Reactive Adaptation of Construction Schedules by Applying Simulation-based Optimization

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Abstract -

This paper deals with the adaption of construction schedule due to real-time data. This real-time data needs to be evaluated regarding the effects on the schedule. If significant delays or other problems are identified, the schedule should be adapted. That means that under the existing condition a new schedule needs to be generated. Thereby, different constraints of the target schedule like contracted delivery dates, milestones or resource allocation should be considered. In the presented approach these additional constraints are modeled and integrated into a simulation model which represents the planned target schedule. By applying simulation-based optimization a new efficient schedule is generated considering existing and additional so-called target constraints. If the identified delays are that large, such that an adaption considering all significant constraints is not possible, some constraints, like resource capacity or shifts, can be relaxed. The proposed concept for reactive adaptation of construction schedules by applying simulation-based optimization is verified by a standard construction schedule example.

Keywords -

Reactive Construction Scheduling; Schedule Adaptation, Simulation-based Optimization

1 Introduction

An efficient execution and control of construction projects depends highly on the accuracy of the underlying construction schedules. In turn, the quality of construction schedules and their being up-to-date depends on the availability of real-time data. In general, up-to-date schedules should include actual information about the overall construction progress, modified planning documents or available equipment. One crucial point is the gathering and evaluation of real-time data regarding their impact on the overall project progress. In the next step the updated or so-called actual schedule can be compared with the target schedule with the aim of detecting significant deviations. In the case that crucial delays are identified, the existing target schedule needs to be adapted. This procedure is known as reactive scheduling. Thereby, additional constraints need to be considered such as fixed material delivery dates, on-site resources, contracted milestones and established sequences. Currently, the adaptation of construction schedules is a manual, time consuming, error prone, and poorly supported process [1]. The aim of the presented research work is to enable an efficient and transparent adaptation of construction schedules considering general project objectives, actual progress information and underlying target schedules. In consequence, new methods need to be developed to model these additional constraints and to modify schedules in an optimal way.

2 Related Work

In practice, a lot of significant real-time data are logistics-related. Real-time logistics data contain information about available material, equipment and personnel as well as updated delivery dates and site conditions. In this context, Auto-ID techniques are appropriate methods to collect logistics data automatically. Biometrics and RFID are typical Auto-ID techniques that can be readily applied on construction sites and the transportation to the construction site. These data imply different types of uncertainties due to infrequent collections, varying transport times, or manual assumptions. By integrating uncertainties into the existing schedule their consequences on construction works can be evaluated.

In [2] the authors developed a goods inward inspection on construction sites for prefabricated components and steelwork for bridge construction. However, their research does not consider evaluation or integration of the collected real-time data for scheduling purposes. In [3] the authors propose an RFID-based controlling management for goods inward inspection and installation of tubes. In order to assess the progress of construction activities an automated progress control by applying laser scanning technology is presented in [4]. Laser scanning technology is utilized to overcome not satisfactory results by image processing and other techniques. Their system is able to assess progress control with minimum human input. In [5] a methodology for indoor location identification and material tracking based on RFID is presented. This automated approach enables acquisition of data about construction project status in almost real-time and detects the locations of worker and material with 100% accuracy. However, none of these researches considers uncertainties and their impact on schedules.

Only few research works exist, regarding the adaption of target construction schedules in case of infeasibility or non-optimality due to disturbances. In [6] a formal identification and re-sequencing process is presented. This approach supports fast development of sequencing alternatives in construction schedules. The approach is based on CPM, which is a dated method not considering resources or working shifts. In [7] another rescheduling approach is presented, which is based on Constraint Programming. Two rescheduling methods are presented, the complete regeneration and the partial rescheduling. However, this rescheduling approach is based on a mathematical model. Additionally, general research for job-shop scheduling exists. A review of scheduling concepts under uncertainties is given in [8]. The authors consider also various rescheduling concepts. However, none of these concepts applies simulation, but all are based on mathematical models.

Regarding the optimization of real construction schedules several research approaches exist. For detailed literature reviews we refer to [9, 10]. In [11] a crossover operator for genetic algorithms is proposed to tackle resource allocation. A time-cost trade-off mechanism to the resource allocation consideration is presented in [12]. Application of genetic algorithms to solve scheduling problems with respect to resource leveling is presented in [13]. In [14] a utilization of the Non-dominated Sorting Genetic Algorithm (NSGA II) [15] to tackle multi-mode resource constraint project scheduling problems (MRCPSP) is presented. Furthermore, the approach also considers resource allocation and resource leveling simultaneously.

In order to apply soft constraints, researchers have investigated how to formalize and model them in an appropriate way. Semiring Constraint Satisfaction Programming as a formalization methodology for soft constraints is purposed in [16]. The authors compare their methodology with Valued Constraint Satisfaction Programming. Furthermore, an exhaustive description of soft constraints and a semiring based framework is given in [17].

However, the utilization of discrete-event simulation models is an established methodology for analysis and planning of construction activities. Domain specific construction activities, resource requirements, and technological dependencies can be described by applying different modeling concepts. For example, a special-purpose simulation-modeling tool for planning and estimating earth-moving operations is developed in [18]. The authors of [19] propose a special purpose tunneling simulation tool. Nevertheless, the effort to model realistic simulation models is very high. Because of this, simulation is not applied often in practice. Therefore, recent research is investigating model driven simulation modeling. With the help of building information models (BIM) and knowledge-based methods, semi-automatic model generation and adaption can be utilized [20, 21]. Moreover, by combining the Constraint Satisfaction Approach with discrete-event simulations, it is possible to guarantee that valid construction schedules will be generated [22].

To our best knowledge, there is no research work available that tackles the integration of uncertain real-time data into simulation models for the purpose of performing a simulation-based optimization with respect to reactive construction scheduling. Therefore, we purpose a concept for reactive construction scheduling in which real-time logistics data are considered for controlling and updating construction schedules.

3 Adaptation of Construction Schedules

In this paper the adaptation of construction schedules is based on actual logistics data. The adaption is one crucial part in the context of reactive scheduling. Reactive scheduling means that real-time data, in this case actual logistics data, are considered for automated controlling and updating of construction schedules. A schematic overview of this approach is illustrated in Figure 1.

The concept consists of four steps. First, the acquisition, preparation and adaption of real-time logistics data is performed. The accuracy and inherent uncertainty depends on the location where the real-time data were collected. In addition, manual assumptions must be taken into account. In the next step, the prepared data is integrated into the construction schedule. For that purpose a simulation model is created which represents the target schedule including all activities, resources and restrictions. Thereby, a fundamental assumption is that construction activities are modeled in a highly detailed manner. For example, to construct a concrete wall-section, single activities for formwork and reinforcement installation, concreting, curing as well as removing the formwork must be specified and scheduled. In consequence, typical schedules consist of several thousands of activities. The real-time logistics data are defined as additional constraints for the involved activities. A sensitivity analysis is performed to analyze how the real-time logistics data affects the schedule and

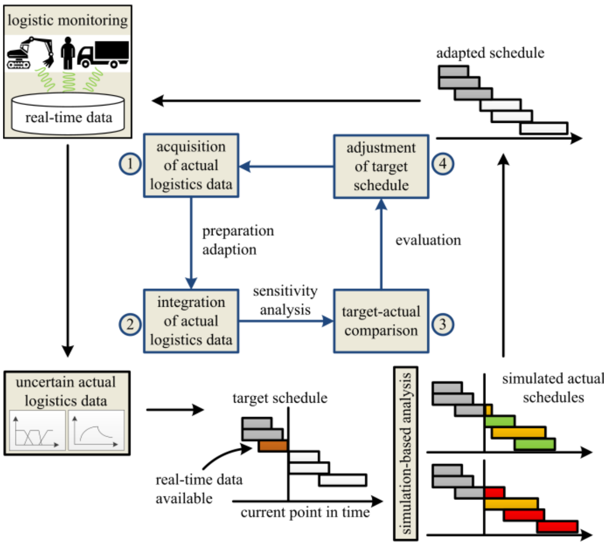

Figure 1. Schematic overview of the reactive construction scheduling approach

the project duration. Based on this target-actual comparison a decision needs to be made, if an adaption of the target schedule is necessary. In the last step, the planned schedule should be updated, if crucial delays or other significant deviations were detected. Thereby, the adaptation should be as much as necessary and as less as possible. That means that execution sequences, resource allocations or the planning of the upcoming weeks should be retained unchanged. The focus of this paper lays on an optimal adaption of the target schedule considering uncertain real-time logistics data.

3.1 Uncertain Real-time Logistics Data

In construction practice, a lot of significant real-time data are logistics-related. Real-time logistics data contains information about available labor resources, material, and equipment as well as updated delivery dates and actual site conditions. All these logistics data have some effects on the execution of the construction activities. For example, if material is not available the execution of related activities cannot be started. In this research real-time logistic data always results in so-called availability constraints for certain objects, like worker, material, equipment or spaces. Availability constraints are implemented as time windows.

Auto-ID techniques, e.g. biometrics or RFID, are appropriate methods to collect logistics data on the construction site or during transportation. Due to infrequent collections, varying transportation times, or manual assumptions the data features varying types of uncertainties.

Usually, such uncertainties are modeled by using probabilistic distributions or Fuzzy sets. In both cases sampling strategies, like random sampling, Latin hypercube sampling, or alpha-cut analysis, are frequently applied to generate discrete values. Discrete values, in this case discrete availability constraints, are required for evaluating the impacts on the schedule. Further information how to model and integrate real-time logistics data can be found in preceding research by the authors in [24]. For the target-actual comparison the results of the single discrete experiments are statistically interpreted. In many cases, an adaption of the target construction schedule is required if the comparison shows a significant deviation and important project goals cannot longer be maintained. In this paper it is assumed that an adaption of the target schedule is necessary and the discrete availability constraints representing the uncertain real-time logistics data are available.

3.2 Constraint-based Simulation

The basis for the reactive adaptation of construction schedules is the application of discrete-event simulation. Simulation is used to generate detailed constructions schedules considering several types of constraints, like precedence relationships, varying resources, shift calendars, and required material. To enable a flexible definition and integration of different constraints, constraint-based simulation is utilized for generating und updating construction schedules [22]. Constraint-based simulation is an extended discrete-event simulation approach. Each time an event occurs all constraints are checked to identify which activity can be started next (cf. Figure 2).

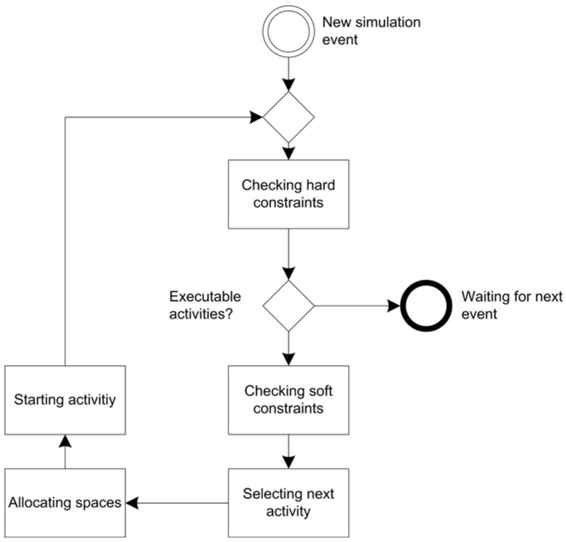

Figure 2. Constraint-based simulation approach

Generally, hard and soft constraints can be defined and checked. Typically, hard constraints are precedence restrictions, resource requirements, earliest starting dates or fixed time windows. Meaningful conditions, like preferred staring times and resource allocations, delivery dates, or established execution sequences, can be modeled as soft constraints. Soft constraints do not have to be satisfied completely. Solely, a fulfillment degree is calculated to evaluate the satisfaction. In this paper all soft constraints are defined based on weighted or k-weighted constraints. If weighted or k-weighted constraints cannot be completely fulfilled, the weights can be used to calculate so-called violation cost factors. For k-weighted constraints the threshold k specifies a lower or upper bound for the calculation of the cost factor. Costs factors can represent monetary costs or abstract costs for an evaluation. Consequently, different schedules can be analyzed regarding their fulfillment by calculating the schedule's total cost factor due to constraint violations.

3.3 Target Schedule Constraints

Due to the fact that the adaptation should be as much as necessary and as less as possible, additional scheduling restrictions based on general project goals and the target schedule should be defined. In the following some typical restriction of construction projects are highlighted. Obviously, this listing is not exhaustive. In some cases additional project specific constraints should be considered. However, additional target schedule constraints can be defined in the same way.

3.3.1 Delivery Dates

Frequently, short-term modifications of some delivery dates are not possible or very costly. This is particularly true, if the delivery is scheduled within a few days. For example if the delivery and the just-in-time placing of pre-casted elements is scheduled in five days, no storage areas are available on the construction site, and the supplier can only guarantee available means of transport in the following five to seven days, the activities for placing the pre-casted elements should not be postponed substantially. Time windows in which certain activities should be scheduled can model delivery date constraints. These time windows are represented by k-weighted constraints. That means, if an activity is scheduled outside the bounds of the time window, additional costs will occur.

3.3.2 Temporal Equipment

Another restriction is the assignment of temporal equipment, like mobile cranes or piling machines. The costs for hiring these machines are often very high and they are usually scheduled within different projects. In consequence, significant postponing of operation times is sometimes not possible or additional supplier need to be contracted. These restrictions can also be modeled by time windows. Activities that require special temporal equipment should be scheduled within the bounds of the time windows.

3.3.3 Established Sequences

Construction activities are often scheduled several times in the same order, in particular, in the context of high-rise buildings with similar structure. That means for each level the same types of activities are defined in the target schedule. One aim is to enable learning effects to increase the performance and the resulting quality. In consequence, the established sequences should not be changed in the scope of the adaptation. Established sequences can be considered by using weighted constraints. Thereby, the violation costs are calculated based on the distance between the activities of a certain sequence compared to the target sequence.

3.3.4 Milestones

Milestones are important events for clients and contractors. A milestone is often put at the end of a stage to mark the completion of a work package or phase. Furthermore, payments are often associated with reaching certain milestones. Therefore, another goal is to keep the defined milestones or not to exceed them significantly. Milestones are modelled as k-weighted constraints. Violation costs occur if the milestone date is exceeded by a certain time.

3.4 Additional Resources

If the current delays are significant or the target schedule is very ambitious, it is sometimes not possible to fulfill the additional target schedule constraints and the general project goals, respectively. In this case, two strategies can be pursued. One possibility is to release certain constraints. Another way is to define additional or reallocate specific resources. Additional resources can be integrated by increasing the amount or extend shifts of critical resources for a certain period. For example, the daily shift can be extended by two hours or the contractors can order weekend shifts. Reallocation means in this context that more resources are scheduled to perform a certain activity to reduce the execution time. However, this is only useful in certain cases.

3.5 Status of Construction

It is obvious that the actual status of construction needs to be taken into account during the adaption of the schedule. Activities which are already completed are no longer considered. Furthermore, the activities which are already started will be continued if possible. However, the allocated resources can be increased to complete the activity in a shorter time. The presented paper does not cover how to collect the actual status of construction. Different techniques from manual inspection to automated approaches using laser scanning, Auto-ID systems or images are possible. In the end, information about the progress of each activity must be defined. Within the constraint-based simulation the actual status of construction is considered as the following. Completed activities are removed. Already started activities get a high priority and all precedence relationships are removed. Furthermore, the duration needs to be adapted based on the actual progress. If actual information about the resources assigned to started activities is available, the same resources should be used again in the scope of the schedule adaptation. Of course, this is only possible, if the resources are still available.

3.6 Simulation-based Adaption

The adaption of a target schedule is based on searching a solution under the consideration of all additional constraints and the uncertain real-time logistics data. In general, this problem is called a constraint satisfaction problem. Due to the fact that not only hard constraints, but also soft constraints and general project goals like time, costs and quality need to be considered, it is advisable to apply some kind of optimization strategy to find a good solution for the constraint satisfaction problem. In this case a good solution is a schedule, which fulfills all hard constraints and minimizes the constraint violation costs. Additional objectives, e.g. minimal project duration, minimal costs and maximal quality, are neglected. As mentioned before, the construction scheduling problem is represented by a complex constraint-based simulation model. Metaheuristic optimization approaches are often applied to orchestrate the simulation model in such a way that the resulting schedule is an optimal or near optimal solution of the constraint satisfaction problem.

In this paper the NSGA-II algorithm is applied. This evolutionary algorithm is chosen due to its advantageous ability to conduct multi objective optimization and because it outperforms other existing multi objective evolutionary algorithms [15]. The chromosomes are defined as an activity list to generate construction schedules. The length of each chromosome corresponds to the number of activities that have to be scheduled. Each activity is modeled by a unique key value. The first key value entry in each chromosome represents the modeled activity that in turn should be scheduled first. The last chromosome key value entry represents another activity that should be scheduled as the last activity. Thus, the order of key values within a chromosome represents the execution sequence of the activities modeled by the key values.

4 Implementation

As it has been mentioned before, one main benefit of the constraint-based construction simulation is that additional constraints can be easily integrated into an existing simulation model. However, defining a realistic and highly detailed simulation model for construction scheduling can be very time-consuming. Due to this fact, a user-friendly software tool has been developed to speed-up the simulation definition process in the last years. The so-called SiteSimEditor is a BIM-based tool to prepare input data for construction simulation (cf. Figure 3).

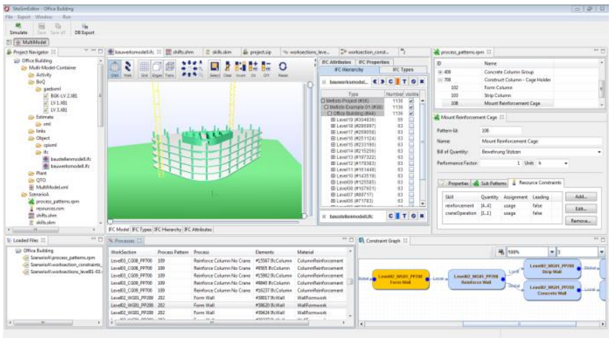

Figure 3. The SiteSimEditor to prepare input data for construction simulation

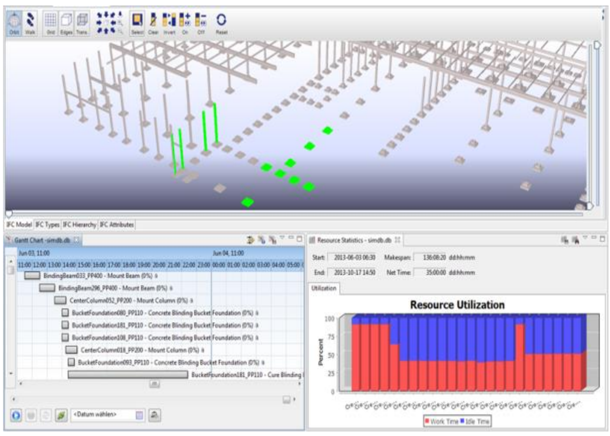

Figure 4. Visualization of simulation results for scheduling a storage building

By importing available project information like 3D building models, construction site layouts, bill of quantities and quantity take-off items, the construction activities and various constraints can be specified interactively. To keep the expenditure of time for data preparation as low as possible, reusable templates have been developed. Currently, several templates for activities, resources, technology dependencies, strategic executions sequences, and working shifts are available.

Based on the prepared and generated input data simulation experiments can be directly executed by using the SiteSimEditor. These simulation experiments are performed by a constraint-based discrete-event simulation engine, which is implemented as a component of the SiteSimEditor. Afterwards the results can be imported and visualized as Gantt charts, 4D animations or in form of different diagrams (cf. Figure 4).

4.1 Simulation Model Adaption

The SiteSimEditor has been extended to integrate target schedule constraints. For defining delivery dates and temporal equipment the existing availability and shift management plugin can be used. In general, for each resource different partially overlapping shifts, associated with duration limits, can be specified and considered within the simulation model.

New components and user-interfaces have been developed to define constraint like milestones or established sequences. However, information about upper bounds or sequences between activities, which should be observed, must be specified manually.

Other important aspects are the definition of additional resources and modified shifts to relax the existing constraints. In many cases this has to be performed to find a realistic adaption of the target schedule and to satisfy more important constraints like milestones or project duration.

5 Demonstration

In order to demonstrate the purposed approach a case study is adapted from literature. The case study is based on a simplified warehouse construction project introduced in [12]. It contains 37 construction activities, and considers precedence and resource constraints. The project is realized with 12 labor resources. Additionally, an adaption has been made to support a mobile crane for casting activities. The mobile crane is available only for a limited time period. Furthermore, a milestone has been defined that marks the point in time when all casting activities should be finished.

Discrete-event simulation is applied to generate a target schedule. The generated target schedule has a make-span of 190 days (cf. Figure 5), which is equal to the results presented in [23]. An additional adaption introduces the availability of real-time logistics data, such as delivery status of needed material. It is assumed that on day 37 of project execution, new real-time data are available. This data reports a delay of material delivery required by activity 7 and 10. In this example the

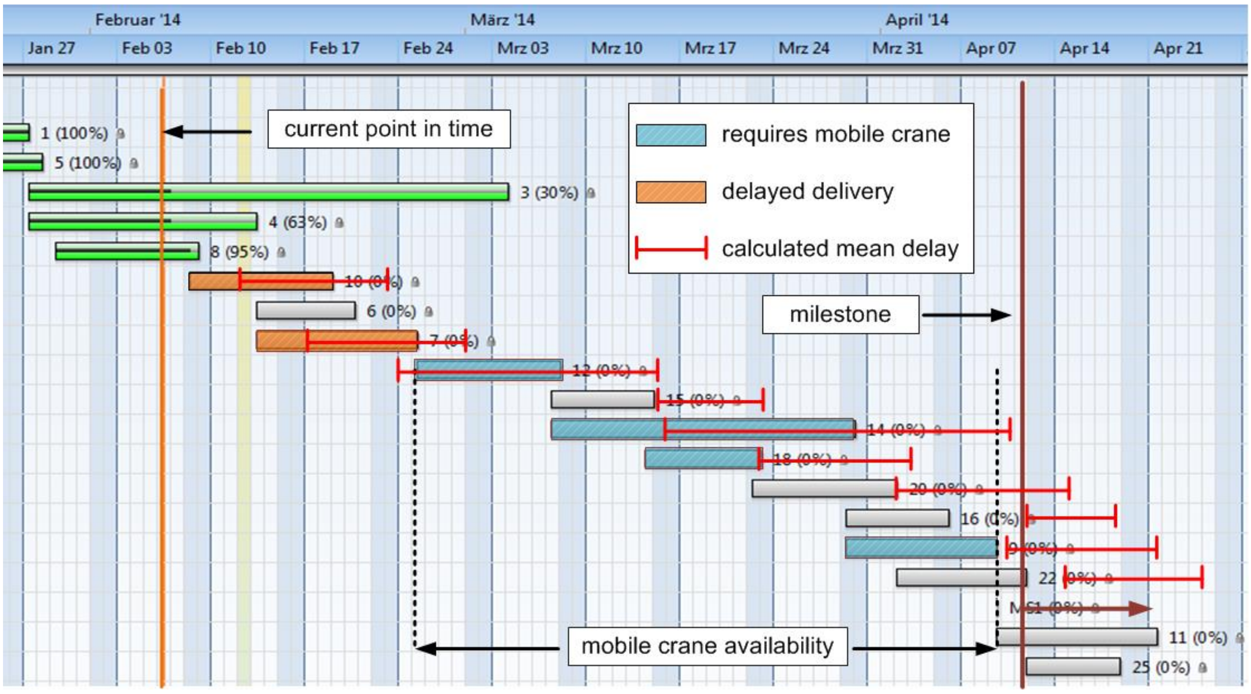

Figure 5. Target schedule excerpt with activity delays, mobile crane requirements, and project milestone

delay is set to seven days to enable traceability. In general, probabilistic or Fuzzy-based delays can be considered and a stochastic simulation and optimization have to be performed.

This data is prepared and integrated into the existing simulation model and a sensitivity analysis is executed. The results of this analysis are depicted in Figure 5 as calculated mean delay. The milestone is delayed by roughly 10 days and the mobile crane is not available when required. Thus, a simulation-based optimization is performed to adapt the schedule. During the reactive rescheduling some constraints are relaxed. The daily shift of the workers was extended by two hours. Furthermore, the required mobile crane is also available on the subsequent days. The relaxation of the mobile crane's availability is modeled as a k-weighted constraint. If the mobile crane is assigned on another, not contracted, day additional costs occur. During the contracted time frame the mobile crane costs 162$ per hour. On additional days, the costs increase to 200$ per hour.

The optimization compromises the variation of activity sequences and resource allocation considering two main objectives: observance of the milestone and minimizing the total resource costs of worker and mobile crane. Four simulations experiments were performed by combining shift and mobile crane extension (cf. Table 1).

Table 1. Simulation experiments for schedule adaption

Experiment	Shift extension	Crane extension
Exp1	-	-
Exp2	X	-
Exp3	-	X
Exp4	X	X

The optimization results of the experiments Exp3 and Exp4 are shown in Table 2. The observance of the milestone cannot be fulfilled for the first two experiments. The experiments Exp3 and Exp4 differ regarding the costs due to shift and mobile crane extension. However, both schedule adaptions are possible. In the next step the project manager needs to decide which adaption is most suitable.

Table 2. Simulation experiments for schedule adaption

	Exp3	Exp4
Milestone	X	X
Costs worker	29.900	43.400
Costs crane	63.146	52.746
Total costs	93.046	96.146

6 Conclusion

The adaption of construction schedules based on real-time data is an important aspect in the context of efficient project execution. However, the planned target schedule should be adapted as less as possible but as much as required. In this paper an adaption approach using simulation-based optimization is introduced. Applying constraint-based simulation generates the construction schedule. The information about the target schedule can be modeled by additional soft constraints. Different target schedule constraints are classified and modeled. By considering these additional constraints in the simulation model, an efficient, adapted schedule can be calculated. The optimization is based on the NSGA-II algorithm. The concept was verified by using an existing use case. It has been shown that solutions can be found which fulfill all hard constraints and additional target schedule restrictions.

Future work will compromise the definition of additional target schedule constraints. Furthermore, stochastic optimization will be integrated to find a robust and reliable adaption. Another important aspect is the availability of real-time data. Additional research work is required to improve the availability and accuracy of real-time data for construction management.

Acknowledgments

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