Importance of secondary processes in heavy equipment resource scheduling using hybrid simulation

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Abstract -

As part of the Architecture, Engineering, and Construction (AEC) industry, heavy civil engineering with its equipment-intensive processes is a current focus of discussion concerning emission reduction. Adopting Industry 4.0 technologies for resource scheduling can significantly increase the savings potential significantly. One of these digital technologies is the Discrete Event Simulation (DES). DES is a proven tool to analyze complex systems in advance but is not widely used in practice. Therefore, the presented work aims at presenting a three-part hybrid simulation framework. One part of the framework, the meso-simulation, has been evaluated using a case study in the field of pile drilling production. The work not only captures the drilling process, and therefore shows the importance of planning the secondary processes in AEC.

Keywords -

Discrete Event Simulation (DES); Agent Based Modelling (ABM); Hybrid simulation; Modeling of manufacturing operations; Production planning and control; Job and activity scheduling; Project schedule optimization

1 Introduction

Given the current climate change, the resource-saving scheduling of equipment has become the focus of optimization methods [1]. In particular, potential is shown by equipment-intensive applications in heavy civil engineering, such as pile drilling production. Large-diameter bored piles for the foundation of buildings are produced by heavy rotary drilling rigs. These processes are of high complexity, characterized by a multitude of influencing factors and are, therefore, treated as a "one-piece flow line on a single machine" [2]. Fischer et al. [2] emphasize that digital technologies can help optimize the scheduling and operation of equipment, which is now heavily based on the experience of the specialty foundation contractors.

Digital technologies in the context of "Construction 4.0" of the European Construction Industry Federation (FIEC) [3], the counterpart of "Industry 4.0" in the Architecture, Engineering and Construction (AEC) industry, can be categorized into three groups: The technologies that (1) collect the data, (2) analyze the data, and (3) predict the data. The data collection is done by sensors, divided into vision-, motion-, and audio-based sensors [4]. The data analysis uses different algorithms of Artificial Intelligence [4]. The data prediction is possible with the help of simulation. In addition to the definition of Jazzar et al. [5], simulation can be defined as an additional Construction 4.0 technology. Simulation enables production processes and material flows on the construction site to be mapped in an abstract manner. In this way, it helps to reduce complexity in advance and makes it visible to the planner so that concrete recommendations/instructions for action can be derived from it [6]. Different scenarios help to plan the optimal use of equipment. The simulation is fed with input parameters from planning and production, e.g., from as-planned or as-built data from Building Information Modeling (BIM) [7] or directly from the data obtained on the construction site, processed as a probability density distribution [8]. The trend is toward an integrated approach of Construction 4.0 technologies for continuous operable functionality across construction phases [5].

Therfore, this paper presents a three-part hybrid simulation framework that allows the integration of input data depending on the level of detail of the current construction progress. We begin with a review of the literature in order to analyze different simulation techniques. Next, the underlying three-part conceptual model is presented. Using case-study data from a real pile drilling project, we describe the implementation of one of the three simulation model parts, which is the meso-simulation. Building up material supply and disposal, we show the importance of the secondary processes within an alleged one-line production flow of the rotary drilling rig. The results of the simulation study help to schedule the optimal amount and type of equipment.

2 Related Work

In addition to common simulation methodology, hybrid simulation or multi-method modelling is a combination of two or more basic simulation methods, such as System Dynamics (SD), Discrete Event Simulation (DES), and Agent-Based Modeling (ABM) [9]. The three simulation methods can be briefly defined as follows: SD is mathematically based on differential equations and uses interacting feedback loops to describe system behavior; ABM consists of agents that represent entities in a complex system and behave individually; DES consists of events whose state changes only at a given time [9].

In combining the three simulation methods, the following different levels of abstraction can be served: High abstraction (strategic level), medium abstraction (tactical level), and low abstraction (operational level) [9]. Using hybrid simulation, a simulation study considers the system under study at different levels and perspectives, leading to a comprehensive understanding of the system [10].

For all of the three models, examples of applications in the field of AEC industry exist. The presented work only concentrates on process logistics mainly represented by discrete variables as used in Tommelein [11], conscious of ignoring continuous site effects [12]. For example, Alzraiee et al. [13] and Scales [14] present a framework combining ABM for scheduling resources of active events and DES for modelling the event's relationships. However, the presented research focuses on the time discontinuous simulation methods of ABM and DES like the following related research.

Zankoul et al. [15] modeled an earthwork operation according to ABM and DES. The comparison of the results show similarities but also the pros and cons for future studies that combine both simulation techniques.

Marzouk and Ali [16] analyzed the pile production with the help of ABM. The rotary drilling rig, the crane, and the pile were defined as agents. A* search algorithm was implemented to find the optimal pile drilling duration. They also considered uncertainties by using probabilistic functions. However, in using only ABM, the simulation model itself showed a very high abstraction level of modelling the pile drilling production and its varieties. The framework was not intended to use external input data to update the model while in execution.

Matejević et al. [17] has combined ABM and DES to evaluate the productivity of concreting including the concrete plant and the concrete trucks delivering the pump on-site. The hybrid model was realized by using the commercial simulation software AnyLogic, which provides block diagrams representing the material flow in DES but also agent state diagrams representing the logical rules of the material flow. The model was applied for the design phase, not considering input data.

3 Research Objective

The research objective is to develop a digital tool for heavy equipment resource scheduling. Based on the literature review, a hybrid simulation approach seems suitable, combining the advantages of the level of detail of ABM and DES. In particular, the modeling of secondary processes is of interest, as these are often not the focus in practice. Furthermore, according to AbouRizk [6], the framework is modular for ease of use to update the model with different external data sources.

The presented work is based on the preliminary works of Wimmer [18], Wenzler and Günthner [19], Fischer et al. [20], and Fischer et al. [21]. These works describe a macro-simulation for scheduling (ABM), a micro-simulation for tracking equipment's telematics data (DES), and a framework to integrate this data via a developed middleware. This hybrid simulation model is perfect for updating the models during execution. However, it is not able to vary uncertainties and construction-specific variables in advance. By adding an additional level of abstraction, named meso-simulation, the new three-part hybrid simulation model allows the calculation of different modes, including different resources and durations. These modes then serve as input to the macro-simulation for computing multi-mode resource-constrained project scheduling problems (MRCPSP) [19].

4 Conceptual Model

Although characterized by its uniqueness, a construction project includes similarities or repetitive processes for simulation [22, 23]. Modularizing them helps to reduce the simulation effort [6]. To finally adopt the simulation in the AEC industry, [24] and Abdelmegid et al. [25] emphasize the role of conceptual models for reproducing the simulated system independently of the software used.

4.1 Overview

The conceptual model of the hybrid simulation model is as follows, see Figure 1: (1) During the planning phase, the user initializes the meso-simulation model, creates different alternative scenarios, e.g., by varying the number of equipment used, and computes each total duration. (2) Dynamically shared via mySQL databse, the resource constraints of each scenario serve as the basis for the macro-simulation computing the optimum schedule. (3) During execution, the optimum schedule is transferred to the micro-simulation using table formats. (4) According to the ISO 15143-3 [26], current available telematics data is requested by the middleware which passes the data to the micro-simulation via TCP/IP protocols. (5) Based on this data, the micro-simulation calculates the construction progress. (6) The current state is then passed to the macro-simulation which calculates the optimal resource scheduling and its total duration. (7) Based on the optimized schedule, the user has the opportunity to compute different modes via the meso-simulation which serve as the basis for decision-making in the execution.

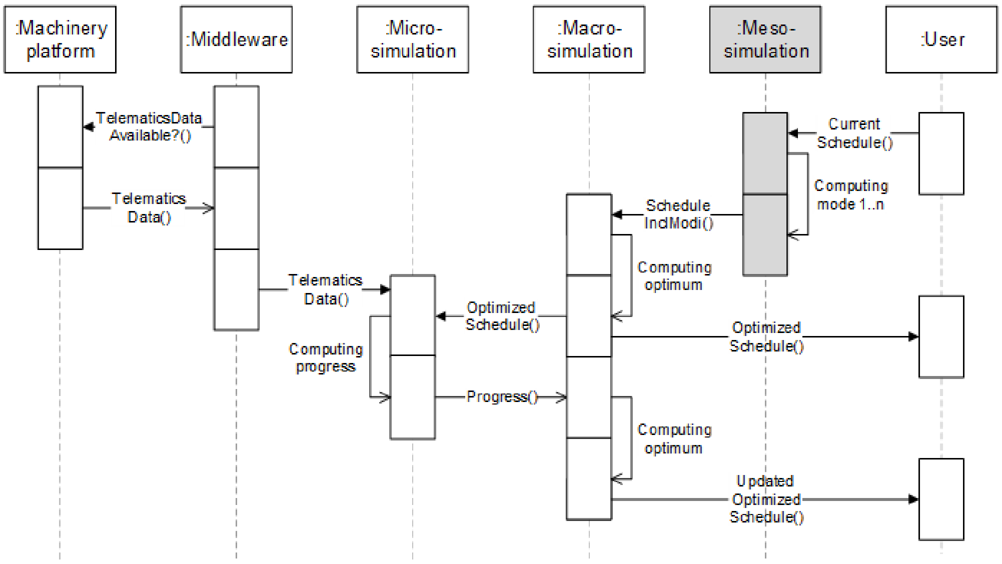

Figure 1. Conceptual model based on Fischer et al. [20] including the new third part, named meso-simulation, of the hybrid simulation approach (gray)

In the following, only the meso-simulation model is described in detail. The essential basis of the meso-model was developed and implemented in previous research projects [27, 28]. However, to the authors best knowledge, there exists no publications on this model exist. This model is the basis for further work which is presented in the following and is described in more detailed in [29] (a co-author of this paper).

4.2 Modularization

According to Wimmer [18], the meso-simulation has a modular structure based on the following main elements, see Figure 2: (1) A standard window including elements for initialization; (2) elements representing characteristic process steps of use cases, such as earthworks or pile drilling; (3) a visualization of the construction site layout.

According to the different characteristics of construction projects, a new model can be quickly established, thereby saving the development duration. Elements in the standard window are aimed to process the data and are explained in the following.

Settings include two components. One component stores the standard data specific for the current project in a list, e.g., the position, length, and number of associated piles. The other component stores the data from each of the specific project entities in a list, e.g., information about each bored pile.

The element *Integration* connects the input data and the simulation. Therefore, one component aims at calculating the detailed data of each entity (such as the bored pile) based on the standard data. Furthermore, an import and an export component exist to either import the data from the database to the model, or to write the simulation results into the database.

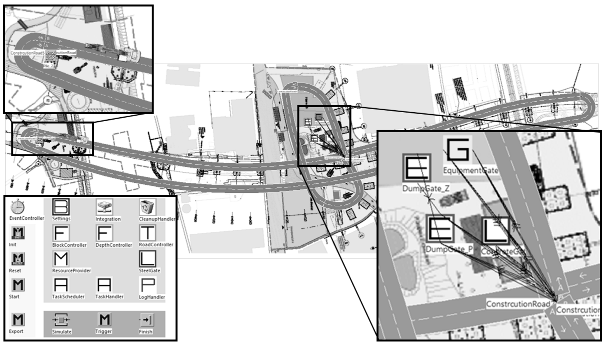

Figure 2. Meso-simulation model including the standard window, construction-site specific elements, and the construction site layout

The element *RoadController* helps to assign the route of the movement elements. First, the position with the shortest distance between the bored pile and the roads is determined, and then a sensor is placed next to it. For example, when a vehicle whose target is the current bored pile reaches this sensor, the current vehicle moves into the network of the bored pile. This is also true when the vehicle leaves the bored pile, i.e., the vehicle moves from the network to the sensor location.

ResourceProvider is an element that lists the resources needed for the current operation and marks the resources for the next operation.

The *TaskScheduler* helps the model start the single operation. If construction processes have the same predecessor, the process with the lower ID is preferred. When this task is completed, the corresponding element is deleted from the construction layout or *TaskHandler*. All tasks are sorted again from the previous work and stored in the *Tasks* table. It is possible to access all data at any time during the simulation to see the completed processes, the working process and the processes that have not started yet. The current model is limited, as two construction processes can not be executed in parallel.

4.3 Simulation Logic

The simulation logic is shown in Figure 3. The construction project in the simulation model is hierarchically ordered according to the bill of quantities. Tasks are all listed after data processing in a list in the *TaskScheduler*, where their status of them can be checked at any time during execution. The duration of each subprocess is determined by the selected probability distribution: normal distribution, lognormal distribution, gamma distribution, or Weibull distribution. To ensure that the results of the simulation are close to reality, the input data should come from experience. However, the execution follows the bottom-up principle, i.e., the element of a subprocess is created on the layout sheet first. When all subprocesses of a process are completed, a message is issued to create the corresponding module of the current process. It is then deleted before the execution of the next subprocess. When all processes are completed, the simulation program calls the element of the project. But the elements concerning the processes and the project do not consume any time consuming within the simulation, so the authenticity of the simulation time is guaranteed.

5 Case Study

A case study was used to implement and evaluate of the presented meso-simulation. The simulation model was realized with the help of Siemens' commercial simulation software Tecnomatix Plant Simulation version 15.1 [30].

5.1 Construction Layout

Data from the real bridge project "Westtangente Rosenheim" (WTRO) in Germany was used to validate the hybrid-simulation. This project was also used in a previous work of the authors [20]. From south to north, the project consists of 32 bridge piers including between 5 and 17 large diameter-bored piles of the same type, ranging from 26 m to 50 m in length. Only the production of the bored piles is focused on this paper. Due to the lack of data, 29 piers with 232 bored piles were simulated within the meso-simulation. The project layout is implemented in the simulation model, see Figure 2.

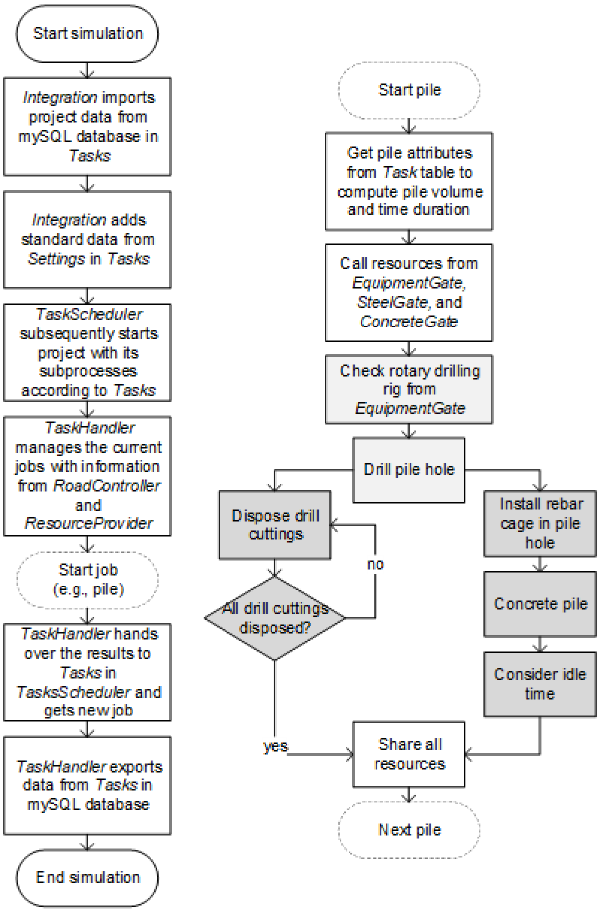

Figure 3. Simulation logic

A two two-lane track represents the transportation path from the construction storage location to the pile drilling location. Mobile units of transporter and entities of moving units represent the equipment and the material resources. Piles are modeled by a standardized network element, including the single process steps of the pile drilling.

5.2 Material Flow

The descending sequence is as follows: (1) project; (2) pile conglomerate (bridge pier); (3) single pile. Figure 3 shows the implemented logic for producing a single pile. When the production of bored piles begins, the rotary drilling rig, excavator, and concrete truck are transported to the location of the related bridge pier through two-lane roads. They park in the warehouse, waiting to be called to work. Once the related process is finished, they leave the location of the bridge pier back to the construction storage location, ready for the next process.

Table 1. Overview of the parameter setting

No.	Equipment type	Parameter	Values
(1)	Rotary drilling rig	Drilling time	50 %, 100 %
(2)	Hydraulic excavator on tracks	Capacity (m^3)	0.3 , 0.56 , 0.87 , 2.5
		Costs (€ TSD)	85.8, 13.25, 182.5, 457
		Number (-)	1 – 4
(3)	Hydraulic excavator on wheels	Capacity (m^2)	0.3, 0.55, 0.65, 0.99, 1.7, 2.5
		Costs (€ TSD)	89.4, 132.5, 178.5, 223, 335.5, 447
		Number	1 – 4
(4)	Wheel loader	Capacity (m^2)	0.7, 1, 1.25, 1.5, 1.9, 2.1, 2.2
		Costs (€ TSD)	61.4, 78.7, 100.5, 140, 145.5, 178, 211.5
		Number	1 – 4

5.3 Parameter Setting

The parameter setting refers to the different modes as input for the macro-simulation. These modes include information about the equipment used, the duration for every single process, and the relationship between the processes. Table 1 presents a summary of the parameters varied in this work and distinguished between four different equipment types. The information about capacity and cost price of different equipment types are based on the BGL [31]. Concrete delivery is excluded.

5.4 Results

(1) The duration of drilling depends on the type of equipment. Thus, two different types of rotary drilling rigs were simulated by reducing the drilling time of one type up to 50 % to analyze and detect the impact on the final project duration. The results show that by reducing the drilling time, the calculated total duration is reduced from 168 days to 131 days (– 28 %). It is clear that the use of a more efficient rotary drilling rig is more conducive to reducing production time.

(2) The analysis depending on different earth-moving equipment is shown in Figure 4. The reduced amount of each experiment is associated with the demand and capacity of the equipment. For this purpose, the demand or type is varied for the individual bored pile; thus, the duration for one bored pile needs to be checked. The single price for each type is also presented in the diagrams.

As can be seen from the three experiments, there is no duration data when the capacity is too small. This is because the smaller volume increases the delivery time and creates conflict with the main process. Therefore, it is not possible to get the corresponding time data for small volumes. In terms of amount, the time is significantly reduced when the demand is two as opposed to just one. The effect on the event is weakened by continuing to increase the demand amount. At the same time there is a clear trend that within the same equipment, the larger the capacity is the more expensive the equipment will be. Therefore, simply choosing equipment with the largest capacity is not the most economical solution.

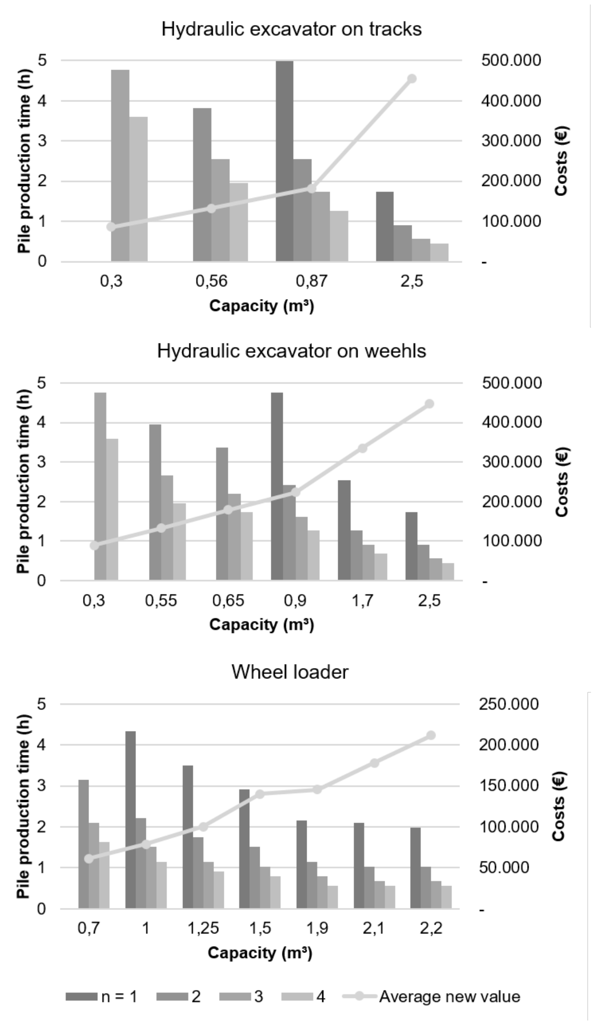

Figure 4. Pile production time depending on the number, capacity, and costs of different earth-moving equipment

6 Discussion

Through the meso-simulation, the project planning data can be generated with empirical values and further transferred to the macro-simulation. The resource requirements and the capacity can be defined within limits according to the requirements. Due to the validated probability distributions, a relatively stable construction time can be obtained. However, the application of this model is limited. Because the build time is hardly affected by a change in resources, only one mode of each process can be simulated during execution with respect to a set of empirical values. If there is a need to change the mode, the corresponding experience values in the data store must be changed. In addition, parallel construction is not possible. For the bridge construction project WTRO, the construction works of each bridge foundation are independent of each other. Therefore, it helps to improve efficiency if independent processes can be carried out in parallel.

7 Conclusion and outlook

The presented study shows the extension of an existing hybrid simulation model. This extension, called meso-simulation, is able to capture the required input data for optimizing a resource-constraint schedule. The presented conceptual model has been evaluated with the help of a real use case related to pile production. This model was further able to capture the material flow on-site in advance. The variation of different equipment types depending on number, capacity, and single price, allows the calculation of process duration for different modes. Future work will extend the hybrid model to analyze the resource sequencing.

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