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Research paper

Proactive scheduling of repetitive construction processes to reduce crews idle times and delays

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Abstract: Duration of construction projects can be reduced by harmonizing construction processes: adjusting productivity rates of specialized crews and enabling the crews to work in parallel as in a production line. This is achievable in the case of projects whose scope can be divided into units where a similar type of work needs to be conducted in the same sequence. A number of repetitive project scheduling methods have been developed to assist the planner in minimizing the execution time and smoothing resource profiles. However, the workflow, especially in construction, is subject to disturbance, and the actual process durations are likely to vary from the as-scheduled ones. The inherent variability of process durations results not only in delays of a particular process in a particular unit but also in the propagation of disruptions throughout the initially well-harmonized schedule. To counteract the negative effects of process duration variability, a number of proactive scheduling methods have been developed. They consist in some form of predicting the conditions to occur in the course of the project and implementing a strategy to mitigate disturbance propagation. This paper puts forward a method of scheduling repetitive heterogeneous processes. The method aims to reduce idle time of crews. It is based on allocating time buffers in the form of breaks between processes conducted within units. The merits of the method are illustrated by an example and assessed in the course of a simulation experiment.

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

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1. Introduction

Managing the construction of complex structures, such as larger multi-family blocks or housing estates, roads, underground infrastructure systems, or building complexes, involves planning and harmonizing multiple construction processes and multiple resources. Many processes of such projects are in fact repeatable – they are to be conducted in many locations within the erected structure using the same methods and resources. Moreover, within a work area (unit) of the structure, the processes are required to be conducted in a specific order, and the same order is kept in other areas. The resources (crews of workers, machine sets) execute their work sharing the confined space. Continuity of their work is of utmost importance, as every hour of idle time generates financial losses and does not bring the completion date nearer. To enable multiple resources to work side by side and in a continuous manner, the planner needs to carefully allocate the resources to separate units and devise an efficient scheme of the crews' moving from one unit to another, so that the work is done and the resources are fully utilized. Projects of this kind – divisible into units whose delivery involves similar sequences of processes, requiring execution of repeatable processes by specialized crews – are often referred to as repetitive projects [3, 13, 14, 22]. Considering the spatial pattern of the units, some authors distinguish two types of projects with repetitive processes: linear and non-linear [3]. With regard to the relationship between the geometric characteristics of the unit and the quantity of process-related work, the projects with repetitive processes are divided into typical and non-typical [33]. Typical projects with repetitive processes consist of activities of the same quantity of work in each unit. However, non-typical projects are more frequent: the processes to be conducted in different units differ in the amount of work; this amount of work may stay in a fixed relationship with the size of the unit for each process to be conducted in the unit (homogenous processes), or such relationship may not be observable (heterogeneous processes). A project considered repetitive may involve some activities that do not repeat. Non-repetitive projects are a separate category of projects. Their scheduling calls for different methods, such as network methods.

The schedules of repeatable projects are often presented in the form of time-location diagrams: two-dimensional diagrams where one axis represents the consecutive units of time (days, weeks, etc.), and the other – the work areas (units). The activity/construction process is represented by a spline whose angle of inclination corresponds to the rate of work.

According to K. Adamiecki, one of the fathers of scientific management, the primary role of schedules is to indicate hidden waste of time caused by insufficient harmonization of processes, and help minimize it. In the case of projects that involve repetitive processes, there exist two categories of time waste: one is the resource (crew) idle time, the other – unnecessary interruptions in the workflow within units.

The first type of waste results from a crew waiting before it can take over a unit from another crew, busy with a preceding process in the considered unit. Any unused potential of the crews means a loss: the crews and/or machine rent need to be paid anyway, and there is no production to justify the spending. Alternatively, if the waiting time is considerable, idle resources can be transferred to other construction sites, but this also generates cost. Moreover, the crews' periods of idleness are the cause of the forgetting effect, so a reduction in productivity rates observable after the break [6, 20]. For this reason, continuity of the work of resources, or at least minimization of resource idle time, is the standard objective of most repetitive project scheduling methods. These are the classic methods of "Line of Balance" [8], "Vertical Production Method" [23], "Horizontal and Vertical Logic Scheduling for Multistory Projects" [29], "Linear Scheduling Method" [18], and "Repetitive Scheduling Method" [12], as well as their modifications [1, 2, 9, 16, 30, 32]. The resource idleness is possible to be eliminated as long as a fixed rhythm of works is achievable, i.e. when all units are of the same size in terms of the amount of work related with each process (typical units), or there is a fixed proportion between the unit size and the amount of work related with each process (non-typical homogenous units). If this is the case, eliminating idle time means also minimizing the project duration. However, if units are non-typical (i.e. there is no fixed unit-to-unit proportion between the amount of work related with consecutive processes), ensuring continuous work for crews increases the project duration. This is due to scheduling the sequences of processes assigned to particular crews to a late start.

The other type of time waste is breaks between successive processes conducted within a particular unit. In the eyes of the construction client, the breaks may indicate that the contractor does not allocate enough resources and is likely to fail to complete the project on time. However, from the point of the contractor, the breaks serve as buffers that compensate for workflow disruptions. With projects divisible into identical units, this type of waste is possible to be eliminated, which automatically minimizes the project duration. With non-typical units, the breaks are inevitable, though they can be purposefully scheduled by shifting the work by successive crews to a late start. This approach protects resource continuity against disruption.

Construction is naturally susceptible to disruption. In contrast to industrial production, its working environment is only partly controllable, and its products, as well as its supply chains, are one-off. Even perfectly harmonized schedules are likely to expire due to variability that results from productivity fluctuations, absenteeism, or any other common problem faced by construction managers. For this reason, construction schedules must account for risk and allow for actions that reduce the impact of random occurrences, especially while planning completion dates and reducing resource idle time.

To address this issue, the authors put forward a method of preparing more risk-resilient schedules dedicated to projects with repetitive processes. The idea is based on allocating buffers throughout the schedule. The buffers are intentional breaks between processes in heterogeneous non-typical units.

The paper is organized as follows: Section 2 is an overview of methods for increasing the reliability of meeting directive deadlines in schedules developed so far; Section 3 presents the author's approach to buffer allocation; Section 4 applies the approach to a case of a relatively simple project and tests its merits by means of a simulation experiment. Section 5 presents conclusions and suggests directions for further research.

2. Methods to improve projects schedule robustness with repetitive processes

Construction projects are complex in nature and take place in a dynamic environment. In the case of projects with repetitive processes, multiple risk factors interact and contribute to the unit-to-unit variation of construction process duration. Many scheduling methods ignore this fact: they require the planner to use deterministic input (resource productivity rates) and produce deterministic output, so the completion dates of processes, project stages, and whole projects. Such schedules easily expire – the as-planned dates prove unrealistic. Exceeding the project milestones and completion date typically involves contractual penalties, disruptions to the schedule of payments (and contractor's cash-flow problems), and thus jeopardizes the contractor's profits. Completing tasks and stages earlier than schedules generates unnecessary idle time and further cash-flow disturbance. It is therefore important to schedule with account for uncertainty to plan more reliable due dates.

Many scheduling concepts have been developed to accommodate uncertainty in non-repetitive projects, modeled using networks (PERT, GANT, discrete-event simulation, etc.). A few methods incorporated simulation techniques for repetitive project scheduling. For instance, Kavanagh [19] constructed a simulation-based model implementing the waiting line theory. Lutz and Halpin [21] applied CYCLONE to find the mean durations of construction processes in a Line of Balance scheduled project. Srisuwanrat et al. [28] used Monte Carlo simulation to plan repetitive activities assuming the stochastic character of process durations. Several authors incorporated the learning effect to enhance the reliability of their models of projects with repetitive processes [6]. However, these works did not consider resource continuity as the model constraint nor the scheduling objective.

An example of a scheduling method focused on efficient resource utilization is the work by Polat et al. [24], who incorporated discrete event simulation into the Line of Balance to check if a particular machine set assures uninterrupted workflow between the off-site and on-site operations.

It should also be emphasized that the simulation does not directly generate a schedule (define deterministic process completion dates): it primarily serves to estimate the probability of meeting the dates, to plan dates that correspond to the assumed probability of their being met, or to assess the resource utilization rates.

In the case of construction, the project schedule is created before the commencement of works to facilitate resource management: subcontracting, planning supplies and auxiliary production. This implies using the so-called offline scheduling approach [11] and anticipating future disruptions. This approach is also referred to as proactive or predictive scheduling [31]. The schedules are expected to be robust: immune to disruptions that may occur in the course of works. A common way to make schedules robust is to introduce time buffers between processes. The buffers are intentional idle time (breaks) and are located to protect the process start dates and to counteract the propagation of disruptions in the schedule. One of the earliest methods of robust scheduling (however, intended for non-repetitive projects), aimed at protecting the completion date against disruption using buffers (project, feeding, and resource buffers) was the Critical Chain by Goldratt [10].

Rogalska and Hejducki [25] integrated Critical Chain Project Management / Buffer Management (CCPM) with Linear Scheduling Method. To increase the reliability of the project completion date estimation and maintaining resource continuity, they use two types of buffers. The project buffer is placed as a dummy task directly before the project finish date, so at the end of the last chain (processes sequence), whereas the feeding buffers appear at the ends of particular chains. The process durations and buffer sizes are calculated according to CCPM. However, the authors do not provide any verification of this approach to judge its efficiency.

Nevertheless, the buffering technique was applied to repetitive project scheduling by many other authors, for instance, Seppänen [27], Bakry [4], and Büchmann-Slorup [7].

Bakry et al. [5] developed an algorithm to optimize schedules of repetitive construction projects considering uncertainties associated with work quantities, crew productivity rates, and cost. Fuzzy set theory was used to model these uncertainties. Time buffers were used to protect activities from delays of their predecessors. The algorithm comprises three steps: schedule optimization to find the optimal crew formation (i.e. yielding either the least project cost or the least project duration), schedule defuzzification, and buffering. Buffers were intended to raise the reliability of the project completion date estimate and protecting resource continuity. Buffer sizes were first calculated separately for each unit and process and then aggregated into a single buffer for each sequence of processes at the least location distance between every two successive activities.

Salam et al. [26] applied the concept of CCPM to develop the Linear Scheduling Method (LSM) to account for risk and variable process durations aiming at maintaining resource continuity. They proposed a new type of buffer (resource conflict buffer), to reduce delays due to resource demand conflicts between sequential activities. They also proposed a procedure to identify the critical chain.

Zhang et al. [34] observed that risks make resource continuity difficult to maintain and proposed a float-based measure of schedule quality to assess its resilience to disruptions. The floats, understood as in the Critical Path Method, were treated as buffers to protect schedule dates against unexpected events. In some way, they increase the stability of the schedule absorbing delays in process start days or increase in their durations. For this reason, the buffer allocation approach is often used to increase the resilience of CPM schedules modeled as networks. However, such floats, allocated in the form of buffers, are not able to protect the schedule against changes in resource availability and cannot ensure resource continuity. This is because the classic CPM ignores resource availability constraints and resource allocation for process execution.

Zhang et al. [34] analyzed schedules of projects with repetitive processes designed using Line of Balance. They identified two cases of floats actually protecting processes against harmful interruptions influencing the implementation and continuity of its immediate successors. The size of floats (and thus the scale of the schedule's robustness) depends on the number of crews. For this reason, Zhang et al. [34] put forward a way to immunizing schedules to disruption by finding a solution of the best trade-off between the number of crews and the robustness.

Jaśkowski et al. [17] observed that the sequence of units affects schedule robustness. Their idea to improve schedules of repeatable projects focused on reducing the probability of the project due date being exceeded and, at the same time, reducing idle time of resources and breaks between processes in units. Their model was based on the Type III Time Couplings approach, with couplings between work fronts and means of realization [15], so without constraints of resource continuity and continuous work in units. Their assessment of schedule robustness against random disruptions consisted in analyzing the scale of delays in project completion, unit completion (or building completion in the case of projects involving erection of multiple buildings), and the scale of extending the time of crews' employment. This analysis consisted in searching for the optimal permutation of units, where optimization meant maximizing the overall measure of robustness. The authors found that permutations of greater project durations involve less idle time of crews and shorter completion times for units (particular buildings). The reason was greater process floats and longer breaks between the processes in units that anticipate random disturbances. The proposed approach needs further development to account for the continuity maintaining constraint (Type I Time Coupling).

3. Proposed proactive method of scheduling repetitive processes

Let us assume that a project involves n construction processes to be repeated in m units. In each unit, the processes are to be conducted in the same order. Each process requires a separate resource (specialized crew or machine set). Only one process is allowed to run in a unit at a time, so a resource can enter a unit to conduct a process only after the preceding process has been completed. The resources are expected to work continuously: immediately after they finish their work in one unit, they should move to the next. The sequence of the resources moving from one unit to another is the same for all resources. The units are not identical and there is no fixed proportion between the size of the unit and the amount of work related with processes.

The project is going to be affected by risks. Process durations are assumed to be random variables. The distribution of process durations is assumed to be triangular. This type of distribution allows the planner to capture skewness of experimental distributions of construction process durations observed in practice and adequately approximates the beta-PERT distribution (considered the most suitable theoretical distribution for such analyses).

Let $T_{i,j}$ represent the random variable of the duration of process i in unit j ($i = 1, 2, \ldots, n$, $j = 1, 2, \ldots, m$). Each variable is described by three parameters: $t^{a}_{i,j}$ – the minimum duration, $t^{c}_{i,j}$ – the most probable duration, and $t^{b}_{i,j}$ – the maximum duration, all defined by a decision-maker. The contractual time for completion for the entire project is set to D; it is expressed as the number of units of time (e.g. days) from the project start, thus it also corresponds to the completion date.

The method comprises the following steps:

1. Construction of the baseline schedule;
2. Sizing buffers;
3. Construction of the robust schedule;
4. Verification of the result – checking the probability of not exceeding the project due date and the scale of resource idle time.

A practically implementable schedule is expected to define deterministic dates. The process durations are modeled as random but, to build the baseline schedule, deterministic values are used as a first approximation. Frequently, durations are estimated using some "standard production rates": the mean or median values calculated using on-site measurements, sometimes adjusted by adding contingencies. However, it is advisable not to cumulate contingencies in baseline estimates to avoid the effects of Parkinson's law and the "student syndrome" [10]. The authors thus assume that the baseline schedule uses process durations (d_{ij}, $i = 1, 2, \ldots, n$, $j = 1, 2, \ldots, m$) corresponding to modal durations.

The deterministic baseline schedule needs to assure resource continuity and minimal project duration. Let $s^{b}_{i,j}$ represent the baseline start date of process i in unit j, $f^{b}_{i,j}$ – the baseline finish date of process i in unit j. The dates can be defined by solving the following linear program (explanations below):

$$\min PD^b : \quad PD^b = f^b_{n,m} \tag{3.1}$$

$$s^b_{1,1} = 0 \tag{3.2}$$

$$f^b_{i,j} = s^b_{i,j} + d_{i,j}, \quad i = 1, 2, \ldots, n, \quad j = 1, 2, \ldots, m \tag{3.3}$$

$$s^b_{i,j+1} = f^b_{i,j}, \quad i = 1, 2, \ldots, n, \quad j = 1, 2, \ldots, m-1 \tag{3.4}$$

$$s^b_{i+1,j} \geq f^b_{i,j}, \quad i = 1, 2, \ldots, n-1, \quad j = 1, 2, \ldots, m \tag{3.5}$$

$$s^b_{i,j} \geq 0, \quad i = 1, 2, \ldots, n, \quad j = 1, 2, \ldots, m \tag{3.6}$$

The objective function (3.1) minimizes project duration and, at the same time, the completion date, of the baseline schedule; both are represented by PD^b. The project start date is set to 0 (equation (3.2)). The processes cannot be interrupted (equations (3.3) and (3.4)). In a unit, a process may start only after its predecessor in this unit has been completed (3.5). Process start and completion dates must be non-negative – the boundary condition (3.6).

The difference between the predefined project due date D and the project completion date calculated in the baseline schedule, PD^b, can be distributed among processes in the form of process buffers $b_{i,j}$ ($i = 1, 2, \ldots, n-1$, $j = 1, 2, \ldots, m$). If a buffer is allocated to a process, this process' float in a unit is increased. Automatically, this shifts the start of the chain of successive processes to a later date and protects start dates of successive processes. As the resources are expected to work continuously, the process buffers must be placed between the finish of a predecessor and the start of a successor in the same unit. This way, the breaks in the workflow within units, $\delta^b_{i,j}$, grow. The duration of these breaks is calculated according to Formula (3.7):

$$\delta^b_{i,j} = s^b_{i+1,j} - f^b_{i,j}, \quad i = 1, 2, \ldots, n-1, \quad j = 1, 2, \ldots, m \tag{3.7}$$

To mitigate the propagation of schedule disruptions, the authors propose to distribute the breaks evenly and avoid bottlenecks.

Apart from the process buffers, a project buffer is to be located as a dummy process that follows the last process in the last unit. Its duration is expressed by b_P.

The size of the process buffers and the start and end dates of the processes in the resilient schedule can be determined by solving the following model:

$$\max z : \; z = \min_{\substack{i=1,2,\ldots,n-1 \\ j=1,2,\ldots,m}} \left\{ \frac{\delta^b_{i,j} + b_{i,j}}{w_{i,j}} ; \; \frac{b_P}{w_P} \right\} + \rho \cdot \sum_{i=1}^{n-1} \sum_{j=1}^{m} w_{i,j} \cdot \left(\delta^b_{i,j} + b_{i,j} \right) + \rho \cdot w_P \cdot b_P \tag{3.8}$$

$$s_{1,1} = 0 \tag{3.9}$$

$$f_{i,j} = s_{i,j} + d_{i,j}, \quad i = 1, 2, \ldots, n, \quad j = 1, 2, \ldots, m \tag{3.10}$$

$$s_{i,j+1} = f_{i,j}, \quad i = 1, 2, \ldots, n, \quad j = 1, 2, \ldots, m-1 \tag{3.11}$$

$$s_{i+1,j} \geq f_{i,j}, \quad i = 1, 2, \ldots, n-1, \quad j = 1, 2, \ldots, m \tag{3.12}$$

$$s^b_{i,j} \geq 0, \quad i = 1, 2, \ldots, n, \quad j = 1, 2, \ldots, m \tag{3.13}$$

$$f_{n,m} + b_P = D \tag{3.14}$$

$$b_{i,j} = s_{i+1,j} - f_{i,j} - \delta^b_{i,j}, \quad i = 1, 2, \ldots, n-1, \quad j = 1, 2, \ldots, m \tag{3.15}$$

$$b_{i,j} \in C, \quad i = 1, 2, \ldots, n-1, \quad j = 1, 2, \ldots, m \tag{3.16}$$

where: ρ – a sufficiently small number, $w_{i,j}$ – relative importance (weight) of keeping some buffer time after completing process i in unit j, w_p – relative importance (weight) of keeping some buffer time after completing all processes in all units.

Relationships (3.9)–(3.13) should be interpreted just as (3.2)–(3.6). Condition (3.14) assures that the project is ready on time. Buffers are sized according to (3.15). The objective function (3.8) maximizes the smallest value of breaks between processes in a unit which should equalize the probability of starting subsequent processes in units at the as-planned dates. At the same time, the optimal solution (i.e. the most robust against disruptions) is selected as the solution of the highest sum of breaks between processes in units. The importance of maintaining some buffer of time between processes in a unit and before the project due date are considered while sizing buffers. The size of process buffers in the first unit can be interpreted as delays in starting subsequent processes.

4. Example

The application of the method and the way of testing results are illustrated by the following example. Let us consider a project to carry out finishing works in a multi-storey public building that involves six construction processes conducted in ten non-typical units (parts of floors). The sequence of processes is the same in each unit. The following processes are executed sequentially: partitions, wiring, plasters, screeds, painting, and flooring. The sequence of units is predefined and corresponds to the number of units. Each process involves a separate specialized crew. Table 1 lists the input, so distribution parameters of process durations in each unit.

The durations are assumed to be random variables of triangular distribution. The values in brackets correspond to the minimal, the most probable, and the maximal durations as judged by an expert.

The deterministic baseline schedule was built using modal durations. Its time-location diagram is shown in Figure 1. The start and finish dates for processes in units were calculated by solving the model described by Equations (3.1)–(3.6) using Lingo 14.0 solver. The baseline project duration is $PD^b = 161$ days.

The breaks between consecutive processes in units were derived from the baseline schedule and fed into models described by Equations (3.8)–(3.16) to calculate buffers. For illustrative purposes, the buffer sizes were calculated according to three different strategies (three series of weights). This way, three cases can be used for comparison.

Table 1. Distribution parameters ($t^a_{i,j}$, $t^b_{i,j}$, $t^c_{i,j}$) of random variables of process durations (in days)

Unit j	Process i					
	1	2	3	4	5	6
	partitions	wiring	plasters	screeds	painting	flooring
1	(9, 15,10)	(10, 16, 12)	(9, 17, 10)	(11, 18, 12)	(7, 15, 8)	(8, 16, 9)
2	(10, 16, 12)	(8, 16, 9)	(9, 15,10)	(7, 15, 8)	(10, 18, 11)	(10, 16, 12)
3	(8, 16, 9)	(7, 16, 8)	(10, 18, 11)	(11, 16, 12)	(9, 15,10)	(10, 19, 12)
4	(9, 16,10)	(10, 19, 11)	(9, 17,10)	(8, 16, 9)	(10, 16, 12)	(7, 16, 8)
5	(7, 16, 8)	(8, 17, 9)	(8, 16, 9)	(10, 18, 11)	(8, 16, 9)	(8, 16, 9)
6	(6, 15, 8)	(7, 15, 8)	(7, 16, 8)	(8, 17, 9)	(10, 20, 11)	(11, 16, 12)
7	(10, 18, 12)	(10, 18, 12)	(9, 17, 10)	(7, 16, 9)	(9, 18,10)	(9, 16,10)
8	(10, 18, 11)	(9, 17,10)	(9, 16, 12)	(10, 19, 12)	(9, 15,10)	(7, 15, 8)
9	(7, 15, 8)	(8, 16, 9)	(9, 15,10)	(7, 15, 8)	(6, 15, 7)	(8, 17, 9)
10	(7, 16, 9)	(10, 18, 11)	(6, 14, 7)	(6, 14, 7)	(10, 16, 12)	(12, 20, 13)

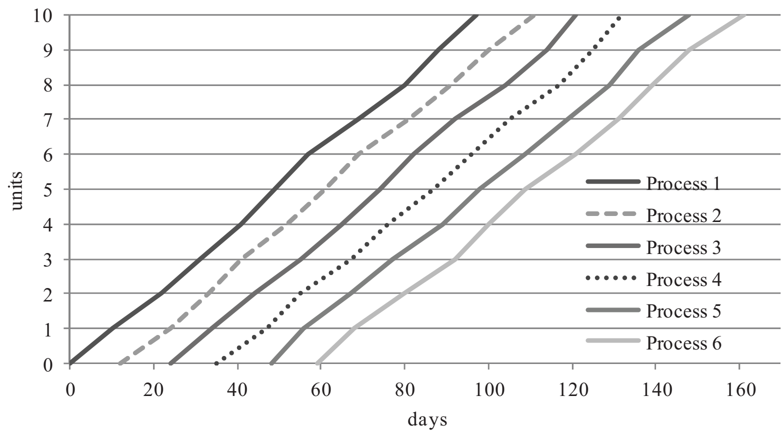

Fig. 1. Baseline schedule (example)

Series 1 based on equal values of weights, as if the planner wanted to protect the start dates of all processes in all units, as well as the project completion date, to the same extent ($w_{i,j} = w_p = 1, i = 1, 2, \ldots, 5, j = 1, 2, \ldots, 10$).

Series 2 – the planner assumed that the later a process and a unit was scheduled, the stronger protection against risks it needed, thus the weights were calculated as follows:

$$w_{i,j} = i \cdot j, \quad i = 1, 2, \ldots, n-1, \quad j = 1, 2, \ldots, m \tag{4.1}$$

$$w_p = n \cdot m \tag{4.2}$$

Series 3 – the planner desired a larger buffer to protect the project completion date and "the later, the bigger" buffers to protect processes in units; the weight for the project buffer was twice the value of that in Series 2, and the process buffers were calculated using Equation (4.1).

The buffer sizes and process execution dates were determined for a range of project due dates (D). In the next step, simulation studies of the solutions were conducted to check if the assumptions were correct. Simulation models were developed using GPSS World (General-Purpose Simulation System) by Minuteman Software. The results are presented in Figures 2–5.

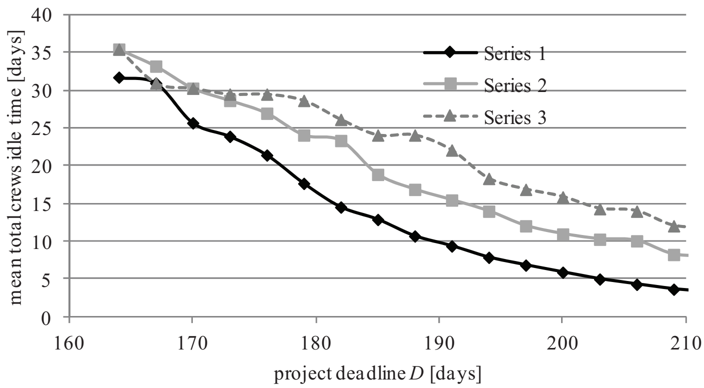

Fig. 2. The relationship between the project due date and the mean total crews idle time for three buffering strategies

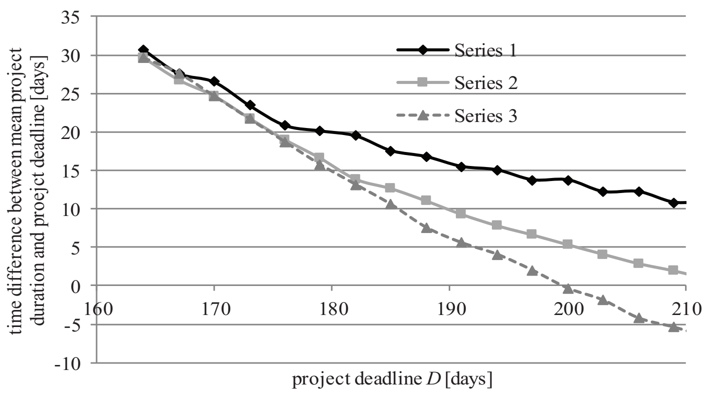

Fig. 3. The relationship between the project due date and the difference between the mean project duration and the due date for three buffering strategies

The highest level of protection of the crews' work continuity was achieved in Series 1: its mean total crew idle time is the lowest within the whole range of project due dates (Figure 2). However, this buffering strategy resulted in a significant exceeding of time – the mean project duration proved by 10 to even 30 days longer than the contractual time for completion (Figures 3 and 4).

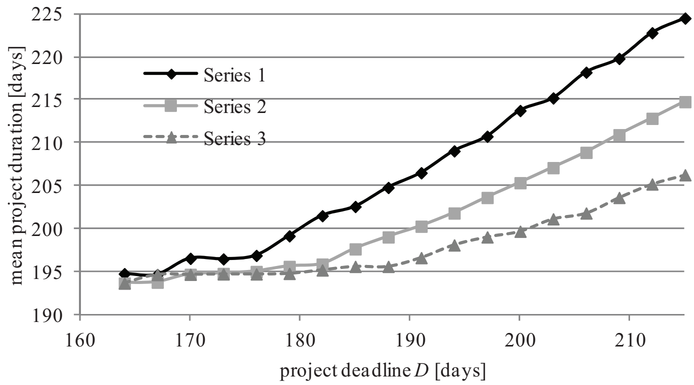

Fig. 4. The relationship between the project due date and the mean project duration for three buffering strategies

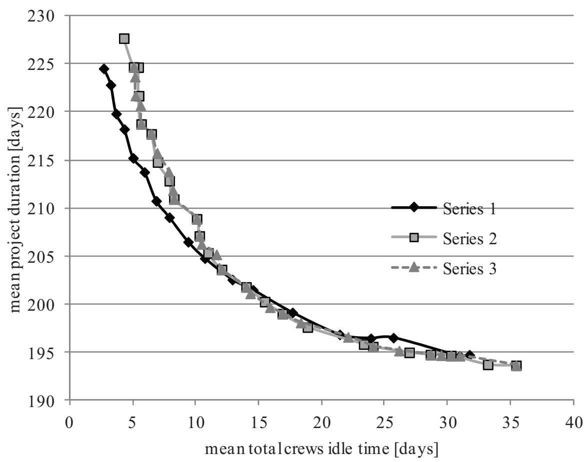

Fig. 5. The relationship between the mean total crews idle time and the mean project duration for three buffering strategies

As expected, the smallest project delays were observed with Series 3 (where the project buffer was the greatest). Increasing the weight of the project buffer while keeping the other weighs the same reduces the mean project delay but increases the mean crew idle time.

Defining weights in optimization models is a complex problem. Figure 5 provides some guidelines in this respect. As in the deterministic model, reducing idle time of crews performing repetitive processes implies increasing project duration. It should be noted, however, that in the case of the mean total crew idle time over 10 days (on average 2 days per crew; the first crew working continuously), similar mean project durations were obtained regardless of the buffering strategy (so approaches to weighting). With lower mean crew idle times, the shortest mean project durations were obtained with equal values of weights (Series 1). This speaks in favor of applying equal protection of process start dates in units.

5. Conclusions

Construction project scheduling should not ignore risks and uncertainties to improve schedule reliability and, in particular, to counteract the delays. Setting contractual due dates without analyzing the probability and scale of delays and with no consideration of how to prevent the delays is likely to end with high contractual penalties. From the point of the contractor, it is also important to plan in a way that assures continuous resource usage. Resource idle time, regardless of its origins (harmonization of work not considered or the effect of random events), generates unproductive costs of downtime pay and reduces the productivity of crews due to the forgetting effect.

In the case of projects with repetitive processes, idle time can be reduced by extending the project's time for completion. This relationship was confirmed by numerous works in the field of scheduling in deterministic conditions. The results obtained in this paper prove its existence also in random conditions.

The most frequently used method to protect the project completion date is adding contingency time and distributing it throughout the schedule in the form of buffers. This paper proposes an approach to buffer allocation that allows both to increase the reliability of meeting the project due date to reduce idle time of resources. Due to the complexity of the problem of determining the relevance of multiple and contradictory optimization objectives, in particular, minimizing the project duration and minimizing the resource idle time, we proposed to choose the solution based on the analysis of the relationship between these conflicting criteria. Simulation studies confirmed that it is reasonable to use buffers of similar size to protect the start dates of processes on consecutive units and to reduce the crews' idle time.

In the case of non-typical heterogeneous units, the execution time of the project is affected by the order in which crews take over the units. For this reason, integration of the proposed approach with the procedure for finding the optimal permutation of plots is an obvious direction of further research.

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Metoda proaktywnego harmonogramowania przedsięwzięć powtarzalnych zapewniająca redukcję przestojów w pracy brygad i opóźnienia w realizacji

Słowa kluczowe: harmonogramowanie przedsięwzięć, budowlane procesy powtarzalne, harmonogramy proaktywne, zarządzanie ryzykiem w budownictwie, metoda symulacji

Streszczenie:

W celu redukcji czasu realizacji obiektów budowlanych, poprzez umożliwienie równoległej pracy brygad roboczych, jest konieczny ich podział na mniejsze części (działki robocze) o wielkości zbliżonej do wielkości frontu pracy brygad. Brygady realizują na kolejnych działkach podobne zadania, dostosowane do kwalifikacji zawodowych posiadanych przez jej członków. Do harmonogramowania realizacji przedsięwzięć powtarzalnych opracowano wiele metod, głównie dla warunków deterministycznych, gwarantujących z jednej strony minimalizację czasu ich realizacji a z drugiej zapewnienie ciągłości pracy brygad. Przestoje w pracy brygad są niekorzystne ze względu na niewykorzystanie potencjału produkcyjnego i straty finansowe spowodowane koniecznością wypłaty wynagrodzenia za gotowość do pracy lub przerzuty na inne place budowy, czy też skierowanie do realizacji innych mniej płatnych robót. Tego typu przestoje można wyeliminować w przypadku, gdy możliwe jest zachowanie stałego rytmu pracy, czyli gdy wielkość działek jest jednakowa (działki jednotypowe), bądź występuje zależność proporcjonalna między ich wielkością a pracochłonnością robót każdego rodzaju (działki jednorodne). Eliminacja

przestojów prowadzi wówczas do minimalizacji czasu realizacji całego przedsięwzięcia. W przypadku działek niejednorodnych (o różnej wielkości i pracochłonności robót) zapewnienie ciągłości pracy brygad paradoksalnie powoduje wydłużenie czasu realizacji przedsięwzięcia (ze względu na późniejsze rozpoczynanie pracy kolejnych brygad).

Na skutek zakłóceń realizacyjnych i oddziaływania czynników ryzyka czasy wykonania procesów na działkach roboczych są zmienne – mogą różnić się od planowanych, przyjmowanych przy tworzeniu harmonogramu. Zmienność czasów wykonania prowadzi do opóźnień w przekazywaniu frontów robot kolejnym brygadom i w efekcie do zakłóceń w ciągłej realizacji ciągów procesów i niedotrzymywania terminów dyrektywnych. Najczęściej stosowanym sposobem zapewnienia ochrony terminów dyrektywnych jest alokacja buforów czasu w harmonogramie. W artykule zaproponowano podejście do alokacji buforów umożliwiające zarówno zwiększenie niezawodności dotrzymania terminu dyrektywnego zakończenia przedsięwzięcia, jak i redukcję przestojów w pracy brygad. Proponowana metoda harmonogramowania proaktywnego przedsięwzięć powtarzalnych obejmuje następujące etapy:

1. Budowa harmonogramu bazowego.
2. Kalkulacja wielkości buforów czasu.
3. Budowa harmonogramu odpornego na zakłócenia.
4. Weryfikacja uzyskanego rozwiązania / planu pod względem prawdopodobieństwa dotrzymania terminu dyrektywnego oraz wielkości przerw w pracy brygad.

W harmonogramie bazowym, dla przyjętych przez decydenta wartości deterministycznych czasu trwania procesów budowlanych, terminy realizacji procesów są ustalane tak, aby zachowana była ciągłość pracy brygad oraz zapewniona minimalizacja czasu realizacji przedsięwzięcia. Różnica czasu dyrektywnego i planowanego w harmonogramie bazowym jest następnie rozdzielona w postaci buforów czasu. Przydzielone bufory zwiększają zapasy czasu na wykonanie poszczególnych procesów na działkach (i jednocześnie terminy rozpoczynania kolejnych ciągów procesów) i tym samym chronią terminy realizacji procesów następnych. Ze względu na konieczność zachowania ciągłości pracy brygad bufory te należy lokalizować na końcach procesów poprzedzających na poszczególnych działkach a przed terminami rozpoczęcia procesów następnych na tych samych działkach. Aby ograniczyć propagację zakłóceń w harmonogramie, proponuje się bufory czasu rozdzielić w sposób gwarantujący równomierne rozłożenie tych przestojów a po zakończeniu wykonywania ostatniego procesu na ostatniej działce ulokowany będzie bufor projektu. Do ustalenia wielkość buforów czasu procesów oraz terminów rozpoczęcia i zakończenia realizacji procesów w harmonogramie odpornym opracowano model matematyczny programowania całkowitoliczbowego. Umożliwia on wybór spośród wszystkich rozwiązań, dla których najmniejsze przestoje na działkach osiągają największe wartości, takich harmonogramów, gdzie łączne rezerwy czasu na działkach są maksymalne – zapewnia poprawę odporności harmonogramu. Model ten może być rozwiązywany za pomocą powszechnie dostępnych tzw. solverów, np. LINGO, GAMMS itp.

Weryfikację uzyskanego rozwiązania w warunkach losowych pod względem prawdopodobieństwa dotrzymania terminu dyrektywnego oraz wielkości przerw w pracy brygad proponuje się dokonywać za pomocą metody symulacji dyskretnej. Ze względu na oddziaływanie czynników ryzyka czasy wykonania procesów na działkach są zmiennymi losowymi. W przykładzie przyjęto, że zmienność czasów realizacji procesów jest opisana za pomocą teoretycznego rozkładu trójkątnego, który pozwala na modelowanie obserwowanej w praktyce skośności funkcji gęstości prawdopodobieństwa i stanowi dobre przybliżenie rozkładu beta-PERT. Modele symulacyjne opracowano w języku symulacyjnym ogólnego przeznaczenia GPSS World (General-Purpose Simulation System) firmy Minuteman Software. Ze względu na złożoność problemu ustalania istotności różnych celów optymalizacji, w szczególności dla przeciwstawnych kryteriów minimalizacji czasu realizacji i minimalizacji przestojów w pracy brygad, proponuje się dokonywać wyboru rozwiązań kierowanych do realizacji na podstawie analizy zależności między ich wartościami.

Przeprowadzone badania symulacyjne potwierdziły, że zasadne jest stosowanie zbliżonych rezerw czasu w celu ochrony terminów rozpoczęcia procesów na kolejnych działkach roboczych i redukcji oczekiwania brygad na zwolnienie frontu robót przez brygady ustępujące.

Ponieważ w przypadku działek niejednorodnych na czas realizacji przedsięwzięcia wpływa kolejność zajmowania działek przez brygady, należy dążyć do zintegrowania proponowanego podejścia z procedurą poszukiwania optymalnej permutacji działek. Wyznacza to kierunek dalszych badań.

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