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EVALUATING SURROGATE MEASURES OF CONSTRUCTION PROJECT SCHEDULE ROBUSTNESS

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─Abstract ─

Projects are subject to various uncertainties that have negative effect on activity durations. This is most apparent in the case of construction projects. The actual completion time of construction projects is reported to be rarely in accordance with initial plans. A schedule considered optimal with respect to project duration may become infeasible due to disruptions caused by uncontrollable factors.

Deficiencies of the existing methods of project scheduling gave rise to the worldwide search for predictive (or proactive) scheduling that is expected to provide robust schedules (immune to disturbances), thus counteracting instability and "nervousness" of a project plan.

The baseline schedule (execution plan prepared prior to the project execution) is to be reliable in terms of not only the total project makespan, but also timing of particular tasks and activities – related with resource management. The main reason for the planner's insisting on stable baseline schedules is the necessity of "advance booking" of key staff or equipment (to guarantee their availability) and keeping fixed delivery dates (as required by suppliers or subcontractors).

A stable schedule with acceptable makespan performance should minimize the instability cost function, defined as the weighted sum of the expected absolute deviations between the predicted start times and the value that the random variable of start time will assume during schedule execution. Computational burden of optimizing this direct measure of schedule robustness in a real-life project environment is quite high. Developing surrogate quantitative measures to provide a good estimate of schedule robustness is essential for building efficient robust scheduling algorithms. For this reasons, the aim of this paper is to evaluate the quality of free-slack-based measures for a benchmark project. The new approach to increasing schedule robustness, based on buffer sizing and allocation, is proposed and tested against the existing free-slack times relocation approaches.

Key Words: *Project management, Robust scheduling, Stable baseline schedule*
JEL Classification: M11

1. INTRODUCTION

Construction projects are influenced by a variety of risk factors, e.g. weather, soil conditions, qualifications and productivity of the staff, crew and subcontractors, accidents, resource shortages, unreliable deliveries, defects. The environment in which the project schedule will be executed is far from being static. Its volatility results in uncertainty and risk in the final cost, duration and quality of the project. The probability that the baseline schedule (constructed as optimal assuming that all parameters are known and do not change with time) will be executed exactly as planned is low. A schedule that is optimal with respect to project duration or cost may largely be affected by disruptions and uncontrollable factors.

Unrealistic completion dates put a burden on various parties of the contract, especially the contractor. Risk should be incorporated into the schedule to make the milestones and project completion dates achievable. The available statistical knowledge of the uncertainties should be used while building the project schedule. This approach – aiming at increasing baseline schedule stability and quality robustness – is called proactive scheduling (Lambrechts et al., 2008). Quality robustness is defined as the probability that the project ends within the projected deadline. Solution robustness (or stability) is measured by the instability cost function (sum of the weighted absolute deviations between the expected real and planned activities starting times). An ideal schedule should combine both types of robustness (Van de Vonder et al., 2005). The weights can be defined as unit costs of delaying the activities' start times and project completion date, related with penalties for making subcontractors start later than agreed, additional materials storing costs etc. In this paper, the authors neglect additional costs or revenues caused by starting activities earlier as planned. Application of stochastic programming to the analysis of the objective function, i.e. instability cost function, where uncertain activity durations are modelled by probability distributions, may involve considerable computational effort. Instead, the authors use surrogate measures of robustness, and choose a simulation technique to assess their pertinence. Developing quantitative measures for estimating schedule robustness (stability) is essential for building robust scheduling algorithms.

Two main techniques are used in proactive scheduling: redundancy-based techniques and contingent scheduling. Both involve allocating time buffers. A contingency buffer at the end of an activity is its integral part, without a clear distinction from the original duration estimate. In the case of redundancy-based scheduling buffers, they take the form of distinct idle times (slacks) and are placed in front of or at the end of an activity to protect activities start times and prevent propagation of disruptions throughout the schedule. The free slack concept is closely related to stability of a schedule, whereas the total slack is related to quality robustness (Hazir et al., 2010).

In the literature, there are only few studies that propose and assess the pertinence of schedule robustness and stability measures. Al-Fawzan and Haouari (2005) defined robustness of schedules as the total sum of the free slacks allocated to increase the ability to cope with small increases in the time duration of some activities that may result from uncontrollable factors. There is a high correlation between robustness and the sum of free slacks (or equivalently the average slack) in job shop scheduling problems (Goren and Sabuncuoglu, 2008). Kobylański and Kuchta (2007) stated that in order to design a robust schedule, the planner should maximize the minimal free slack or the minimal ratio: free slack/activity duration. This way, the start date of each activity would be protected (which means solution robustness) and the makespan of the whole project would be assured (which means quality robustness). This way, the approach fuses solution and quality robustness. Lambrechts et al. (2008) introduced a nonlinear utility function for robust scheduling. Chtourou and Haouari (2008) used twelve alternative robustness predictive indicators to select the best schedule with resource constraints.

2. PROPOSED MEASURE OF PROJECT ROBUSTNESS

In the opinion of the authors, two main factors should be taken into consideration while determining the size of the time buffer: the variability of all the processes that precede the buffer in the schedule, and weights (i.e. unit costs) of processes' start times disruption.

The precedence relationships between schedule activities, i.e. construction processes, are modeled by a unigraph $G = \langle V, E \rangle$, directed, acyclic, in activity-on-node representation with single start and end nodes. $V = \{1, 2, \ldots, n\}$ is a set of construction processes (nodes), $E \subset V \times V$ is a bi-argument relation representing precedence relationships between processes (arcs).

Each process is assigned a duration d_j, established using mean productivity estimates, equal to mean values of durations distributions. These duration estimates are used for creating the initial baseline schedule.

Each non-dummy process j has a weight c_j that denotes the unit cost of delaying its start, the delay being the difference between its actual and baseline start times. The cost of the final dummy activity n is the cost of delaying the project completion beyond the predetermined (e.g. contractual) fixed due date T_d.

Processes whose $c_j > 0$ start in accordance with railway policy – not before the start date predefined in the baseline schedule. The objective is to build a stable precedence-feasible schedule with the makespan of T_d. This is to be done by minimizing the function of schedule instability cost, defined as the weighted sum of the mean delays of the actual starting times with respect to the initial baseline schedule.

Buffers δ_j are introduced to prevent propagation of disruptions throughout the schedule. These buffers are idle periods between the planned start of a process considered and the latest planned finish of its predecessors (the earliest start of the process).

To estimate a delay, it is necessary to perform simulations, especially in the case that different process starting policies are used during project execution, such as the railway or as early as possible policy.

Buffer size is established in the following steps:

1. Calculation of the minimal project duration $T_{\min}$, early start times of all activities, s_j^0, and their total slacks, $slack_j^0$, according to the initial baseline schedule based on mean values of activity durations, d_j.

2. Simulations of the project progress on the basis of the network model assuming that activity durations are random variables of predefined probability distribution, and that the activities start in accordance with the assumed starting policy.

The simulation enables the planner to estimate mean values of activity delays $\Delta s_j = s_j^1 - s_j^0$, where s_j^1 is the mean start date of a process $j \in V$ calculated on the basis of simulation results.

Assuming that the contractual project duration is known and equals T_d, the total slack of an activity $j \in V$ is $slack_j = slack_j^0 + T_d - T_{\min}$.

The existing slacks in the baseline schedule, having the form of time buffers, should be allocated among processes according to process weights, w_j, calculated according to the formula:

$$w_j = c_j \cdot \left(\Delta s_j + 3\sigma_j\right),$$

where σ_j is the standard deviation of the simulated activity start dates.

3. Robustness of the schedule will be measured by the minimum of the ratios $\delta_j / (slack_j \cdot w_j)$. The mathematical model for buffer sizing problem can be formulated as follows:

$$\max z = \min_{j \in H} \left\{ \frac{\delta_j}{slack_j w_j} \right\}$$

$$s_1 = 0$$

$$s_j - \delta_j \geq s_i + d_i, \ \forall (i, j) \in E$$

$$s_n + d_n \leq T_d$$

$$s_j \geq 0, \ \forall j \in V$$

$$\delta_j \geq 0, \ \forall j \in V$$

$$\delta_j = 0, \ \forall j \in V \setminus H$$

$\delta_j \in \boldsymbol{int}, \ \forall j \in H$,

where $H = \{j : w_j > 0\}$.

3. ASSESSMENT OF THE ROBUSTNESS MEASURES' PERTINENCE - EXAMPLE

Figure 1 presents an example of a construction project network model. Table 1 lists the estimates of parameters of activity durations under assumption that probability distributions of these durations are triangular (a_j – the shortest possible duration, m_j – the most probable duration, b_j – the longest possible duration, d_j – the mean duration), and c_j – the unit costs of delaying the activity start. Minimal project duration in the initial baseline schedule calculated on the basis of mean process durations is 277 days. We investigated pertinence of 8 surrogate measures and quality of the adapted float factor heuristic for buffer sizing (Van de Vonder et al., 2005). All investigated measures were maximized to find the robust schedule. The project due date was set on 290 days after start. Processes of $c_j > 0$, except the end node, start in accordance with railway policy, and the remaining processes – as soon as possible. The mean delay and standard deviation of each process were established by Monte Carlo simulation (30000 runs). Simulation was used also for evaluation of instability cost. Simulations were conducted by means of GPSS World^{tm} Personal Version by Minuteman Software (education license). Free slacks fs_j and buffers sizes δ_j were calculated by solving linear programming models using LINGO 12.0 Optimization Modeling Software. The results of calculations are presented in Table 2. Using measures no. 1, 2, 4, 6, we allocated the free slacks only to direct predecessors of processes with $c_j > 0$. Buffers allocated in front of processes with $c_j > 0$ when using measures no. 3, 5, 7, 8, 9.

The schedule with buffers calculated by maximizing our proposed robustness measure has the lowest instability cost. The slack distribution rule employed by the proposed approach considers both duration variability and propagation of disruptions in the network and seems to provide better results than the maximization of simple measures. One of the disadvantages observed during simulations is overprotection of the start dates that occurs in the case of processes on the end of the network paths. It can be reduced by incorporating additional buffer size constraints in the mathematical model.

Figure-1: Graph of precedence relations between work pakages in example

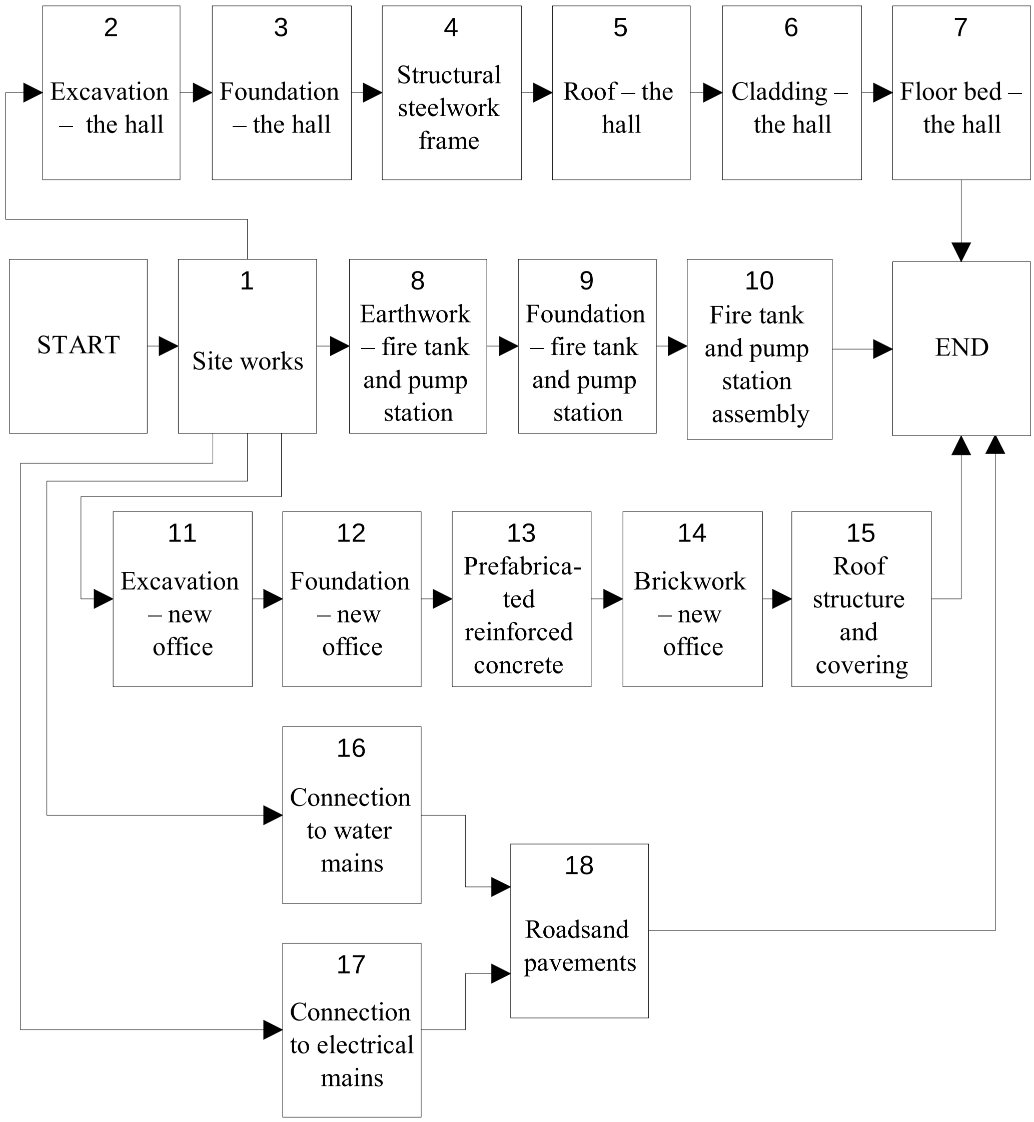

Table 1. Estimates of processes durations and unit costs of start delaying (example)

j	Process / work pakage	The shortest possible duration a_j	The most probable duration m_j	The longest possible duration b_j	The mean duration d_j	Unit cost of start delaying c_j
1	Site works	24	25	29	26	0
2	Excavation – the hall	19	20	24	21	0
3	Fundation – the hall	34	35	41	37	0
4	Structural steelwork frame – the hall	47	50	56	51	1
5	Roof – the hall	34	40	51	42	0
6	Cladding – the hall	52	58	68	59	1
7	Floor bed – the hall	34	40	49	41	0
8	Earthwork – fire tank and pump station	2	3	5	3	0
9	Fundation – fire tank and pump station	4	5	7	5	0
10	Fire tank and pump station assembly	15	20	37	24	0
11	Excavation – new office	5	7	10	7	0
12	Fundation – new office	18	20	25	21	0
13	Prefabricated reinforced concrete – new office	12	15	29	19	1
14	Brickwork – new office	22	25	30	26	0
15	Roof structure and covering – new office	10	12	16	13	0
16	Connection to water mains	40	45	55	47	0
17	Connection to electrical mains	70	75	90	78	0
18	Roadsand pavements	44	50	60	51	0
19	END	0	0	0	0	1

Maximizing the minimal buffers' or slacks' sizes leads to decrease of the schedule instability cost, but better performance can be obtained when all buffers or free slack sizes are leveled. Maximizing the sum of the free slacks or buffers leads to overprotection of some of the processes' start dates, but at the same time it does not provide sufficient protection of project completion date. As a result, the instability cost of the protected schedule is larger than that of the initial unprotected one.

4. CONCLUSIONS

A stable baseline schedule is crucial for the success of construction projects. Schedule disruptions result in difficulties with managing subcontractors and suppliers. Furthermore, not keeping to the contract due date and milestones is usually connected with penalties.

Table 2. Results of instability cost evaluations

No.	Robustness measure	fs_3	fs_5	fs_{12}	fs_7	fs_{10}	fs_{15}	fs_{18}	δ_4	δ_6	δ_{13}	δ_{19}	Instability cost
1	Sum of the free slacks	13	0	178	0	232	0	135	13	0	178	0	5.2750
2	Sum of weighted slacks[1]	13	0	178	0	232	0	135	13	0	178	0	5.2750
3	Sum of buffers	13	0	178	0	232	0	135	13	0	178	0	5.2750
4	Minimal free slack[2]	5	4	4	4	4	4	4	5	4	4	4	1.0639
5	Minimal buffer[3]	5	4	4	4	4	4	4	5	4	4	4	1.0639
6	Minimal free slack[4]	5	4	174	4	232	4	135	5	4	174	4	1.2865
7	Minimal buffer[5]	5	4	174	4	232	4	135	5	4	174	4	1.2865
8	Proposed measure	2	4	17	7	232	161	135	2	4	17	7	0.7727
9	Adapted float factor heuristic	4	5	89	4	232	89	135	4	5	89	4	0.8666
10	Initial baseline schedule	0	0	0	13	232	178	135	0	0	0	0	3.7411

[1] processes weight is calculated as the sum of its unit cost and unit costs of its immediate and transitive successors start delays;
[2] sum of the free slacks of remaining processes is minimized;
[3] sum of buffers of remaining processes is minimized;
[4] sum of the free slacks of remaining processes is maximized;
[5] sum of buffers of remaining processes is maximized;

In the paper we have analyzed the pertinence of several schedule robustness measures. The proposed robustness surrogate measure seems better than measures based on free slacks, but it assumes that probability distributions of activity durations are known.

An extensive simulation-based analysis of schedule robustness is suggested for future research to verify if the proposed method proves useful for solving practical buffer allocation problems in construction.

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