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ROBUST SCHEDULING IN CONSTRUCTION ENGINEERING

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Abstract. *In construction engineering, a schedule's input data, which is usually not exactly known in the planning phase, is considered deterministic when generating the schedule. As a result, construction schedules become unreliable and deadlines are often not met. While the optimization of construction schedules with respect to costs and makespan has been a matter of research in the past decades, the optimization of the robustness of construction schedules has received little attention. In this paper, the effects of uncertainties inherent to the input data of construction schedules are discussed. Possibilities are investigated to improve the reliability of construction schedules by considering alternative processes for certain tasks and by identifying the combination of processes generating the most robust schedule with respect to the makespan of a construction project.*

1 INTRODUCTION

To set up construction schedules, knowledge about construction methods, process durations, resources, and boundary conditions is required. When a construction schedule is set up, much data is not exactly known, i.e. the schedule is created based on estimated data. Nevertheless, the common scheduling method in construction management, the Critical Path Method (CPM), treats all input data as deterministic and thus neglects uncertainties inherent to the input data. Changes and deviations from the initial schedule, which occur in the construction phase, are therefore highly probable and, in fact, construction schedules are known to be unreliable. The unreliability of construction schedules poses a serious problem in construction engineering, because construction projects involve many different stakeholders. Common objectives in construction scheduling are the minimization of costs and time, i.e. the makespan. Due to changes during the construction phase, these optimized values are often not met. Therefore, the this study aims at investigating methods to set up more reliable schedules by maximizing schedule robustness with respect to the makespan.

Robustness is a term that is widely used and needs to be specified depending on the context. In this work, a robust schedule is a schedule for which the actually realized makespan deviates only little from the initially determined value, even if the input data deviates significantly from the estimations made during the planning phase. To assess the robustness of a schedule, the uncertainties inherent to the input data must be taken into account. Although these uncertainties are different in nature (e.g. unknown weather conditions, unexpected soil conditions, availability of resources, etc.), their effect can well be modelled by variable instead of deterministic process durations. To quantify the robustness of a schedule, a criterion comparing the makespan determined with deterministic data to the makespan determined with variable process durations needs to be defined.

Optimization of schedule robustness has been investigated in different domains. Usually, the robustness of a schedule is improved by varying the order of tasks. In the case of construction schedules, however, the order of tasks is typically not variable but fixed due to the specific boundary conditions. Instead, there often exist alternative processes for some tasks, but the choice of a certain process is usually made based on cost and time efficiency. In this work, the choice amongst alternative processes is investigated with respect to their influence on schedule robustness. It should be emphasized that not the robustness of separate processes is assessed, but the robustness of the combination of different alternative processes of a certain schedule. In the following, a short overview of existing literature concerning schedule robustness is given, and a method is presented for assessing and improving schedule robustness providing alternative processes.

2 SCHEDULE ROBUSTNESS

A common method in construction management to determine deadlines and makespans is the Critical Path Method (CPM). A network plan is drawn and, with process durations considered deterministic, the makespan is calculated as the length of the longest path in the network. As, at the time of generating the schedule, much input data is not yet exactly known but estimated, deviations from the initial schedule during the realization phase are highly probable. The so called Program Evaluation and Review Technique (PERT) has been developed almost at the same time when CPM has been proposed. PERT choses a stochastic approach with process durations defined by distribution functions. Due to simplifications made for the computation of the makespan based on stochastic process durations, the mean value and the standard deviation of the makespan are underestimated. Therefore, although considering uncertainties, PERT does not result in more reliable schedules than the purely deterministic CPM. In addition to stochastic approaches, fuzzy methods have also been investigated for scheduling problems [1]. An overview of scheduling under uncertainties can be found in [2].

Robust scheduling is a term that requires further specification depending on the context. In literature, different robustness criteria have been defined, depending on the characteristics of the schedule that is meant to be robust. In [3], the sum of weighted differences between actual and planned process start times based on process durations defined by distribution functions is used. The author of [4] investigates the number of processes that are affected by changing one process duration. In [5], a criticality index based on fuzzy process durations is defined, which measures the probability for a path to become the critical path. These examples illustrate that robustness has manifold aspects and cannot be assessed by one general criterion.

Optimization of schedules for certain robustness criteria can also be found in the domains of single machine problems and vehicle routing problems, as reported, e.g., in [6], [7], and [8]. Usually, the investigated problems require the identification of the optimal sequence of processes without processes running in parallel. However, in construction scheduling, the sequence of processes is largely predefined and many processes are running in parallel. The presented work investigates the potential of alternative processes and their combinations in order to optimize schedule robustness.

3 ASSESSMENT AND OPTIMIZATION OF THE ROBUSTNESS OF CONSTRUCTION SCHEDULES

In this study, the robustness of construction schedules is assessed as the insensitiveness of the makespan towards changes in process durations. It is assumed that the order of tasks is fixed, but that for some tasks there is an option of choosing between two or more alternative tasks. First, a model is developed to represent a schedule with variable process durations and alternative processes. Second, a criterion is defined to assess the schedule robustness, to be used as objective function in an optimization algorithm, to identify the most robust combination of alternative processes.

3.1 Modelling schedules with uncertainties and alternative processes

The schedule is represented by a simple, directed graph, with the set of vertices being a set of events and the set of edges being a set of tasks. A task represents the transformation from the as-is state into the target state, the states being described in the corresponding start and end events respectively. For the realization of a task, two or more alternative processes may exist, i.e., each task may have a set of processes from which one process is finally chosen. For n tasks with m alternative processes each, this leads to m^n possible combinations of processes. A vector $\boldsymbol{c}$ is defined, with the *i-th* element of the vector identifying the index of the process that is chosen for task i from its set of alternatives processes. This is an efficient way of representing possible combinations of processes. Uncertainties inherent to the input data are taken into account by assuming all process durations to be normally distributed random variables. Each edge of the graph is weighted by the duration of the represented process.

3.2 Assessing the effect of variable process durations

The effect of variable process durations on deadlines and makespans is investigated. For this purpose, a criterion is defined that compares the makespan determined based on deterministic process durations, in the following labeled m^{ref}, with the makespan reflecting variable process durations, in the following labeled M^{unc}. The variable process durations are described by normal distributions, with σ, defined by the project manager, describing the risk that the duration will deviate from its most probable value and μ set to the most probable value. m^{ref} is calculated based on the most probable values that are considered to be deterministic; it is therefore a discrete value and corresponds to the value calculated with traditional approaches. M^{unc} is determined via a Monte Carlo simulation and is described by a normal distribution. The mean value of M^{unc}, μ^{unc}, might equal m^{ref}, but only if there is a dominant critical path. As soon as deviations in the process durations trigger a change of the critical path, μ^{unc} becomes larger than m^{ref}. The criterion to quantify the difference between m^{ref} and M^{unc} is defined as the difference of the 95% quantile of the distribution representing M^{unc} and the reference makespan m^{ref}:

$$R = Q_{95}^{unc} - m^{ref} \tag{1}$$

3.3 Optimizing schedule robustness

The robustness criterion defined above is used as objective function for the optimization of the schedule robustness. The most robust combination of processes is identified with a genetic algorithm to avoid the time-consuming computation of each possible combination.

The indices of the chosen processes in one possible combination are contained in the vector $\boldsymbol{c}$ mentioned above. The *i-th* element of $\boldsymbol{c}$ contains the index of the process chosen for task t_i out of its set of alternative processes. The vector $\boldsymbol{c}$ is considered as an „individual“ within the genetic algorithm, the elements being its „genes“. Eq. (1) is used to evaluate the fitness of the individuals. For each individual, the determination of the fitness value requires the computation of m^{ref} and M^{unc} involving a Monte Carlo simulation for the calculation of M^{unc}. Starting from a randomly generated initial population, the genetic algorithm, through crossover and mutation, identifies the combination of processes that is robust with respect to the criterion defined in Eq. (1).

4 CASE STUDY

To validate the method proposed in this work, several network plans have been tested within a case study. The defined robustness criterion takes into account the susceptibility of the schedule for changes in the critical path, reflected by the difference between m^{ref} and μ^{unc}. It should be mentioned that, as a consequence, the most robust combination is not generated by simply choosing for each task the most robust process from its set of alternative processes. The described method is able to consider the situation appropriately. For details, the interested reader is referred to [9].

5 CONCLUSIONS AND OUTLOOK

The effects of uncertainties inherent to the input data of construction schedules have been discussed. A model has been developed that takes into account these uncertainties, describing the process durations with distribution functions instead of discrete values. At the same time, the model allows for considering alternative processes for each task. For a defined robustness criterion, quantifying the influence of uncertainties in process durations on the makespan, the most robust combination of alternative processes is identified by applying a genetic algorithm. In a case study, the effectiveness of the proposed method could be demonstrated. In future research efforts, the effect of correlations of processes as well as the effect of different stochastic distributions may be investigated. Given the conflict between the total length of the planned makespan m^{ref} and the schedule robustness, additional work may envisage a reasonable trade-off between minimizing m^{ref} and maximizing the schedule robustness.

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