paths and time buffers in the modified Goldratt's method", *Archives of Civil Engineering*, vol. 59, no. 3, pp. 313–320, 2013, doi: 10.2478/ace-2013-0017.

[13] P. Jaśkowski, "Methodology for enhancing reliability of predictive project schedules in construction", *Eksploatacja i Niezawodność-Maintenance and Reliability*, vol. 17, no. 3, pp. 470–479, 2015, doi: 10.17531/ein. 2015.3.20.

[14] E. M. Goldratt, *Critical chain*. Great Barrington: The North River Press, 1997.

[15] S. Van de Vonder, E. Demeulemeester, W. Herroelen, and R. Leus, "The use buffers in project management: The trade–off between stability and makespan", *International Journal of Production Economics*, vol. 97, no. 2, pp. 227–240, 2005, doi: 10.1016/j.ijpe.2004.08.004.

[16] S. Van de Vonder, E. Demeulemeester, W. Herroelen, and R. Leus, "The trade–off between stability and makespan in resource-constrained project scheduling", *International Journal of Production Research*, vol. 44, no. 2, pp. 215–236, 2006, doi: 10.1080/00207540500140914.

[17] D. Gupta and T.C. Maravelias, "On the design of online production scheduling algorithms", *Computers and Chemical Engineering*, vol. 129, art. no. 106517, 2019, doi: 10.1016/j.compchemeng.2019.106517.

[18] D. Gupta and T.C. Maravelias, "Framework for studying online production scheduling under endogenous uncertainty", *Computers and Chemical Engineering*, vol. 135, art. no. 106670, 2020, doi: 10.1016/j.compchemeng.2019.106670.

[19] S. Van de Vonder, E. Demeulemeester, and W. Herroelen, "A classification of predictive-reactive project scheduling procedures", *Journal of Scheduling*, vol. 10, pp. 195–207, 2007, doi: 10.1007/s10951-007-0011-2.

[20] S. Rostami, S. Creemers, and R. Leus, "New strategies for stochastic resource-constrained project scheduling", *Journal of Scheduling*, vol. 21, pp. 349–365, 2018, doi: 10.1007/s10951-016-0505-x.

[21] M. Janczura and D. Kuchta, "Proactive and reactive scheduling in practice", *Research Papers of Wrocław University of Economics*, vol. 238, pp. 34–51, 2011.

[22] F. Deblaere, R. Demeulemeester, and W. Herroelen, "Reactive scheduling in the multi-mode RCPSP", *Computers & Operations Research*, vol. 38, no. 1, pp. 63–74, 2011, doi: 10.1016/j.cor.2010.01.001.

[23] J. Pasławski, "Flexibility approach in construction process engineering", *Technological and Economic Development of Economy*, vol. 14 no. 4, pp. 518–530, 2008, doi: 10.3846/1392-8619.2008.14.518-530.

[24] J. Eder, M. Franceschetti, and J. Lubas, "Conditional schedules for processes with temporal constraints", *SN Computer Science*, vol. 1, art. no. 231, 2020, doi: 10.1007/s42979-020-00242-8.

[25] S. Van de Vonder, F. Ballestin, E. Demeulemeester, and W. Herroelen, "Heuristic procedures for reactive project scheduling", *Computers & Industrial Engineering*, vol. 52, no. 1, pp. 11–28, 2007, doi: 10.1016/j.cie.2006.10.002.

[26] H.A. Suwa, "A new when-to-schedule policy in online scheduling based on cumulative task delays", *International Journal of Production Economics*, vol. 110, no. 1-2, pp. 175–186, 2007, doi: 10.1016/j.ijpe.2007.02.015.

[27] M. Milat, S. Knezic, and J. Sedlar, "A new surrogate measure for resilient approach to construction scheduling", *Procedia Computer Science*, vol. 181, pp. 468–476, 2021, doi: 10.1016/j.procs.2021.01.192.

[28] F. Zuo, E. Zio, and Y. Yuan, "Risk-response strategy optimization considering limited risk-related resource allocation and scheduling", *Journal of Construction Engineering and Management*, vol. 148, no. 11, 2022, doi: 10.1061/(ASCE)CO.1943-7862.0002392.

[29] D. Schatteman, W. Herroelen, S.V. Vonder, and A. Boone, "Methodology for integrated risk management and proactive scheduling of construction projects", *Journal of Construction Engineering and Management*, vol. 134, no. 11, pp. 885–893, 2008, doi: 10.1061/(ASCE)0733-9364(2008)134:11(885).

[30] Q. Cao, X. Zou, and L. Zhang, "Multiobjective robust optimization model for generating stable and makespan-protective repetitive schedules", *Journal of Construction Engineering and Management*, vol. 148, no. 9, 2022, doi: 10.1061/(ASCE)CO.1943-7862.0002348.

[31] M. Poshdar, V.A. González, G.M. Raftery, F. Orozco, and G.G. Cabrera-Guerrero, "A multi-objective probabilistic-based method to determine optimum allocation of time buffer in construction schedules", *Automation in Construction*, vol. 92, pp. 46–58, 2018, doi: 10.1016/j.autcon.2018.03.025.

[32] I. Bakry, O. Moselhi, and T. Zayed, "Optimized acceleration of repetitive construction projects", *Automation in Construction*, vol. 39, pp. 145–151, 2014, doi: 10.1016/j.autcon.2013.07.003.

[33] W. Bozejko, Z. Hejducki, and M. Wodecki, "Flowshop scheduling of construction processes with uncertain parameters", *Archives of Civil and Mechanical Engineering*, vol. 19, no. 1, pp. 194–204, 2019, doi: 10.1016/j.acme.2018.09.010.

Proaktywo-reaktywna metoda harmonogramowania przedsięwzięć powtarzalnych – koncepcja uwzględnienia ryzyka na etapie planowania i realizacji

Słowa kluczowe: zarządzanie ryzykiem przedsięwzięcia, harmonogramowanie przedsięwzięć, procesy powtarzalne, optymalizacja harmonogramu, metoda symulacji

Streszczenie:

Najlepsze rezultaty realizacji przedsięwzięć budowlanych są osiągane wówczas, gdy brygady pracują bez przerw i po zakończeniu procesu na jednej części obiektu (działce roboczej) mogą rozpocząć pracę na działce kolejnej, na której zakończono wykonanie procesów poprzedzających.

Dzięki ciągłości pracy brygad i powtarzalności realizacji tych samych zadań na poszczególnych działkach roboczych może wystąpić efekt uczenia się i redukcji czasu wykonania zadań. Zakłócenia w realizacji robót, na skutek oddziaływania czynników ryzyka o charakterze losowym, mogą prowadzić do opóźnień w wykonaniu procesów poprzedzających i w efekcie do przestojów w pracy brygad oraz wydłużenia czasu realizacji całego przedsięwzięcia. W związku z tym istotne jest rozwijanie metod harmonogramowania uwzględniających dynamikę rzeczywistego przebiegu wykonania procesów w zmiennych warunkach realizacyjnych. Redukcja odchyleń terminów zaplanowanych od rzeczywistych umożliwia zmniejszenie kosztów związanych z ich przekroczeniem, m.in. zamrożenia środków obrotowych w zapasach, przestojów w pracy brygad roboczych, kar umownych za niedotrzymanie terminów kontraktowych itp. Zdeterminowane terminy realizacji procesów w harmonogramie pozwalają na tworzenie planów produkcji pomocniczej, optymalizację zaopatrzenia budowy w materiały i sprzęt, pozyskiwanie zasobów ludzkich i zawieranie kontraktów z podwykonawcami. Ryzyko wystąpienia opóźnień może być uwzględnione już na etapie harmonogramowania poprzez określenie wielkości buforów czasu i ich alokację w harmonogramie. Takie podejście jest określane mianem harmonogramowania proaktywnego. Nawet mimo uodpornienia harmonogramu przy zastosowaniu metod proaktywnych, w trakcie realizacji mogą pojawić się nieprzewidziane zdarzenia, które powodują, że ochrona taka jest niewystarczająca i rozpoczęcie kolejnych zadań w zaplanowanych terminach jest niemożliwe ze względu na opóźnienia procesów poprzedzających lub niezwolnienie niezbędnych zasobów. Zachodzi wówczas konieczność reakcji – podjęcia działań redukujących odchylenia od planu lub aktualizacji planu. W reakcji na zakłócenia są podejmowane działania zmierzające do skrócenia czasu procesów jeszcze niewykonanych (zmiana wariantu technologicznego wykonania procesu, zatrudnienie dodatkowych zasobów, praca w nadgodzinach lub wydłużony tydzień pracy).

W artykule zaproponowano podejście do uwzględnienia ryzyka o charakterze proaktywno-reaktywnym, wykorzystujące metodę symulacji cyfrowej w celu oszacowania wielkości opóźnień terminów rozpoczynania kolejnych procesów z uwzględnieniem reaktywnych działań redukujących czas ich wykonania na działkach roboczych, podejmowanych już w fazie realizacji.

W proponowanej metodzie proaktywno-reaktywnego harmonogramowania przedsięwzięć powtarzalnych zakłada się, że czasy realizacji procesów są zmiennymi losowymi o znanej funkcji gęstości i parametrach rozkładu. Metoda obejmuje następujące etapy:

1. Opracowanie wstępnego harmonogramu bazowego, tworzonego przy następujących założeniach: czasy realizacji procesów na działkach roboczych są równe wartościom oczekiwanym zmiennych losowych, procesy są realizowane w sposób ciągły – brygady robocze przechodzą na kolejne działki (w tym samym porządku) bez przerw, a kolejny proces na działce roboczej może rozpocząć się nie wcześniej niż po zakończeniu wykonywania procesu poprzedzającego na tej działce roboczej. Harmonogram bazowy pozwala na wyznaczenie terminów rozpoczynania ciągów procesów i zakończenia realizacji całego przedsięwzięcia.

2. Badania symulacyjne przebiegu realizacji przedsięwzięcia dla wstępnego harmonogramu bazowego.

Na tym etapie jest tworzony komputerowy model symulacyjny przedsięwzięcia. W każdym przebiegu symulacyjnym są generowane czasy wykonania procesów na działkach z ustalonych rozkładów zmiennych losowych. Zakłada się, że brygady są dostępne (gotowe do pracy) w terminach wynikających ze wstępnego harmonogramu bazowego. Badania symulacyjne pozwalają wyznaczyć wartości średnie czasu przestojów w pracy poszczególnych brygad w realizacji ciągów procesów oraz estymować rozkład czasu realizacji całego przedsięwzięcia.

3. Tworzenie zbioru harmonogramów bazowych.

We wstępnym harmonogramie bazowym procesy są rozpoczynane w terminach najwcześniejszych, gwarantujących ciągłość pracy brygad. Na skutek zmienności czasów wykonania procesów w rzeczywistości występują przerwy w pracy brygad (przy wydłużeniu ponad wartość oczekiwaną czasu realizacji procesu poprzedniego na działce roboczej na rozpoczęcie pracy oczekuje brygada realizująca proces następny; w przypadku skrócenia czasu realizacji procesu na danej działce roboczej przez daną brygadę – musi ona oczekiwać na zakończenie procesu poprzedniego na kolejnej działce roboczej). Zmienność czasów wykonania procesów powoduje również przekroczenie terminu zakończenia określonego w harmonogramie wstępnym bazowym a nawet terminu dyrektywnego (określonego w umowie). Aby ograniczyć propagacje zakłóceń w harmonogramie zaproponowano opóźnić terminy rozpoczynania kolejnych procesów (na pierwszej działce roboczej). Powoduje to wydłużenie czasu realizacji całego przedsięwzięcia w harmonogramie sporządzonym dla wartości oczekiwanych czasów realizacji procesów. Założono, że jest akceptowany nowy termin zakończenia, co pozwala na wprowadzenie dodatkowych opóźnień rozpoczynania ciągów procesów.

Rozdział czasu w postaci dodatkowych opóźnień (dodawanych do ustalonych opóźnień we wstępnym harmonogramie bazowym) będzie dokonywany proporcjonalnie do określonych w poprzednim etapie wartości średnich czasów przestoju oraz dziennych kosztów przestoju w pracy brygad. Przyjęto, że jednostkowy koszt w pracy brygady realizującej proces generuje straty. Wielkość opóźnień jest ustalana poprzez rozwiązanie modelu matematycznego programowania liniowego (proporcjonalnie do generowanych strat określonych w badaniach symulacyjnych). Pełnią one funkcję buforów chroniących terminy rozpoczynania realizacji ciągów procesów oraz zapobiegającą przestojom w pracy brygad i opóźnieniom w realizacji poszczególnych procesów na działkach i całego przedsięwzięcia.

Zbiór harmonogramów bazowych (z różnymi terminami rozpoczynania kolejnych ciągów procesów) jest tworzony dla ustalonej, skończonej liczby wartości wydłużenia terminu zakończenia przedsięwzięcia.

4. Badania symulacyjne przebiegu realizacji przedsięwzięcia dla harmonogramów bazowych i wybór końcowego harmonogramu bazowego.

Celem prowadzonych badań symulacyjnych jest ocena wygenerowanych w poprzednim etapie harmonogramów bazowych. Ponieważ ochrona terminów realizacji procesów i ciągłości pracy brygad za pomocą poprzednio ustalonych buforów jest zwykle niewystarczająca, proponuje się dodatkowo możliwość wdrożenia dodatkowych działań redukujących wpływ czynników ryzyka i przyczyniających się do skrócenia wykonania procesów opóźnionych, np. poprzez zastosowanie pracy w nadgodzinach, w wydłużonym tygodniu pracy lub zatrudnienie dodatkowych zasobów. Skutkuje to możliwością realizacji każdego procesu na każdej działce roboczej zmodyfikowanym wariantem o czasie będącym zmienną losową o ustalonych parametrach i rozkładzie oraz o dziennym dodatkowym koszcie jego zastosowania.

Przyjęto, że za każdy dzień przekroczenia terminu dyrektywnego wykonawca płaci karę umowną. W badaniach symulacyjnych są ustalane średnie wartości: czasu przestojów w pracy brygad realizujących poszczególne procesy, średni czas zastosowania zmodyfikowanego wariantu wykonania każdego procesu oraz średni czas opóźnienia terminu zakończenia w stosunku do terminu dyrektywnego.

Dla poszczególnych harmonogramów jest ustalany średni łączny koszt działań redukujących wpływ zakłóceń (kar, strat i dodatkowych nakładów). Do realizacji jest kierowany harmonogram z najmniejszą wartością tak określonego średniego łącznego kosztu.

Sposób wykorzystania proponowanej metody przedstawiono na przykładzie budowy sześciu budynków w stanie surowym. Zakres rzeczowy przedsięwzięcia obejmuje wykonanie pięciu procesów powierzonych do wykonania odrębnym brygadom. Są to: roboty ziemne, stan 0, konstrukcja nadziemia, dach, elewacja.

Większość metod projektowania harmonogramów odpornych na zakłócenia realizacyjne jest tworzonych dla przedsięwzięć budowlanych typu kompleks operacji, obejmujących realizację procesów niepowtarzalnych, dla których zależności kolejnościowe są modelowane z wykorzystaniem technik sieciowych. Metody te są prezentowane w zastosowaniach w różnych dziedzinach gospodarki, ale istnieje niewiele przykładów ich zastosowań w zarządzaniu przedsięwzięciami budowlanymi. W szczególności występuje tu deficyt w odniesieniu do planowania przedsięwzięć złożonych z procesów powtarzalnych (np. budowa dróg, rurociągów energetycznych, sieci kanalizacyjnych czy budynków wysokich), gdzie można wskazać tylko nieliczne badania w tym zakresie bazujące na harmonogramowaniu dynamicznym, czy poszukiwaniu optymalnych uszeregowań działek roboczych w celu zwiększenia stabilności harmonogramu. Wydaje się, że ze względu na podatność produkcji budowlanej na wpływ zmiennych warunków realizacji istotne jest rozwijanie koncepcji uwzględnienia ryzyka w dedykowanych metodach harmonogramowania przedsięwzięć powtarzalnych. Zastosowane podejście zakłada utworzenie harmonogramu bazowego przed rozpoczęciem realizacji robót, w którym są ustalone istotne przy realizacji powtarzalnych procesów terminy zatrudnienia poszczególnych brygad je wykonujących. Harmonogram taki zawiera bufory czasu w postaci opóźnień w rozpoczynaniu kolejnych ciągów procesów. Ich zadaniem jest częściowa antycypacja zakłóceń realizacyjnych i zabezpieczenie ciągłości pracy brygad. Wielkość buforów są określane z uwzględnieniem działań podejmowanych w reakcji na zaistniałe opóźnienia, w celu skrócenia czasu wykonania procesów, które nie mogą rozpocząć się w wcześniej zaplanowanych terminach. Jakość uzyskiwanych harmonogramów jest oceniana z wykorzystaniem techniki symulacji komputerowej. Zaproponowane podejście proaktywno-reaktywne do harmonogramowania umożliwia dobór optymalnych działań redukujących negatywny wpływ zjawisk losowych na przebieg produkcji pod względem kosztów związanych z karami za przekroczenie zakontraktowanego terminu zakończenia przedsięwzięcia, stratami wynikającymi z przestojów w pracy brygad czy dodatkowym wynagrodzeniem za pracę w nadgodzinach lub w wydłużonym tygodniu. Zastosowana technika badań symulacyjnych pozwala także odwzorować i planować inne polityki w zakresie wyboru czy terminu implementacji podejmowanych działań w reakcji na zakłócenia realizacyjne. Poszukiwanie optymalnych decyzji w tym zakresie może to stanowić kierunek dalszych badań.

Received: 2023-02-21, Revised: 2023-04-25