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Bridge construction schedule generation with pattern-based construction methods and constraint-based simulation

I-Chen Wu [a,*], André Borrmann [b], Ulrike Beißert [c], Markus König [d], Ernst Rank [b]

[a] Department of Civil Engineering, National Kaohsiung University of Applied Sciences, Kaohsiung, Taiwan
[b] Chair of Computation in Engineering, Technische Universität München, Munich, Germany
[c] Chair of Construction Engineering and Management, Bauhaus-University, Weimar, Germany
[d] Institute for Computational Engineering, Ruhr University Bochum, Bochum, Germany

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ABSTRACT

This paper presents a novel methodology which assists in automating the generation of time schedules for bridge construction projects. The method is based on a simulation of construction works, taking into account the available resources and the interdependencies between individual tasks. The simulation is realized by means of a discrete-event simulation software originally created for plant layout in the manufacturing industry. Due to the fact that the fixed process chains provided are too rigid to model the spontaneous construction task sequences, a constraint module that dynamically selects the following task has been incorporated.

Constraint module input data is formed by activity packages comprising of the affected building element, the required material, machine and manpower resources, as well as the technological pre-requisites of the activity to be performed. Since manual creation of the large set of activity packages is laborious and error-prone, a 3D model-based application has been developed which allows the interactive assignment of construction methods to individual building elements. To facilitate this process, a level-of-detail approach has been implemented which allows the user to successively refine both the process model and the corresponding product model.

The discrete-event simulation system uses all the given information to create a proposal for the construction schedule automatically, which may then be refined using standard scheduling software.

1. Introduction

Scheduling a construction project means to coordinate resources of workers, machines and materials in a time-efficient way in order to realize a construction project within the projected time and costs.

Traditionally, construction schedules are manually specified using Gantt chart techniques and the critical path method (CPM). A number of commercial management software solutions in the industry use these two concepts. However, the software is unable to assess schedule correctness, especially of process duration for a given amount of available resources, as well as its inability to optimize the schedule according to total costs or total duration work against the application of these methods within more complex scheduling tasks.

The simulation of construction processes has proven to be a suitable approach for detailed investigation of construction schedules [1]. In this case, individual activities, their dependencies and the availability of resources are taken into account. However, preparing the input data for such a simulation is a time-consuming and error-prone process. This paper introduces a new methodology which is based on interactively refining both the building model and its corresponding process model. It guides the scheduler and dramatically facilitates the generation of input data for the process simulator. The result of the interactive process is a large set of '*activity packages*' which combine atomic activities with the required resources, such as labor, material, and equipment, as well as establish links to the preceding activities.

These process components cover all information required to run the simulation. In the presented approach, the constraint-based simulation is employed, which exhibits the necessary flexibility to model construction processes with greater realism.

2. Related work

Since the 1960s, it has been recognized that discrete-event simulation (DES) provides a powerful tool to model and evaluate construction processes, including the overall project duration as

* Corresponding author. Tel.: +886 7 381 4526; fax: +886 7 383 1371.
E-mail addresses: kwu@cc.kuas.edu.tw (I.-C. Wu), borrmann@bv.tum.de (A. Borrmann), ulrike.beissert@uni-weimar.de (U. Beißert), koenig@inf.bi.ruhr-uni-bochum.de (M. König), rank@bv.tum.de (E. Rank).

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well as the utilization of resources. The link node model developed by Teicholz [2] is the earliest known method for construction simulation. Subsequently, researchers employed general purpose DES programs such as GPSS [3,4] to simulate construction processes.

To give the user the possibility of focusing on construction-specific processes, the domain-specific simulation programs CYCLONE [5] and ICONS [6] have been developed. Their successors INSIGHT [7], MicroCYCLONE [8], DISCO [9], STROBOSCOPE [10] and SIMPHONY [11] further facilitated the preparation of the simulation engine's input data and the interpretation of its output.

Discrete-event simulation helps in analyzing defined workflows (usually represented by directed graphs) and to identify possible bottlenecks by providing the means to study resource utilization. By adapting the amount of resources employed, the user is able to carry out what-if analyses [12]. However, finding the optimal amount of resources requires a vast amount of simulation runs [13]. Researchers have therefore proposed the integration of DES with heuristics [14] and sophisticated optimization techniques such as Tabu search [13], genetic algorithms [12,15], simulated annealing [16], and Particle Swarm Optimization [17,18].

However, most of these approaches do not consider the optimization of the topology of the activity graph. This refers to the question of determining which activity to start first if a specific resource is required by several activities, where its availability is limited in amount or capacity. It is well known that for more complex construction processes, this "resource flow" [17] is the main source for optimizing the overall construction process.

Using the constrained-based simulation approach introduced by Beißert et al. [19,20], valid execution schedules considering the resource availability can be generated automatically using DES. Contrary to CPM and other simulation frameworks, like CYCLONE or SIMPHONY, this approach does not require an explicit process chain (i.e. activity graph) to be modeled. Instead, conditions for executing an activity, such as technological preconditions and the availability of certain resources, are modeled locally as constraints on the respective activity. Consequently, the constraint-based approach guarantees a high flexibility of modeling construction processes, if additions or new pre-requisites in processing occur. The model can be easily adapted by simply adding or removing certain constraints. During runtime, the DES system checks for activities where all constraints have been fulfilled. It randomly selects from these activities the next activity to be executed as long as sufficient resources are available. On the one hand, this approach dramatically increases the solution space, since it accounts for all variations of the activity sequence. On the other hand, it facilitates schedule calculation, because the creation of a global model of the entire construction process is not required. Furthermore the scheduling decisions become more transparent to other involved persons of the project.

Depending on the problem definition, the solution space may be extremely large. To find a good solution, a Monte-Carlo analysis may be applied, generating a significant set of solutions which can be later analyzed against project objectives. The constraint-based simulation approach can be coupled with Greedy randomized adaptive search procedures [21] or simulated annealing [22] to reduce the number of simulation runs, thereby speeding up the search for global optima.

The methodology presented in this paper makes use of the constraint-based simulation approach while focusing on the preparation of the input data. For most simulation systems, the task of generating input data remains tedious, time-consuming and error-prone. This has been identified by many researchers as the main cause of the slow adaptation of simulation technology in the construction industry. This is especially true for small scale projects where low budgets prevent long and laborious preparation phases.

As a possible solution, the integration of DES with 3D product models has been proposed. For example, the simulation system for heavy earthmoving operations presented in AbouRizk and Mather [23] has been integrated with a 3D CAD model. In this case, simulation models are automatically generated from the CAD model. A similar approach is followed by Chahrour and Franz [24]. Wang et al. [25] developed a 4D management system for construction planning and resource utilization, where a 3D geometrical model is linked with resources to compute the resource requirements. However, all of these approaches rely on the utilization of predefined CAD components whose definition includes a description of the construction processes required to build them.

The methodology proposed in this paper aims at enabling the scheduler to use any kind of 3D model (i.e. product model) and interactively build the necessary input data for a constraint-based simulation by assigning construction patterns to individual components. Using this methodology provides further flexibility to the schedulers. The construction patterns encapsulate basic knowledge of a construction method, such as the composing activities and their precedent relationships. Following the concepts of construction method modeling [26], the proposed methodology makes use of a hierarchical approach which allows the scheduler to subsequently refine both the product model and the assigned construction patterns.

The proposed methodology is illustrated using a bridge erection example. Currently, only a small number of researchers have applied simulation technology on bridge construction processes. In Huang et al. [9] the erection of cable-stayed bridges is simulated using DISCO, a graphical user interface for the MicroCYCLONE simulation engine. In Hong and Hastak [27], the application of fiber-reinforced composites for the rehabilitation of bridge decks is compared against precast concrete using CYCLONE methodology. In Zhang et al. [28], the advantage of cell-based representation and analysis of spatial resources is discussed using the example of re-decking works at a bridge in Montreal. Said et al. [29] compared the construction of bridge decks with balanced cantilevers cast in situ against one using precast cantilevers using the STROBOSCOPE simulation engine.

Besides discrete-event simulation, there are also other technologies used for generating schedules. This includes agents-based approaches [30,31], for example. Other researchers are tackling the complexity of coordinating schedules among a multitude of concurrent projects [32]. However, this is out of scope of the work presented here.

3. Constraint-based simulation

3.1. General approach

The traditional process simulation approach, where rigid sequences of activities are defined (i.e. the preceding and succeeding activities are specified in advance), is only suitable for processes which are mainly driven by machines, such as earthwork processes. However, most construction processes have dynamic and spontaneous sequences of activities.

The constraint-based simulation approach has been developed to overcome the limitations of fixed activity graphs and to realize greater flexibility [19]. In this case, the scheduling problem is described as a constraint satisfaction problem [33], i.e. for each construction activity, all requirements for its execution are captured as constraints. This includes the requisite preceding activities, equipment, manpower, materials and space [19,20]. The solutions to the constraint satisfaction problems become valid execution orders for construction activities when all the associated constraints are fulfilled.

The analytical solution of complex constraint satisfaction problems is extremely time-consuming. In contrast, simulation