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.2025.156188

ARCHIVES OF CIVIL ENGINEERING

Vol. LXXI ISSUE 4 2025

 pp. 561 –574

Research paper

Reactive scheduling of repetitive construction projects by allocating additional resources

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Abstract: Repetitive construction projects involve the sequential execution of the same type of construction process at different locations (units). Work crews responsible for a particular type of process complete their work in one unit and then move on to the next. In practice, it is not possible to divide the built facility into identical units. In such a case, reducing the execution time of the project leads to interruptions in the workflow of the crews. Better results can be achieved by changing the order in which the units are processed by the crews. The use of the flow-shop system, well known in production scheduling, makes it possible to reduce the execution time of this type of projects, but makes the schedules vulnerable to random disturbances: the resulting delays can propagate throughout the schedule and generate idle time for crews completing their processes on time. Therefore, rescheduling may become inevitable to meet the deadlines. This paper presents a linear programming mathematical model for reactive scheduling that takes into account the possibility of allocating additional crews and allows for the possibility of changing the sequence of units. It makes it possible to meet the target date for completion of the project and to reduce the downtime of the working crews. The proposed approach to respond to schedule disruptions is illustrated by an example. Potential tools for solving the model were also pointed out, which can form the basis for creating a decision support system in the execution phase of repetitive projects.

Keywords: construction project scheduling, reactive scheduling, resources allocation, mathematical modelling, linear programming

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1. Introduction

The construction phase of a project is particularly exposed to various disruptive factors [1]. The risk of time and cost overruns is a burden for both the contractor and the client, as well as the challenge for planners and managers who are expected (and required) to produce reliable schedules robust enough to stay valid and economical even in the face of random or unexpected events. This approach is referred to as proactive or predictive planning [2]. Redundancy techniques are commonly used to ensure the processes', the milestones', and the entire projects' completion dates are met. They typically involve schedule buffering to protect the key dates against the impact of anticipated disruptions. However, buffering is likely to result in longer as-planned duration of project stages or even the whole project. As keeping project duration short is the common planning objective, the project team restricted by a short project completion time and heavy delay penalties may not be in position to add extra time to the schedule in the form of buffers. In such a case, if they plan all work according to the shortest technically viable time, the schedules become very vulnerable to expiration under risk, meaning difficulty in reacting to disturbances and resulting in liquidated damages, need to renegotiate, resource downtime cost, increased site logistics costs, lost opportunity, as well as create problems in coordinating own workforce and subcontractors in other projects [3].

The problem of disturbance is particularly important in scheduling repetitive projects [4]. The term "repetitive" is used not in reference to the nature of project results (e.g. buildings), but because of the nature of processes (schedule tasks/activities), which are repeated many times at numerous locations within a built facility [5]. To schedule them, the planners apply methods similar to the flow shop system intended for the industrial production planning. Such planning involves breaking down the works into activities to be entrusted to specialized crews, as well as dividing the built facility into units where the activities are performed typically in the same sequence in every unit. As soon as one crew completes a process and leaves for another unit, the next crew may take over the unit to deliver their work. In this way, processes can partially overlap in time and schedules can be compressed compared to a case where each process in the entire built facility had to be completed before the next process could begin. As a rule, the scheduler tries to keep each crew's work continuous, so he analyzes the workload in each unit and plans the crew composition so that the crews can move from unit to unit without waiting. These rules are applied to scheduling the construction of multistory buildings, roads, or pipelines, which are naturally divisible into sections where the same sequences of operations are to be performed. Considering that such projects are capital-intensive, long-lasting, and structurally complex, they are naturally prone to risk. The number of risk factors and the strength of their impact are characteristic for each project [6]. Nevertheless, common events such as untimely component delivery, inclement weather, plant failure, and workforce absenteeism strongly affect stability of production rates and cause workflow disturbance that easily propagates from process to process: units become available to the next crew at moments different than intended, and the meticulously devised plans fail. Thus, the planning process must assume that some measures are going to be taken during construction to prevent significant changes of process or milestone dates. This approach is referred to as reactive scheduling [7].

The literature presents examples of reactive scheduling applied to non-repetitive projects modeled as networks, focusing mainly on limited resources [3]. The analyses of reactive scheduling of repetitive projects are rare. Among the latter, Bakry et al. [8] presented an algorithm for schedule updating, dynamic rescheduling and optimized acceleration. There is possibility to select acceleration strategy, for example: working overtime, working double shifts, working weekends, and employing more productive crews. Hegazy and Kamarah [9] proposed an integrated framework for scheduling, optimization, and control of repetitive projects scattered across large geographical areas; they concluded the optimization models need to be expanded to support project control stage and proposed an iterative schedule updating procedure to mitigate delays at the lowest cost. Jaśkowski et al. [7] combined the proactive and reactive approaches and put forward an algorithm for defining the start dates of consecutive crews; they based on simulations and assumed that reactive measures will be applied as the processes progress to accelerate their delivery.

The modified schedule should generally be similar to the original schedule. This includes, among others, minimizing the number of processes with changed start dates and minimizing the scale of difference between the new and the original dates. This is to avoid supply chain disruption. The share of processes with changed dates and the number of processes assigned to extra resources can be used as measures of schedule stability. An obvious measure for evaluating rescheduling proposals is the cost of changes introduced to the original schedule. Therefore, to minimize changes, the reactive scheduling proposals should compare effects of accelerating individual processes at specific units, accelerating process sequences repeated at successive units [7], or accelerating groups of process sequences at parts of the facility yet to be completed.

The paper analyzes the possibility of reducing the duration of process sequences by employing additional crews (resources) to perform these processes in parallel at other units, as well as by changing the order in which the units are processed by the crews. The proposed reactive scheduling approach can be applied both periodically and in immediate response to a disturbance that results in a delay that exceeds a predefined threshold.

The paper is organized as follows: Section 2 compares methods applicable to compressing repetitive schedules. Section 3 presents the mathematical formulation of the rescheduling problem. Section 4 presents the model in application to a simple illustrative case. Section 5 presents conclusions and directions for future work.

2. Schedule compression methods for repetitive projects

In the face of delays due to random disturbances, the manager takes steps to offset their negative impact. Rescheduling process with a primary goal to meet the original project due date naturally focuses on reducing the durations of unfinished processes. It can be carried out using any method of compressing repetitive schedules. However, meeting the due date at any cost is rarely the objective, and the planner strives to achieve schedule stability, so to minimize the difference between the original and the new schedule. The reason is that thorough changes result in extra costs and effort throughout the supply chain.

The scheduling literature frequently uses the shortest duration as the main optimization criterion. A number of methods dedicated for repetitive scheduling have been proposed; their origins are in the organization of industrial production and optimizing production lines. An example is the Line of Balance (LOB) [10]. It focuses on assigning resources (the crews) to sequences of processes to be repeated at locations (units) that are identical in terms of the type and amount of work. The shortest duration of the project is achievable if the durations of different processes at a unit are the same or very similar, and this can be achieved by careful planning of the composition of the crews to assure the desired crew production rates. Hegazy et al. [11] put forward a geometrically driven heuristic procedure to extend the modeling capabilities of the conventional Critical Path Method (CPM) and LOB; a practical feature was to allow mid-activity changes of crews (adding or removing some crews) to equalize process execution times and improve the crews' workflows. Zou and Li [12] proposed a LOB resource allocation method based on the branch-and-bound algorithm to optimally assign crews and minimize their number. Considering the problem of crashing repetitive construction schedules, Tomczak and Jaskowski [13] proposed a decision model that assumed relocating resources from non-critical to critical processes, and helped decide if to hire extra resources (subcontractors) to complete delayed project on time if the supply of in-house workforce was limited.

In the case of production industry, assembly lines are optimized to keep the workflow continuous with resources fully utilized. Similarly, LOB assumes that the crews work continuously, so the resource flow from unit to unit is uninterrupted. The resource continuity condition was present in most scheduling methods designed for repeatable projects, in contrast to the classic CPM. For scheduling erection of buildings that can be divided into discrete units (floors, segments), the literature proposed, among others, Disturbance Scheduling [14] or Horizontal and Vertical Logic Scheduling for Multistory Projects [15], whereas Linear Scheduling Method [16] was intended for roads, tunnels and pipelines. The common feature of these scheduling methods is the graphical representation of the schedule, showing progress of activities in time in the form of a time-location diagram.

With this standardized way of presenting schedules, Harris and Ioannou [17] were able to propose a generalized Repetitive Scheduling Method (RSM), applicable to both vertical and horizontal construction, that ensures uninterrupted resource utilization. The method involves identification of the so called controlling sequence of activities that determines the duration of the project as a whole. As in the case of CPM's critical path, speeding up the controlling sequence's processes reduces the project's makespan. From the practical side, RSM acknowledges that the units may not be identical.

In general, assuring resource continuity is the principal of repetitive scheduling. It may be desirable for technological reasons and, in most cases, is the most economical, as resource downtime generates nonproductive costs [18]. Moreover, disruptions in the resource workflows reduce the beneficial effect described by the learning curve (productivity increase over time due to gaining experience and routine with repetitive activities). However, the more constraints in scheduling models, the "worse" solutions. If the scheduler tries to minimize the project duration under a strict resource continuity constraint, the resulting optimal schedule is likely to have a longer makespan than a schedule optimized with a more relaxed approach to resource utilization. Therefore, the literature presents a variety of repetitive scheduling algorithms that allow resource discontinuities to improve other criteria of project performance.

The decision to allow resource downtime may result in a considerable shorter project duration. Thus minimizing project duration and maximizing resource continuity can be considered conflicting criteria of optimization. Hyari and El-Rayes [19] considered this fact as a bicriteria optimization problem and proposed a model organized in three modules. The first module generates a preliminary schedule, the second uses a multicriteria genetic algorithm to generate a set of non-dominated solutions, and the third module allows the selection of the final schedule. Ipsilandis [20] developed the Multi Objective Linear Programming model (MOLP-LRP) that accounts for more optimization objectives: apart from the usual minimizing the project duration and minimizing resource downtime, they included minimizing the unit completion time and the cost. By changing the model parameters, the user can perform a trade-off analysis between project duration, downtime, and cost.

Having observed that interruptions in the workflow may result in shorter project makespans when one or more "fast" activities are trapped between "slower" ones, Hegazy and Kamarah [21] designed a High-Rise Scheduling Model (HRSM). It incorporated genetic algorithms-based cost optimization that determines the combination of construction methods, number of crews, and work interruptions that meet the logical relationships within each floor and among floors of varying sizes. They combined the merits of CPM and LSM: the works related to the building's story are scheduled using the network model (horizontal constraints), and the relationships between processes in consecutive stories are modeled as vertical constraints. Their model is capable of exporting results to popular scheduling systems such as MS Project.

Agrama [22] presented a flexible multiobjective model based on LOB scheduling technique. Its advantage consists in modeling the works to be conducted at a particular unit by non-serial typical activity networks that allow for the activities' overlapping in time. The objective function of this model combines three criteria: total cost, total actual crews, and total interruption for all activities.

lama and Moselhi [23] proposed a multi-objective optimization method that integrates LSM and the critical chain project management (CCPM). The objective function combines three criteria, simultaneously minimizing the project duration, the cost, and work interruptions. The method produces a deterministic schedule with sized buffers. The method responds to the uncertainty of productivity rates of crews, work quantities, and availability of resources using fuzzy set theory.

Roghabadi and Moselhi [24] introduced a new type of activity float time that allows for calculating the required crew productivity rate that minimizes crew work interruptions without delaying successor activities and without affecting the optimized project duration. This scheduling model minimizes the project duration, project cost, crew work interruptions and interruption costs. Interruption cost includes the cost of crew downtime as well as mobilization and demobilization costs. Dai et al. [25] provided evidence that tolerating controlled workflow interruptions helps smoothing resources.

As can be seen from the publications presented above, the search for a trade-off between the amount of downtime and the duration of the project or other criteria is a standard assumption. Small amounts of downtime are considered acceptable, but the models never ignore the continuity question. Some researchers additionally consider the impact of work discontinuities at individual units on the execution time of the project as a whole [26]. In the case of multi-building projects, where individual buildings are treated as separate units, these discontinuities increase the execution time of individual buildings. With the project dividable into identical units, the continuity of crew work and work at units can be achieved together with the minimum project duration. However, if the units differ, the shortest project duration is achieved only with relaxed requirements on resource continuity and continuity of work at units. The relationships between the work performed by a particular crew at successive units and the relationships between successive activities performed at a unit are referred to as time couplings. The combinations of simultaneously considered interrelationships were the basis for identifying three basic project organization methods [27]: Time Couplings Method I (TCM I) assumes that the resource continuity is the planning objective, TCM II insists on keeping the workflow in each unit continuous, TCM III aims to minimize the project duration, but takes into account the above-mentioned relationships while allowing crew downtime or interruption of workflow at a unit. Thus, the time couplings represent the common organizational and technological constraints characteristic for construction projects. Radziszewska-Zielina and Sroka [28] presented interactive scheduling tools that enable the user to prioritize the organizational time couplings and decide which of them must be maintained. This approach helps customize schedules to a variety of objectives: assuring continuity of all or selected resources, in a particular set of units or in all units, etc. The same method was applied to handle different priorities on technological constraints [29].

The repetitive units of the project must be arranged in some logical sequence. This sequence has to be established to suit some technological and technical needs. For instance, the stories of a building's structure are to be erected sequentially from the bottom to the top, but they can be finished in any order, even simultaneously. The impact of processing the units on the project duration was considered, among others, by Hejducki and Mrozowicz [27]. They developed branch-and-bound-based algorithms for each TCM variety to find the optimal order of units. Podolski [30] noted that scheduling problems of repetitive project can be drawn from classic flow-shop models used in manufacturing; to find the optimal sequence of units he developed a tabu search algorithm.

Huang and Sun [31] considered repetitive projects that involved different scopes of works carried out by groups of crews at units. They assumed that a number of crews can be employed to deliver processes of the same type, and that any order of processing units for each crew was acceptable. They developed a heuristic algorithm to minimize the total project duration while assuring continuity of crew work. Jaskowski and Biruk [32] described this problem using a mathematical linear programming model. In [33], the same authors presented a model for resource allocation and finding the optimal sequence of unit processing, assuming that the scope of works was the same in all units.

As resource and work continuity are frequently considered conditions that can be relaxed, the time couplings that represent them can be defined as soft relationships. Soft logic, as understood by Tamimi and Diekmann [34], refers to the relationships between the activities that are technically independent and could be delivered in parallel. Soft logic in defining precedence relations among processes of the same type in different units was applied by Fan, Sun and Wang [35] to schedule repetitive construction projects.

3. The model for reactive rescheduling repetitive construction project

The proposed mathematical model of the reactive scheduling problem for repetitive construction projects rests upon a set of assumptions. First, the construction processes require different skills. Therefore, specialized crews or machine sets, later referred to as resources, are to be employed for specific processes.

Second, to equalize execution times of different processes to be conducted in a unit, the model allows that the composition of a resource can be modified, but with limitations. The resources are assumed to be composed of teams of workers or machine subsets (later referred to as teams), and their composition is to be fixed. Therefore, a resource can be modified only by adding or removing a whole team. This results in the discrete, and not continuous, effect of changing the productivity of a resource, with an obvious impact on process duration. Thus, an ideal equalization of process durations may be impossible, which means inevitable disruptions of the resource workflow. However, as shown in the literature review, allowing them can contribute to reducing the project execution time.

Third, another option to be considered in search for schedule compression, is the possibility to hire extra resources, outside the pool of resources used in the original schedule. Their support is limited to processes they specialize in, and they are intended to work at units different than these served by their original counterparts, in parallel to the work provided by their original counterparts. The composition of the extra resources may differ from their original counterparts, with the effect on production rates and process duration. Thus, the duration of a process delivered at two identical units, one served by an extra resource, and one by its original counterpart, may differ.

Fourth, the extra resources are assumed to be in-house resources of the contractor subject to arbitrarily defined availability. The model does not consider hiring subcontractors nor analyzing economic effects of choosing between in-house and subcontracted workers, nor the efficiency of resource utilization across the whole contractor's organization. This is a strictly project-centered perspective.

Fifth: although the best theoretical results (elimination of resource downtime, continuous work at units) are achievable if the units are identical, in practical cases the division into units cannot be arbitrary. Thus, the proposed model assumes that units differ in terms of quantity of work, and there is no proportional relationship between the size of the unit and quantity of work related with a particular process. In this case, the project duration is affected by the order in which the resources occupy the units; an example illustrating this fact is the classic flow-shop problem for two processes, and the algorithm to find the optimal solution proposed by S. Johnson). The order of processing units can be set the same for all resources (as in TCM methods), but it can be also defined separately for each resource.

Let us assume that the schedule is to be updated starting at moment τ, when some processes i out of the whole set of project processes I have been completed in some units j. Process i to be delivered in unit j (a sub-process of process i) is denoted by a pair of indices (i, j): what is to be done, and where. Let J^{τ} denote the set of units where not all processes have been completed, and I_j represent the set of processes to be conducted at unit $j \in J^{\tau}$. At each unit, the processes must be completed in a fixed order resulting from technological constraints, and they must run in sequence. Therefore, at each unit $j \in J^{\tau}$ the next sub-process $(i+1, j)$ can start on completion of sub-process (i, j). The start dates of sub-processes in units are represented by $s_{i,j}$, $i \in I_j$, $j \in J^{\tau}$, and the durations (updated and expected) as $d_{i,j}$, $i \in I_j$, $j \in J^{\tau}$.

In the original schedule, each process was assigned to a particular resource. As the schedule is updated, additional resources can be introduced as reinforcement. Thus, the planner can define a set of resources R_i that are available and capable of delivering process i. The model assumes that the original resource allocated to process i is number 1 in each set R_i.

As initially assumed, a number of resources can serve the same process, but never in the same unit: they can do their job concurrently in different units.

The expected duration of sub-process (i, j) if entrusted to resource $r \in R_i$ is denoted by $t_{i,j,r}$. The decision on selecting a resource to deliver sub-processes is modeled by means of binary variables $x_{i,j,r} \in \{0, 1\}$, $x_{i,j,r} = 1$ if sub-process (i, j) is allocated to resource r, otherwise $x_{i,j,r} = 0$. To model the sequence of sub-processes entrusted to the same resource in a pair of units p and q (so the sequence in which this resource is to move from unit to unit), another group of binary variables is used: $y_{i,p,q} \in \{0, 1\}$, $y_{i,p,q} = 1$ if sub-process $(i,\ p)$ is to precede sub-process (i, q), otherwise $y_{i,p,q} = 0$. Therefore:

$$x_{i,j,r} \in \{0, 1\}, \quad \forall i \in I_j,\ \forall j \in J^{\tau},\ \forall R_i \tag{3.1}$$

$$y_{i,p,q} \in \{0, 1\}, \quad \forall i \in I_j,\ \forall p,\ q \in J^{\tau}, \tag{3.2}$$

while

$$y_{i,q,p} = 1 - y_{i,p,q}, \quad \forall i \in I_p \cap I_q,\ \forall p,\ q \in J^{\tau},\ p < q, \tag{3.3}$$

where: $x_{i,j,r}$ – binary variable modelling allocation of resource r to execute sub-process (i, j), $y_{i,p,q}$ – binary variable modelling sequence of execution process i on units p and q.

Sub-processes whose original start date was τ form the set I_{τ}. In the updated schedule, they are to continue with the originally allocated resources. Therefore:

$$s_{i,j} = \tau, \quad \forall (i, j) \in I_{\tau}, \tag{3.4}$$

$$x_{i,j,1} = 1, \quad \forall (i, j) \in I_{\tau}, \tag{3.5}$$

where: $s_{i,j}$ – start date of sub-process (i, j).

The project is completed as all processes at all units are delivered. The project completion date is also not allowed to exceed the due date, so

$$s_{i,j} + d_{i,j} \le T_d, \quad \forall i \in I_j,\ \forall j \in J^{\tau}, \tag{3.6}$$

where: $d_{i,j}$ – duration of sub-process (i, j).

Any sub-process (i, j) can be delivered strictly by one resource:

$$\sum_{r \in R_i} x_{i,j,r} = 1, \quad \forall i \in I_j,\ \forall j \in J^{\tau}. \tag{3.7}$$

The duration of sub-process (i, j) delivered by resource $r \in R_i$ is:

$$d_{i,j} = \sum_{r \in R_i} t_{i,j,r} \cdot x_{i,j,r}, \quad \forall i \in I_j, \ \forall j \in J^\tau, \tag{3.8}$$

where: $t_{i,j,r}$ – expected duration of sub-process (i, j) if entrusted to resource r.

The sub-process start dates must be non-negative:

$$s_{i,j} \geq 0, \quad \forall i \in I_j, \ \forall j \in J^\tau. \tag{3.9}$$

The processes are to be delivered according to the logic of works (technological constraints). The sequential relationships are the same at each unit and denoted by a graph $G = \langle I, E \rangle$, where $E \subset I \times I$ is the set of graph arches (process precedence relationships):

$$s_{v,j} \geqslant s_{u,j} + d_{u,j}, \quad \forall (u, v) \cup E, \ j \in J^\tau. \tag{3.10}$$

A resource cannot process more than one unit at a time, thus it moves from unit to unit in sequence, on completing its work in the preceding unit:

$$s_{i,p} + d_{i,p} \leq s_{i,q} + M \cdot (1 - y_{i,p,q}) + M \cdot (2 - x_{i,p,r} - x_{i,q,r}), \quad \forall i \in I_p \cap I_q, \ \forall p, \ q \in J^\tau, \ p \neq q, \ \forall r \in R_i, \tag{3.11}$$

where: M – sufficiently large number.

The schedule updated in reaction to disturbances should involve as little extra cost as possible. As one of the rescheduling constraints was completion no later than at the original due date, these extra costs exclude liquidated damages. It is also assumed that there is no change in resource allocation to sub-processes started at moment τ, so no additional costs are incurred here. The only source of extra costs related with rescheduling is the resource downtime. Therefore, the objective function of the model minimizes the total downtime of the employed resources:

$$\min z : \quad z = \sum_{i \in I_j} \sum_{r \in R_i} \left(\delta_{i,r} - \sum_{j \in J^\tau} t_{i,j,r} \cdot x_{i,j,r} \right), \tag{3.12}$$

where $\delta_{i,r}$ is the period of resource being engaged for the project, calculated as a difference between the resource's start on site to deliver process i in units intended for this resource:

$$\delta_{i,r} \geq s_{i,q} + d_{i,q} - s_{i,p} - M \cdot (2 - x_{i,p,r} - x_{i,q,r}), \quad \delta_{i,r} \geq 0, \quad \forall i \in I_p \cap I_q, \ \forall p, \ q \in J^\tau, \ \forall r \in R_i. \tag{3.13}$$

The mathematical model with the objective function (3.12) and constraints (3.1)–(3.11) and (3.13) is linear, and its variables are continuous and binary. It can be solved using general-purpose linear programming solvers are available on the market, but because of the computational complexity of permutation problems, dedicated applications can be also built. These can base on metaheuristic algorithms, such as evolutionary algorithms, and encode solutions as chromosomes containing, among other things, binary values of decision variables.

4. Example

Let us consider a schedule of finishing works in a five-story office building. Each story is a separate unit. Finishing each story involves the same set of processes: installation of partition walls, plastering, flooring, painting, and installation of suspended ceilings, to be conducted in the same sequence in each unit. However, the work quantities differ from unit to unit due to the differences in the functional layout. Each process is originally assigned to a specialized crew denoted by A, B, C, D, E, accordingly.

The progress check conducted 30 days from the project start indicates that the first process is significantly delayed compared with the original schedule causing downtime for the subsequent crews. Thus, the planner compiles a list of options to speed up the remaining processes. Table 1 shows the expected duration of sub-processes in particular units if entrusted to available resources (the original ones, marked with uppercase letters, and to be employed as reinforcement, and marked with lowercase letters). The durations are expressed in working days.

Table 1. Project data (input for the analysis)

Unit number	**Partitions Duration in days**	**Plastering Duration in days**		**Flooring Duration in days**		**Painting Duration in days**		**Suspended ceilings Duration in days**	
	A	**B**	**b**	**C**	**c**	**D**	**d**	**E**	**e**
1	–	–	–	–	–	6	–	4	4
2	–	–	–	5	–	4	5	5	5
3	–	1	–	5	4	7	8	4	4
4	–	4	4	3	3	4	5	4	4
5	5	6	5	6	5	4	6	5	5

Considering the current delay, the production rates of the original resources, and the assumption of resource continuity, the project, if continued according to the logic of the baseline schedule, would be completed in the next 30 days, so 6 working days (calendar week) after the due date. Therefore, the project needs to be rescheduled.

The first rescheduling attempt assumes the relaxation of some organizational constraints without adding extra resources. This relaxation allows changes in the sequence of units and resource downtime. In this case, this proves not enough to reduce the project duration.

The second attempt considers the effect of introducing new resources in addition to relaxing constraints as in the first attempt. Complementary crews b, c, d, e can be employed. However, process 1 at unit 5 is to be continued by resource A, process 2 at unit 2 by resource B, process 3 at unit 2 by C, and process 4 at unit 1 by D ass planned in original schedule at the 30 day.

The model was solved using LINGO 15.0. The schedule of process execution considering the current delay, the production rates of the original resources, and the assumption of resource continuity is shown in Fig. 1.

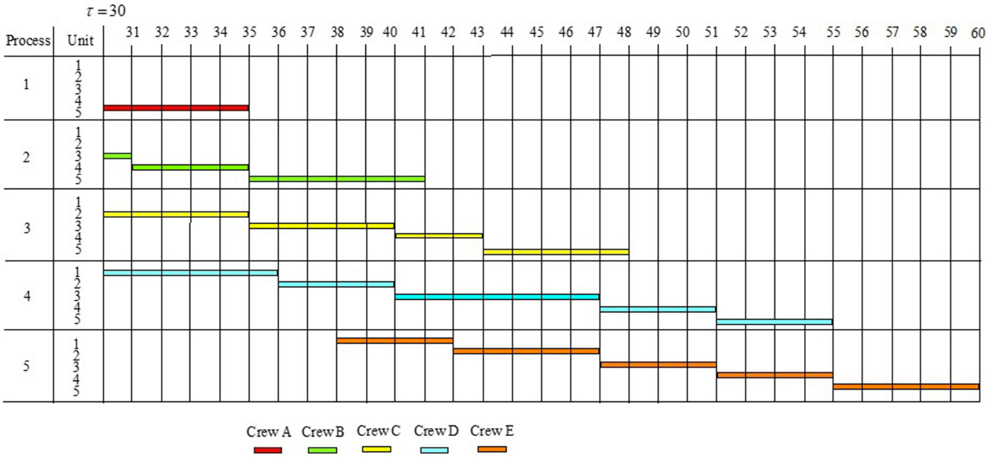

Fig. 1. Project schedule considering the current delay, the production rates of the original resources, and the assumption of resource continuity

The optimal reactive schedule is presented in Fig. 2.

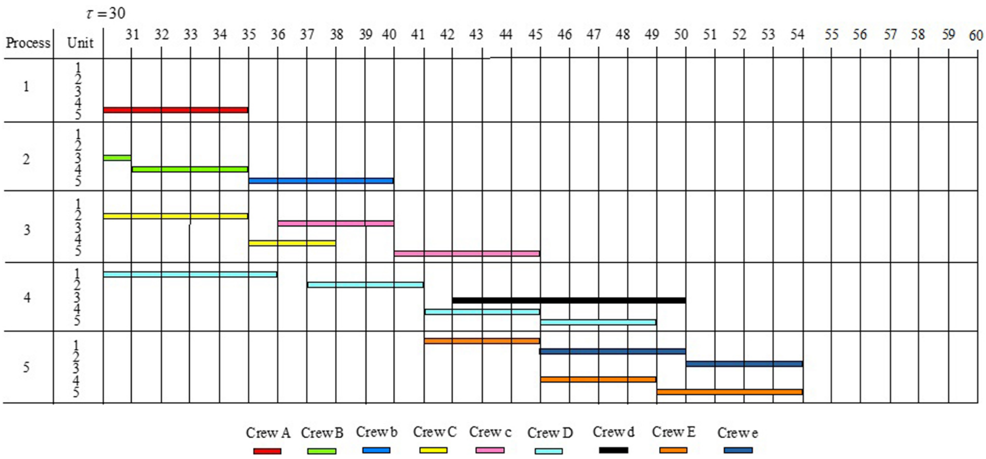

Fig. 2. The optimal reactive schedule (example)

The duration of the project is thus reduced by 6 days to 54 days. Only one resource, D, has a downtime of one working day. Compared with the original schedule, no radical changes occur to the sequence in which the resources move from unit to unit. However, this result is specific to the example and may be explained by small differences between process durations in different stories of the building.

5. Conclusions

Creating baseline schedules is an important task in project planning. These schedules are required to define the completion date and other milestones necessary to organize the project's supply chain. They are based on assumptions and estimates that are not necessarily confirmed as the project progresses. However, forecasts are inherently subject to error and uncertainty. Access to historical data on process execution times and previous projects is limited, which reduces the reliability of even the most sophisticated statistical models developed to describe the impact of random phenomena on task execution and variability in construction process durations. Thus, despite careful proactive planning, some unforeseen delays in the execution times of individual processes and project stages, or the need to perform additional work, cause schedules to expire. Therefore, there is a need for methods to update schedules to deliver the project with results as close as possible to the original objectives.

The reactive scheduling model for repeatable projects proposed in this paper was intended to help reduce the delivery time of remaining tasks by allocating additional resources and determining the optimal sequence of units while minimizing resource downtime. The mathematical formulation in the form of the linear programming problem is seemingly simple. Finding an exact solution to a simple illustrative case was possible using a general-purpose application (LP Solve), but the computational effort increases with the number of constraints. Solving models of real-scale construction projects will call for more efficient metaheuristic solvers. Future research will therefore be aimed at developing a dedicated computer scheduling system for problems.

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.

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Aktualizacja harmonogramów powtarzalnych procesów budowlanych z uwzględnieniem zatrudnienia dodatkowych zasobów

Słowa kluczowe: harmonogramowanie przedsięwzięć budowlanych, harmonogramowanie reaktywne, alokacja zasobów, modelowanie matematyczne, programowanie liniowe

Streszczenie:

Przedsięwzięcia budowlane obejmują często różne procesy budowlane realizowane kolejno na częściach obiektów (działkach roboczych). Do ich wykonania organizowane są brygady robocze, które po wykonaniu zadań na jednej części obiektu przechodzą na kolejną działkę roboczą. W rzeczywistości ze względów konstrukcyjnych podział obiektu na jednakowe części jest niemożliwy, co powoduje że skrócenie czasu realizacji przedsięwzięcia jest możliwe do uzyskania przy wprowadzeniu przestojów w pracy brygad, a z drugiej strony lepsze wyniki można uzyskać zmieniając kolejność zajmowania działek roboczych przez brygady. Zastosowanie systemu pracy flow-shop, znanego w przemyśle, pozwala na skrócenie realizacji tego typu przedsięwzięć, jednak powoduje, że w przypadku wystąpienia losowych zakłóceń przy realizacji spowodowane nimi opóźnienia mogą propagować w całym harmonogramie i powodować przestoje w pracy brygad realizujących swoje procesy terminowo. W tej sytuacji konieczna jest aktualizacja harmonogramu. W celu dotrzymania terminów dyrektywnych konieczne jest podjęcie działań w reakcji na zakłócenia. W artykule zaprezentowano model matematyczny programowania liniowego do harmonogramowania reaktywnego uwzględniający możliwość zatrudnienia dodatkowych brygad oraz dopuszczający możliwość zmiany kolejności zajmowania działek. Umożliwia on dotrzymanie terminu dyrektywnego zakończenia realizacji przedsięwzięcia oraz ograniczenie przestojów w pracy brygad roboczych. Skuteczność zaproponowanych sposobów reakcji na zakłócenia realizacyjne zaprezentowano na przykładzie. Wskazano również na potencjalne narzędzia rozwiązania modelu, które mogą stanowić bazę do tworzenia systemu wspomagania podejmowania decyzji w fazie realizacji przedsięwzięć powtarzalnymi procesami.

Received: 2024-10-23, Revised: 2024-11-05