Cyclic Update of Project Scheduling by Using Telematics Data

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Abstract: Discrete-event simulation (DES) is not really used in construction industries that require more flexibility. However, use cases can be found where DES can support the construction industries. One use case is schedule optimization. This paper presents an agent-based DES method for optimizing schedules in the construction industry taking resource-dependent process-lengths into account. The approach is based on a theoretical level. Furthermore, there is a high potential when it is updated with actual equipment data. Therefore, we combine the project schedule optimization with a detailed model to update the equipment activities using a cyclic approach. This hybrid simulation approach is evaluated by taking a real use case of pile manufacture as an example. The results show the possibilities for the combination of different types of DES models in the context of the optimization of construction site performance.

Keywords: Discrete event modeling and simulation, Petri nets, Event-based control, Multi-agent systems, Modeling of manufacturing operations, Production planning and control, Job and activity scheduling, Project schedule optimization, MRCPSP.

1. INTRODUCTION

Considering the ongoing digitization of the construction site, data collection and its use is a central issue. Today, machinery already sends information via telematics (ISO 15143-3, 2016). Up to now, current equipment data is hardly ever or not been used at all to support the planning of construction progress. Its use, however, provides a high potential for quick reactions to delays in construction (Günthner and Borrmann, 2011, p. 68).

One possibility for the use of production data is the discrete-event simulation (DES) of construction processes. Therefore, this paper presents a hybrid simulation approach for updating project scheduling with real construction progress in a cyclic manner. This hybrid approach corresponds to two different simulation levels:

- **Macro-simulation** based on the project schedule optimization of Wenzler and Günthner (2016) for computing multi-mode resource-constrained project scheduling problems (MRCPSP);
- **Micro-simulation** based on a detailed process simulation for tracking equipment activities.

The project schedule optimization of the macro-simulation offers the possibility of calculating the effect of variable resource allocations on the process duration and the corresponding work chains as well as their consequences for the overall project. In contrast, the micro-simulation models the single process steps and represents, therefore, the subprocesses of the macro-simulation. Additionally, it uses the equipment’s activity data to calculate the current state of the construction progress.

The cyclical connection of macro- and micro-simulation aims to continuously adapt the scheduling based on the events that have just occurred. This kind of re-scheduling is in line with the research work in lean construction of Tommelein (1998), who says that a project schedule without “re-scheduling as work progresses leads to process inefficiencies and less-than-optimal project performance” (Tommelein, 1998, p. 3). The aim of this approach is to be able to make well-founded recommendations for the next steps to support decision-making and thus increase construction output.

This paper gives an overview of related work on either macro- and micro-simulation levels. Based on current research gaps, the authors present the conceptual model of the new hybrid simulation approach, its implementation, and its test. This approach refers to bored pile production.

2. RELATED WORK AND RESEARCH OBJECTIVE

Looking at the problem of scheduling in the construction industry from a theoretical point of view, processes are characterized by having a known start and end time and mutual dependencies and resources that the processes use (Artiges et al., 2013). The resources include the machinery, materials or areas used. The goal is to string the processes together in such a way that resource availability and priority relationships are maintained, e.g. to obtain the shortest possible execution time.

This optimization problem is also known in science as the “resource-constrained project scheduling problem” (RCPSP). RCPSP belongs to the NP-hard class of problems which cannot be solved exactly in a feasible time (Blazewicz et al., 1983).
Classical scheduling approaches like the deterministic critical path method (CPM) (Kelley, 1961), and its extension to the stochastic method with the often-used PERT technique (program evaluation and review technique) (Malcolm et al., 1959), do not consider resource requirements and thus capture only a fraction of the complexity of the problem.

In civil engineering, however, the consideration of cost-intensive resources is of great interest. For the solution of RCPSP, branch-and-bound methods (Johnson, 1967) or lower-bound methods (Heilmann and Schwindt, 1997) can be used. As indicated by the names of the procedures, the problem is divided into several sub-problems, so-called branches, and their solution is limited by defined bounds. Despite the bounds, these exact methods reach the limit of acceptable computing time for more complex problems. Furthermore, (Meta-)heuristic approaches exist, such as particle swarm optimization (Jarboui et al., 2008), the simulated annealing procedure (König and Beißert, 2009), genetic algorithms (Van Peteghem and Vanhoucke, 2010; Agarwal et al., 2011), the ant-colony-algorithm (Li H. and Zhang, 2013) or the Tabu search (Thomas and Salhi, 1998; Artigues et al., 2003) which are less time-consuming. In contrast to the exact solution methods, these approaches have the disadvantage that an optimal solution cannot be guaranteed. To weight and sequence the individual processes, the resource-dependent solution approaches are based on priority rules, such as the “greatest rank positional weight all” rule and the “minimum slack” rule. According to the “greatest rank positional weight all” rule, the process with the longest succession relationships is prioritized (Klein, 2000). The “minimum slack” rule gives priority to the process with the lowest buffer times (Kolisch, 1996).

Previous work already investigate to what extent resource-dependent scheduling can be simulated. Hönenburg et al. (2017) dynamically updates a DES model using synthetically generated equipment data to control the execution on the construction site. Ahn et al. (2015) provide a framework for automatic DES modeling based on equipment activity data for model’s updating and computing construction progress are missing.

Concluding the evaluation of previous work, it becomes clear that it is crucial to update simulation models to control and ultimately influence construction progress. However, the following weaknesses can be identified:

(1) Simulation approaches solving MRCPSP are not used in the execution phase as they do not include an automatic update of construction progress;
(2) Simulation approaches solving MRCPSP are not linked with detailed approaches for investigating detailed execution processes;
(3) Simulation approaches using equipment’s activity data for model’s updating and computing construction progress are missing.

Based on the research gap, this paper provides a new hybrid simulation approach. This approach aims to continuously update a project schedule optimization model with construction progress data, in which equipment activity data is integrated via a detailed simulation model (Günthner and Bornmann, 2011; Kühn, 2006); see Fig. 1.

3. RESEARCH METHODOLOGY

This paper follows the advice of Abdelmegid et al. (2020) of first focusing on the simulation study phase. Therefore, we describe the conceptual model in the context of a digital twin. This conceptual model considers the hybrid simulation approach as well as the technical adaption of the equipment on the construction site using a developed middleware. The hybrid simulation approach is then applied to a specific use case of pile production. In the following, this paper describes the implementation and the test phases of the macro- and micro-simulation models.
4. CONCEPTUAL MODEL

The conceptual model of the hybrid simulation approach requires a high-level architecture (HLA) (AbouRizk et al., 2011). The sequence diagram in Fig. 2 represents the communication between the five objects of the HLA: the proprietary manufacturer platform, the middleware, the micro-simulation, the macro-simulation, and the user.

As soon as a target schedule is available or the execution phase is reached, the schedule reads into the macro-simulation. Independently of the micro-simulation, the optimal schedule can be calculated according to Wenzler and Günthner (2016). However, the micro-simulation is needed as it includes the schedule’s sub-processes. These sub-processes reveal the individual process steps of a construction project defined by the equipment activities. Up to now, equipment’s activities are determined manually on the construction site. However, Fischer et al. (2021) also present an approach for detecting activity data automatically by using machine learning algorithms. In this case, a middleware transfers the equipment activity data from the manufacturer platform into the micro-simulation (Fischer et al., 2020). This methodology is according to the ISO 15143-3 (2016) where machinery sends data to the manufacturer platform. Once the micro-simulation receives data from the middleware, the current status of the construction progress is calculated. The results are fed back into the macro-simulation, and the sequence can start again.

As mentioned in this paper, we focus on the presentation of the hybrid simulation approach concerning the implementation of the cyclical connection of the macro- and the micro-simulation as shown in gray; see Fig. 2.

5. DATA ACQUISITION

A bridge project called “Westtangente Rosenheim” serves as a basis for the realization of the conceptual model. This project involves the production of large-diameter bored piles as bridge foundation. As this pile production is an iterative equipment-intensive process dominated by the rotary drilling rig, it is very well suited to the conceptual model presented. Besides, this project is well documented due to its special pile design (Cudmani et al., 2020).

In total, the project comprises more than 230 large bored piles assigned to 32 axes. Activity data from one rotary drilling rig are documented for 16 bored piles referring to five axes.

In particular, the piles are produced according to the Kelly drilling being the most commonly used method for the production of large-diameter bored piles. It consists mainly of the production steps of drilling, reinforcing, and concreting; see Fig. 3.

Fig. 3. Schematic representation of the Kelly pile production: (1) positioning, (2) drilling, (3) reinforcing, (4) concreting, (5) casing pulling (Bauer Group, n.d.)

The used data includes inter alia: the project schedule and telematics data of the used rotary drilling rig (sensor data plus activity data). The project schedule provides the sequence of the bored piles, their start and end times. The equipment sensor data are defined as time series (every second). Only the depth of the bored pile is considered. The equipment activity data of the used rotary drilling rig are timestamps, determined manually. They are selected based on predefined activities. These activities are single process steps to describe the whole pile production process using the Kelly drilling method.

6. IMPLEMENTATION AND EVALUATION

6.1 Macro-simulation

The macro-simulation is based on the work of Wenzler and Günthner (2016). They use a multi-agent approach for computing multi-mode resource-constrained project scheduling problems (MRCPSP). They enable the update of an existing project plan based on its current status. Thereby existing information is arranged under consideration of restrictions. In the following, the initial model, implemented into Siemens’ simulation software Tecnomatix Plant Simulation Version 15.1, is described.

Multi-agent system: In particular, the multi-agent approach includes two agents for processes and resources. This approach always selects one process from the allowed processes to determine when it will be executed next (Horenburg, 2014). The same applies to the resources. To determine the priority of the process, the macro-simulation has a selection of implemented priority rules. Wenzler and Günthner (2015) investigate different priority rules using the standardized project plans “project scheduling problem library – PSPLIB” from Kolisch and Sprecher (1997).
In this paper, the rule, called “Long Path Following”, is chosen as it turned out to be robust (Wenzler and Günthner, 2015). This rule checks all the possible successor agent paths within the bidding process in the exchange for the currently considered agent to determine the critical path. The prioritization is then based on the proximity of the agents to the critical path in descending order. Thus, the “most critical” agent, i.e., the one closest to the critical path, receives the highest priority. For the handling of the different modes per process, the process is enrolled with the average duration of its modes. The resource limitation is not taken into account. After computing the optimal schedule, the result is displayed as a Gantt chart; see Fig. 4.

Export of simulation results: The time progress, the start and end time, the mode of each process, and the number of sub-processes must be passed to the micro-simulation. These five attributes are assigned to each process after the calculation of the optimal schedule and transferred to the micro-simulation in the appropriate exchange format. This is done by exchanging standardized data files (tables).

It is necessary to extend the existing macro-simulation with common functions from practical experience. Thus, two additional features have been implemented as follows.

Set start time: For real use cases, a few processes can be used with a limitation on the start time. This function ensures the requirement for the start time so that the simulated project schedule is adapted; see Fig. 4 a). The single specific start time can be entered directly in the exchange format.

Link between processes: In addition to the implemented end-to-start relationship (see Fig. 4 b)), the project schedule can also have a start-start, start-end and end-end link between two processes. Thus, these three are added to the model in combination to have the ability to add real use cases; see Fig. 4 c)–d).

6.2 Micro-simulation

The micro-simulation allows the acquisition of equipment activity data and the associated recording of the actual state to pass this on to the macro-simulation; see Fig. 2. The model is implemented into Siemens’ simulation software Tecnomatix Plant Simulation Version 15.1 and is as follows.

Data import and preparation: Three data sets run the micro-simulation: the equipment’s activities, the drilling depth, and the optimized project schedule from the macro-simulation. The equipment activity data set lists the type of activity plus timestamp to calculate its duration. The drilling depth per second allows the micro-simulation to visualize and calculate the ongoing drilling depth. The macro-simulation input transfers the planned construction schedule with the preliminary and subsequent processes, their sequence, their start, and end times.

Process flow: The mapping of the process is modeled by a standardized process module, which covers the previously defined activities from the rotary drilling rig. A token is used to check and visualize which process state

![Fig. 4. Exemplary project schedules showing the implemented features](image)

The equipment is currently in every second. As the tool depth is recorded via the sensor data, the current drilling depth level is displayed. Once the bored pile is finished according to the activity data, the micro-simulation calculates the construction progress based on the current simulation time, the number of sub-processes related to each process.

Export of simulation results: The result is provided to the macro-simulation via the defined exchange table. Therefore, the timely progress, the end time, and the remaining time are written into the exchange file.

6.3 Evaluation

The evaluation of the implemented conceptual model is limited to the five axes due to the poor data basis. The project schedule is shown in Fig. 5 a). The red line shows a snapshot from a selected time point during construction; see Fig. 5 b). In contrast to the planned project schedule, the as-built production of the bored piles from Axis A took longer (dotted line). Based on the calculated construction progress of the micro-simulation, the macro-simulation shows the optimized project schedule. The results show that the bored pile duration is shorter as-planned, so that the process length of Axis C is, in total, shorter. Fig. 5 c) shows the next update cycle, where the time of the second bored pile of Axis C takes longer than the first, so that the updated schedule is, in turn, adapted.

7. CONCLUSIONS AND OUTLOOK

This paper presents a cyclic combination of an existing multi-agent approach based on MRCPS (macro-simulation) together with a detailed process simulation (micro-simulation). The micro-simulation includes equipment telematics data to consider construction progress. By integrating activity data, the micro-simulation can track the process steps on the construction site and pass on the actual duration of the process to the macro-simulation. The macro-simulation has been extended to import this data and generate a new optimized schedule based on it. Furthermore, an export function is implemented to transfer the updated schedule data back to the micro-simulation.
Fig. 5. Selected section of the project schedule before and after updating with the current actual state (red line)

For the evaluation of this cyclical approach with a real use case, options are added to fully map restrictive connections between individual processes. With this new exchange between two approved simulation methods, it is now possible to profit from both: the optimization of schedule tasks and the control option of the current execution. Furthermore, the initial model is supplemented by the properties of real construction schedules. This feasibility study thus lays the foundation for further research to develop an integrated and automated feedback control system for construction progress.

This work is still based on the static integration of the activity data. Current efforts of the authors are running in connection with a newly developed middleware to be able to retrieve the equipment’s data directly from the proprietary manufacturer platforms and to re-import them into the simulation via a socket interface and specially defined TCP/IP protocols (Fischer et al., 2020). Before integrating into the simulation, the data needs to be analyzed, e.g., by using machine learning algorithms to detect equipment activities (Fischer et al., 2021).

The current micro-simulation model also lacks an option to compare the planned resources with the resources ultimately used. A high-performance solution for data exchange between macro- and micro-simulation is also of interest, e.g. via database. A further combination of the micro-simulation with the illustration of the equipment movement or the process on the construction site is pursued. In the future, combining this approach with the object-oriented approach of the Building Information Modeling (BIM) looks highly promising.

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