Research Article

Sławomir Biruk* and Łukasz Rzepecki

Simulation model for resource-constrained construction project

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Abstract: Repetition of the same processes on different objects or units of a construction project and their concurrent execution makes it necessary to use the same limited resources at the same time. Managers prefer simple heuristic priority rules to scheduling construction activities, but there is not one the best for all projects. In addition that the experience from deterministic scheduling problems and priority-rule methods cannot always be directly transferred to stochastic environment.

The paper presents the pure reactive simulation model for planning construction projects in random conditions, taking into account the availability of renewable resources. Conducting simulation tests allows for various priority rules to determine the distribution of construction project duration and evaluate the robustness of the schedule.

The paper analyzes the effectiveness of the selected priority rules in a pipe line project. In the analyzed project, the Dynamic Minimum Slack rule ensures the lowest average duration of the project in random conditions and the highest quality robustness. The analysis of the simulation results can help the construction manager to choose the procedure ensuring the timely completion of the construction project in the stochastic environment.

Keywords: construction management, renewable resources, random duration, priority rules

1 Introduction

The schedule and budget of the project can be analyzed from two separate points of view. The investor's goal is to minimize the time and cost of the project, while the goal of the construction contractor is to look for such a scenario (resource allocation) so that the total costs incurred by him

were as low as possible. The construction planning should therefore take into account the random nature of the processes' duration and resource availability.

There are three strategies for including uncertainty in the project planning process: proactive, reactive, and stochastic scheduling. In the proactive approach, a robust schedule is created for possible execution disruptions. A common way to protect the schedule against possible disturbances is incorporating time buffers [1–4]. The reactive scheduling consists of revising the schedule in response to an emerging disruption [2, 5]. When an unexpected event occurs the baseline schedule is repaired or completely new reschedule is generated for activities planned for execution after a disruption. In stochastic project scheduling, no baseline schedule is created. Subsequent activities are added to the partial schedule previously determined based on the so-called scheduling policy, which in every decision point adds new activities taking precedence and resource constraints into consideration. The scheduling policy can use information contained in the network, information about activity planned durations, a partial schedule created for the decision point, or the activities resource usage [6].

The construction processes are subjected to many risk factors, *e.g.*, weather, site and geological conditions, organizational problems or poor safety procedures [7], therefore, the initial schedule becomes outdated quickly and the management of the project course requires the selection of the order in which activities are started, taking into account the level of resource availability at the time of making the decision. Managers prefer simple heuristic priority rules (PRs) rather than the use of complex optimization methods that are often incomprehensible to them [8]. The resource-based policies are a direct adaptation of the PRs and the parallel schedule generation scheme in deterministic environment to stochastic resource-constrained project scheduling (SRCPS). The PRs require low computational effort and therefore, they can be used to analyze large scale projects.

The effectiveness of the PRs application in deterministic environment was analyzed by many researchers for the single or multi-project scheduling, *e.g.* in papers [9–13].

*Corresponding Author: Sławomir Biruk: Lublin University of Technology Lublin, Poland; Email: s.biruk@pollub.pl

Łukasz Rzepecki: Lublin University of Technology, Faculty of Civil Engineering and Architecture, Poland

The research was aimed at comparing the effectiveness of the PRs (influence on the project completion time). For this purpose, the test sets [14] or computer generated networks were used. The generators allow to carry out the full factorial experiment due to the network complexity, lower and upper limit of the resources, and activity resource requirements, etc. [15].

The literature analysis indicates that there is not one the best PR in the scheduling resource-constrained project. It is recommended to examine different PRs, in particular when the optimal solution is not known or project duration cannot be estimated by other, more accurate methods. The effectiveness of PRs depends primarily on the project complexity, the degree of resource contention, and resource distribution [9, 10, 12]. Different objectives of project managers and portfolio managers may cause their preference for other decision rules [9].

Kanit *et al.* [16] analyzed the effectiveness of three PRs: the Maximum Remaining Path Length (MRPL), Latest Finish Time (LFT), and Minimum Slack Time (MSLK) in scheduling of ten Turkish housing estate projects. PRs with high performance were selected on the basis of the literature survey. Based on the research conducted, the authors found that in six cases the MRPL priority reduced the project duration, LFT in three, and MSLK in only one project.

Biruk [17] has proposed a computer-based Renewable Resource Management System for a Construction Company (RRMSCC), which is applicable to planning and monitoring the progress of the construction project portfolio. The decision managers are assisted by dispatching rules, and not as it is in practice, on their experience and intuition.

To evaluate different rules for the allocation of limited resources in stochastic conditions, simulation tests are most often used. The simulation method allows to determine the distribution of the total project duration and, consequently, to evaluate the risk of meeting the project due date agreed with the owner.

Chen *et al.* [18] analyzed 12 PRs commonly used in the deterministic resource-constrained project scheduling problem (RCPSP) and five new simulation-based PRs. Analysis of the examples showed that the experience from using PRs in the RCPSP cannot always be directly transferred to the project scheduling in stochastic environment. Authors have developed guidelines for managers to choose the most appropriate rule in the RCPSP.

Wang *et al.* [19] carried out the full factorial experiment in order to examine the PRs for the stochastic resource-constrained multi-project scheduling problem. The data set included 420 project portfolios, each consist-

ing of three individual projects. The portfolios were examined at randomly generated 42 unique combinations of the resource parameters. Studies may be the basis for selecting the right priority rule from both a project and portfolio managers perspective.

Yang [8] examined 13 dispatching rules for resource-constrained projects with and without well-estimated activity durations. To assess the impact of the estimation accuracy of the activity duration on the dispatching rule effectiveness, three sets of estimated activity durations were used. The examples analyzed showed that the minimum average duration of the project is generated using: Most Immediate Successors, Rank Positional Weight, Greatest Cumulative Resource Demand, and the Minimum Slack Time PRs.

Li *et al.* [20] developed a procedure based on common random numbers for comparison of feasible sequences obtained by the simulation method using different PRs for scheduling projects with random activities duration. The feasibility schedules meeting the precedence and the resource constraints are generated using simulation strategy based on activity scanning method. Alternatives were assessed using the average project duration.

To describe the complex dependencies between project activities, the Design Structure Matrix (DSM) was used instead of a precedent relationship [21, 22]. The use of DSM allows modeling the impact of reworks activities, learning effect, and concurrency in performing the activities. The simulation based model allows determining distribution of total project durations with complex dependencies between projects activity.

Depending on the aim of the project manager, the ranking alternatives (schedules generated using different PRs) can be created based on: average time of project completion (quality metrics) or quality robustness measures. Herroelen and Leus [2] defined quality robustness as an insensitivity of the project due date on the occurrence of disruption. Robustness measures can be derived from the simulation examination of a project. Wang *et al.* [19] proposed the relative deviation metric RM_i based on the comparison simulation and the exact project duration:

$$RM_i = \frac{ST_i - DT_i}{DT_i} \quad (1)$$

where: ST_i is the mean project duration calculated by the Monte Carlo simulation method for the i PR; DT_i – project duration calculated using deterministic estimates for the duration of the activities.

Sadeghi *et al.* [23] presented the original method of projects planning in random conditions, considering limited availability of resources named by authors as the DE-

SPEL (Discrete Event Simulation with Probabilistic Event List). It allows determining the distribution of the project duration in only one simulation run. This method is similar to the network analysis in the PERT method, because it only takes into account the dates of the event on the longest path which is determined on the basis of the availability of resources. Different PRs were used in the DESPEL system.

Ghomi and Ashjari [24] presented a simulation model for the implementation of three projects connected by shared resources. The model was programmed in the GPSS (General Purpose Simulation Language). Only a random resource allocation rule was applied and the aim of the analyses was to obtain the probability density function of the project's completion time of each of the three projects depending on the availability of resources and to evaluate a resources utilization degree.

Hu and Mohamed [25] proposed a two-step algorithm for dynamic allocation of resources while ensuring the continuity of construction processes. The authors believe that too many resources (work teams, construction machines) carrying out work on working sites can lead to a decrease in productivity and increase the risk of accidents.

Li *et al.* [20] presented a model with the availability of different resources. Due to the computer implementation, the precedence and resource constraints were presented in the form of an incidence matrix and resource matrix. The authors used different PRs for dispatching resources (Shortest Processing Time, Minimum Slack Time, Latest Finish Time, Greatest Resource Demand, and the Most Immediate Successors) to find the solution with the shortest average execution time. The common random numbers were used to compare the variants.

AbouRizk and Wales [26] proposed an approach combining the discrete and continuous simulation method. The first module of their model (discrete simulation) maps the course of a construction project using a network model, while the second one (continuous simulation) imitates the environmental conditions affecting the duration of activities.

The Qualitative Simulation Graphs (QSG) model proposed by Ingalls and Morrice [27] maps the PERT networks with resources in the form of an acyclic graph, which represents all acceptable schedules, regardless of the adopted strategy of resource allocation and randomness of activities duration.

2 Description of the simulation model

A construction project is modeled using the activity on node network. The activities duration can be modeled by a triangular or uniform distribution. The triangular distribution is simple and understood by practitioners – it is a good approximation of the beta distribution used in the PERT method, and differences in the risk assessment when using both distributions are insignificant [28, 29]. The uniform distribution can be used in cases where it is easy to estimate only extreme values, while it is difficult to estimate the mode of the process duration. It is also necessary to specify activity resource requirements, the limit of their availability and their weight (cost of use).

In each simulation run, the activities duration are drawn from probability distributions using the inverse transform method [30]. The activities start time are calculated in accordance with the Critical Path Method. Processes are started in the earliest dates after meeting the precedence and resource constraints. The choice of processes takes place in accordance with the parallel scheduling scheme [31]. In every decision point, which is the activity finish date, the level of resources availability resulting from the release of renewable resources by the completed process is updated. Then a list of processes that can be started is ordered in accordance with the assumed PR. After updating the partial schedule, the level of resource availability is adjusted and selection is repeated until the set of processes possible to start is empty. In the case where there are several processes possible to start and the selected PR does not decide which one should be chosen, then the process is selected based on the random rule.

In the simulation model the following PRs were incorporated:

- Shortest Processing Time (SPT),
- Most Immediate Successors (MIS),
- Greatest Resource Demand (GRD) – the product of the duration and a weighted sum of the resource requirements,
- Greatest Resource Utilization (GRU) – gives priority to that combination of activities which maximizing weighted sum of resources usage (requires the use of a 0-1 integer linear programming),
- Minimum Slack Time (MSLK) – slack is calculated for planned activities duration (mean values of duration) based on the resource-unconstrained CPM method,
- First Come First Served Rule (FCFS),

Table 1: Duration, type, and number of resources for individual activities

Activity	Duration [days]			Resource requirements			
	t_a	t_b	t_c	R1	R2	R3	R4
Excavation	5	9	16	1	0	2	0
Manhole	7	9	14	0	1	2	0
Boring	13	17	24	0	0	1	1
Pipe lying	7	9	11	0	1	2	0
Pipe thrusting	10	12	17	0	0	1	1
Backfilling	5	7	12	1	0	1	0

- Most Delay Process (MDP) – process delay is calculated as the difference between the planned start date (calculated for the deterministic model with no resource constraints) and the current resource allocation date,
- Dynamic Earliest Finish Time (EFTD) – for each process, the finish date is calculated as the start date determined on a partial schedule, increased by the planned duration,
- Dynamic Minimum Slack (MSLKD) – the slack time of an unscheduled activity is based on partial schedule and planned activities duration,
- Dynamic Latest Start Time (LSTD) – the earliest start time of an unscheduled activity depends on the finish times of the scheduled activities.

In the simulation model, the event-based approach [30] was used. Changes in the state of the system (decision points) are observed only in the dates of starting and ending of activities. Conducting of k independent simulation runs allows determining the total expected project duration on a specified confidence level ($1-\alpha$) with the availability of resources and the distribution of the project duration for each PR. As a consequence, it gives the opportunity to estimate the risk of meeting the deadline set with the owner and estimate the project robustness. The PRs verified by simulation method can be a valuable hint for the project and portfolio managers. The simulation model was programmed in Java standard edition 8, using Eclipse IDE.

3 An analysis of pipe line project in stochastic environment – an example

The example analyzes the impact of PRs on piping project duration and robustness of schedules in stochastic envi-

Figure 1: Sewage system diagram **Figure 2:** Activities relationships in piping project

ronment. The project was divided into 8 pipeline sections between 9 manholes. The scope of works in five sections includes line excavation with timber pilling, manholes, pipe laying, and backfilling. On the other three sections, the pipeline was made with trenchless technology (Figure 1). A precedence relations among activities of the examined project is shown in Figure 2.

4 types of resource were examined: two excavators (R1), two cranes (R2), 3 working crews (R3), and one thrust boring machine (R4). The activities resource requirements are included in Table 1. For the GRU rule, the values of activities weights are equal respectively: $w_1 = 0.1667$, $w_2 = 0.1667$, $w_3 = 0.0555$, $w_4 = 0.2222$, $w_5 = 0.1111$, $w_6 = 0.2778$.

Table 2: Simulation results

No	Priority rule	DT_i deterministic project duration [days]	ST_i mean of project duration [days]	Probability of meeting the project deadline [%]	Average exceeding the project deadline [days]	RM_i relative deviation metric [%]
1	LSTD	193.0	199.2	100.0	0.0	3.2
2	MSLKD	193.0	198.7	100.0	0.0	2.9
3	EFTD	199.0	226.2	59.3	11.8	13.7
4	FCFS	196.5	208.8	99.5	1.4	6.2
5	MIS	193.0	200.3	100.0	0.0	3.8
6	MDP	193.0	213.0	91.5	3.9	10.4
7	GRD	197.0	220.5	71.6	7.3	11.9
8	GRU	197.0	222.5	69.7	9.6	12.9
9	MSLK	193.0	202.5	99.9	1.5	4.9
10	SPT	200.0	227.8	54.8	12.1	13.9

Figure 3: The cumulative distribution function for the project deadline

The triangular activities probability distribution were assumed based on optimistic t_a , pessimistic t_b , and the most likely estimates t_c (Table 1).

10 000 simulation runs were carried out for each priority rule, based on which the average duration of the piping project ST_i , the average overrun of the project due date, and the probability of meeting the project deadline were calculated. The due date which was agreed upon with the owner for 229 days. The results are shown in Table 2. The robustness of schedules generated using the different

PRs was determined using the relative deviation metric (Eq. 1), in which DT_i was determined using the proposed simulation model for the resource-constrained construction project, assuming deterministic activity duration with an expected value of random variables. Figure 3 presents distribution functions of project duration with all tested PRs.

The construction manager, when choosing the scheduling policy must take into account the average time of the project implementation, the probability of meeting

the project deadline, and quality robustness. If several criteria are considered at the same time, he should decide of using Multi-Criteria Decision Making Methods. In the analyzed project, the best choice is the Dynamic Minimum Slack (MSLKD) rule – this rule ensures the shortest time of implementation in deterministic conditions, the lowest average duration of the project (calculated using the Monte Carlo method) in random conditions, the highest probability of meeting the deadline date and the lowest value of the relative deviation metric. The schedule obtained using the Dynamic Latest Start Time (LSTD) rule is more sensitive to random factors than solution generating using the MSLKD rule – the RM_i metric grows from 2.9 to 3.2. The solution created by the MIS rule has a relatively low RM_i equal to 3.8, additionally the MIS is a deterministic rule, it does not need to be recalculated during the implementation of processes and therefore it can be preferred by a construction managers.

4 Conclusions

The construction projects are realized under risk conditions. For this reason, schedules developed for deterministic conditions are quickly becoming obsolete. Construction managers taking the corrective actions most often rely on their own experience and intuition. Scheduling optimization algorithms are incomprehensible by them, and often they do not have access to the right optimization tools. A stochastic project scheduling (purely reactive/online strategy) most accurately describes the decision situation: a construction manager is to choose the order of activities (dispatching resources) taking into account the level of resource availability at decision points (activities' start dates), to minimize the project completion time. The indication may be the scheduling policy, which was verified by simulation method before the implementation of the project.

The paper analyzed the effectiveness of selected PRs during the implementation of the pipe line project. Based on the research, it was found that the most effective PR for the analyzed example is the MSLKD rule. Its use leads to the shortest average duration of the project and ensures the lowest value of relative deviation metric (robustness measure for schedule). The construction manager can, however, choose the MIS rule, which gives similar results. However, it is simpler to use because priorities have constant values during the implementation of the entire project (priority of activities are simply calculated only once).

Further work should be guided in two directions. The first includes the extension of the simulation model, primarily by implementing a larger number of scheduling policies, not just PRs. The simulation model should also take into account the impact of various risk factors, e.g., dynamic changes in renewable resource level caused by work absences or equipment failures, weather impact, rework, changes in project scope, or dynamic new project arrival. It is also advisable to include other types of time distribution of activities, primarily the beta-PERT distribution, which is widely used in the construction industry. The simulation analysis of the project will allow to understand the causes of delays and facilitate management of its course in uncertainty conditions.

The second direction of further research should focus on the literature survey on the use of scheduling policies in construction projects and on the study of efficiency of different PRs for real construction projects. Creating a database and categorization of construction projects based on characteristics such as: project complexity, degree of resource contention, and resource distribution can be a helpful tool for both the project and the portfolio managers in the understanding and management of uncertainty.

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