A Pattern-Based Approach for Facilitating Schedule Generation and Cost Analysis in Bridge Construction Projects

I.C. Wu, A. Borrmann & E. Rank
Computation in Engineering, Technische Universität München, Munich, Germany

U. Beißert
Construction Engineering and Management, Bauhaus-University, Weimar, Germany

M. König
Theoretical Methods of Project Management, Bauhaus-University Weimar, Germany

ABSTRACT: The paper presents a computational method to help in automating the generation of time schedules for bridge construction projects. The method is based on the simulation of the construction works, taking into account the available resources and the interdependencies between the individual tasks. The simulation is realized by means of the discrete-event based simulation software originally created for plant layout in the manufacturing industry. Since the fixed process chains provided there are too rigid to model the more spontaneous task sequences of construction projects, a constraint module that selects the next task dynamically has been incorporated. The input data of the constraint module is formed by work packages of atomic activities. The description of a work package comprises the building element affected, the required material, machine and manpower resources, as well as the technological pre-requisites of the task to be performed. These input data are created with the help of a 3D model-based application that enables to assign process patterns to individual building elements. A process pattern consists of a sequence of work packages for realizing standard bridge parts, thus describing a construction method which in turn represents a higher level of abstraction in the scheduling process. In the last step, the user specifies the available resources. The system uses all the given information to automatically create a proposal for the construction schedule, which may then be refined using standard scheduling software.

1 INTRODUCTION

1.1 *Overview and related work*

The creation of construction schedules today is a tedious and time-consuming manual process. It basically relies on the knowledge and expertise of the scheduler and is hardly subject to optimization efforts. Slight modifications in the schedule might serve to reduce the amount of resources needed, which in turn lowers the costs or project execution time. A great deal of research has accordingly been invested in solving the problems of construction scheduling already.

In construction projects, scheduling is almost exclusively based on experience, so some researches attempt to capture human knowledge to solve the scheduling problem. Such systems represent the expertise in the form of a set of data and rules stored on the computer. For example, Mikulakova et al. (2008) employ case-based reasoning techniques to use scheduling experience from previous projects. Their execution sequence is presented to the project manager as a possible solution and can be adapted to new conditions. Mohamed et al. (2002) present an integrated knowledge-based system for estimating and scheduling construction costs. Other researchers focus on applying graph techniques to analyze the tasks involved in completing a given project, especially the time needed to complete each task, and identifying the minimum time needed to complete the entire project. For example, the critical path method is the most common technique employed today for drawing up robust schedules. Koo et al. (2007) present a formal identification and re-sequencing process using the Critical Path Method (CPM) which supports the rapid development of sequencing alternatives in construction schedules. Pontrandolfo (2000) emphasizes the complexity of construction projects and the uncertainty that surrounds any estimation of the length of a certain activity, resulting in a higher criticality of project scheduling. Addressing this problem, he uses PERT-state and PERT-path techniques, focusing on network complexity and time uncertainty. Biruk et al. (2008) present a new methodology for project scheduling with repetitive processes using a Petri-nets based approach.

Other researchers apply multi-constraint optimization algorithms to get an almost optimum solution with respect to resource consumption and project duration. In (Beißert et al., 2007) a constraint-based simulation approach is presented to generate valid execution schedules considering different construction requirements and execution restrictions. Based on a constraint-based simulation concept the metaheuristic Greedy Randomized Adaptive Search Procedures (GRASP) can be applied to generate valid and optimized solutions rapidly (Beißert et al., 2008). Zhang et al. (2006) introduce a methodology for solving the multimode resource-constrained project scheduling problem based on particle swarm optimization (PSO). Senouci et al. (2008) present a genetic algorithm-based multi-objective optimization model for the scheduling of linear construction projects.

Whenever knowledge-based systems are applied to generate a construction schedule, only partial schedules are provided. Extra effort is required to adapt these schedules for practical use. On the other hand, whenever Monte Carlo simulation techniques are used to generate construction schedules, a multitude of simulation runs has to be performed in order to get a significant set of solutions that can be evaluated afterwards. The generation of an optimal solution is not guaranteed using Monte Carlo simulation. Apart from these drawbacks, the preparation of input data is also tedious and time-consuming (König et al., 2007).

1.2 *Applied Methodology*

This paper presents a pattern-based scheduling approach. Based on pattern-based models valid schedules can be generated using the constraint-based simulation approach (Beißert et al., 2007) while taking different kinds and quantities of resources into account. Afterwards, the generated schedules can be analyzed in terms of costs and the utilization of resources using standard project planning tools (Figure 1).

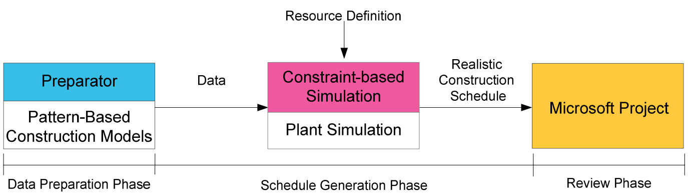


Figure1. The basic concept presented in this paper

Our research work initially focuses on bridge construction processes, which display two important characteristics: (1) Normally, a standardized construction method is applied in order to complete the bridge construction project economically and efficiently; examples being the *formwork carriage method* and the *incremental launching method*. (2) Bridge structures consist of a number of similar and identical features, such as the piers or segments of the bridge's superstructure. Accordingly, the construction firm executes the same processes repetitively to construct these segments and parts of the bridge.

With our approach, patterns are used to encapsulate the repetitive construction processes. The patterns specify certain construction methods coupled with the relevant process steps and the resources required to execute these processes. In addition, these patterns incorporate performance factors which relate the amount of work and the available resources to the time required for its completion. Thus, these patterns provide a general specification for the construction methods and accordingly represent a knowledge base within this approach. The patterns can be reused in various bridge construction projects. Due to the fact that the performance factors are applied to the specific elements from the building product model, these patterns guarantee a high flexibility in modeling processes.

The input data required for the constraint-based simulation is derived from the product model and the patterns. Thereby, the product model delivers elements to be constructed, their dimensions and positions as well as the appropriate construction method for realizing these tasks. The resource requirements and performance factors are derived from the pattern.

Before starting the simulation, it is necessary to specify the available resources. This includes the labour force including their individual qualifications, the machinery and auxiliary construction equipment that is available. The simulation application subsequently generates a realistic schedule for the execution of the project which takes not only the construction method requirements but also the project-specific conditions into account.

2 PATTERN-BASED CONSTRUCTION MODELS

This section defines and describes the proposed pattern-based construction models. These models employ a hierarchical system to acquire specific knowledge relating to the construction method procedures, their sequence and the resource requirements. A hierarchical computational representation of construction method models was originally proposed by Fischer et al. (1996). Figure 2 shows the hierarchical work breakdown structure of a bridge construction, where the planner generates a high-level activity, such as “Construct Bridge” and selects and applies a certain construction method. Thus the bridge is divided into a set of lower-level activities such as “Construct Abutment”, “Construct Pier” and “Construct Superstructure”. Once again, the planner selects and applies certain construction methods for each of these activities: for example, in order to carry out the "Construct Pier" activity, the planner may apply the "Reinforced Concrete" construction method to elaborate it further into the activities on level 3. On completion of the "Construct Basement" activity, the planner then applies the "Cast-in-Site" construction method to proceed to the level 4 activities.

After specifying all the activities that are needed to execute the bridge construction, these activities have to be linked to the corresponding building components in the product model. However, not only the activities themselves but also their mutual technological dependence as well as information on the resource requirements have to be assigned before the activities can be simulated. For this reason, a prototype software system, named "Preparator", has been developed. The "Preparator" uses so-called *process patterns* to generate the required information (Figure 3). Each process pattern is composed from a number of *work packages*.

Apart from specifying the materials (type and quantity), laborers (qualification) and machines (type) required for completing the activity concerned, the work package also provides the performance factors associated with the resources.

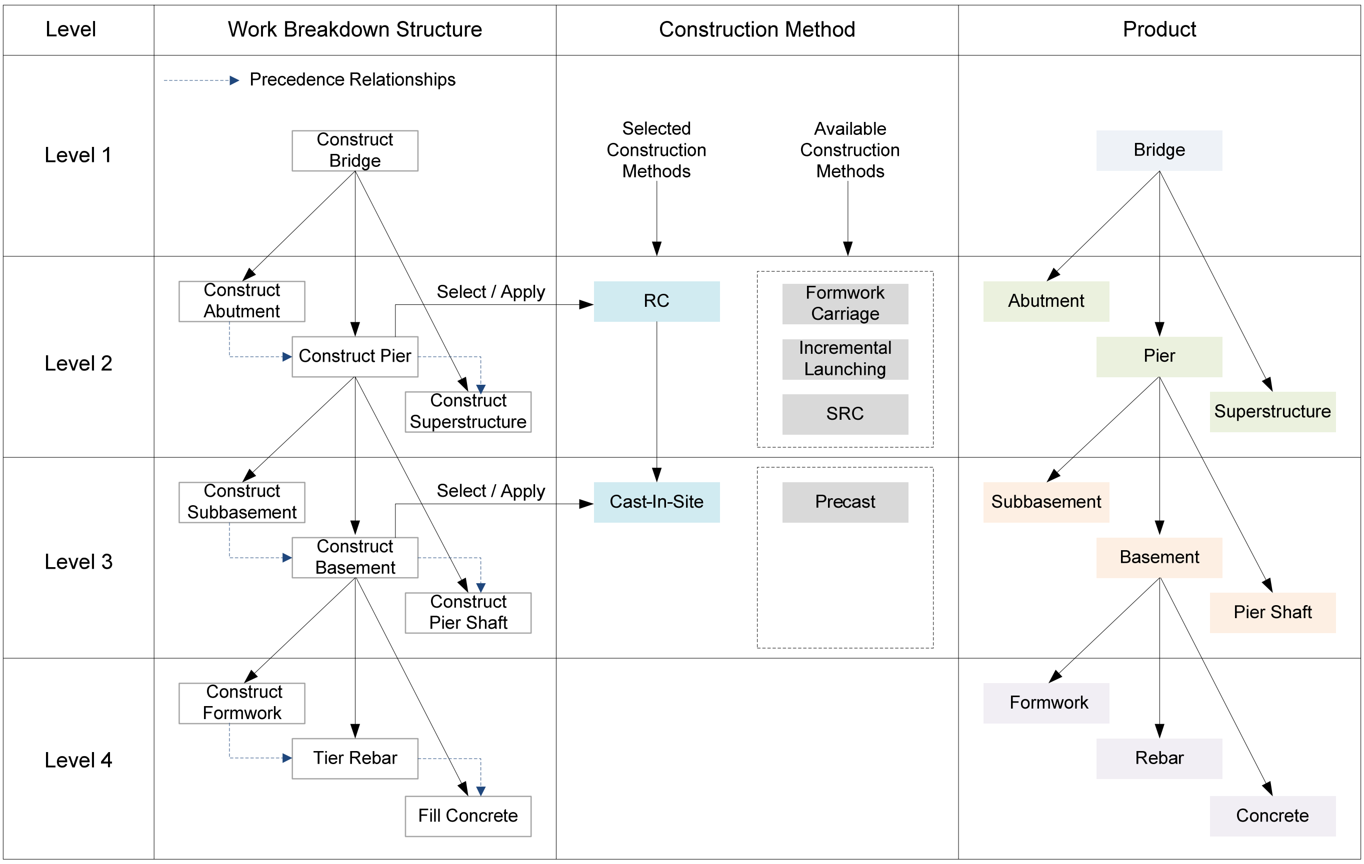


Figure 2. Level-of-Details for WBS, Construction Method and Product Model

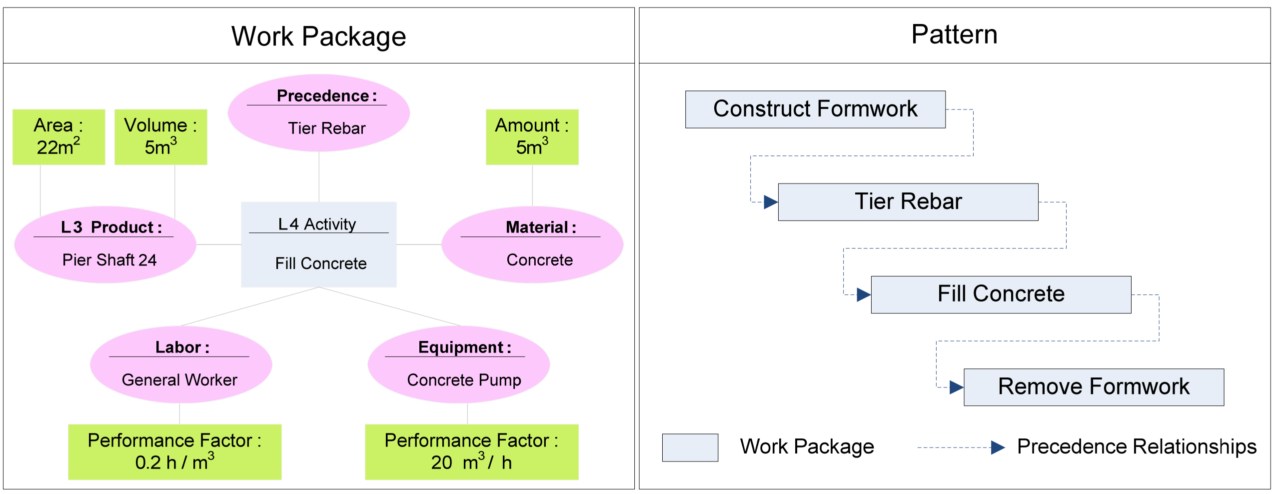


Figure 3. The concept of work package and pattern

At this stage of the planning phase it is possible to derive and determine the quantity of the required material from the geometry of the building component. Also, the performance factors of the resources are specified. However, the number of laborers and machines to be used is defined at a later planning stage, just before starting the simulation. This increases the flexibility of the approach presented in this paper. The scheduler is allowed to change the simulation conditions without changing the basic input data.

The work package also defines preceding activities that need to be finished before the activity in question can be executed. This information is derived from a *process pattern* that specifies the technological dependencies between individual activities. We have introduced the concept of process patterns to avoid the tedious, time-consuming task of assigning a multitude of individual work packages to each building component. These patterns only define the most stringent conditions of the execution. This means that all preceding tasks need to be completed beforehand. A typical example is that the “Construct Formwork” activity has to be completed before the subsequent activity “Fill Concrete” can be started.

A pattern combines a set of work packages and related precedence relationships to complete a building component according to a standard construction method. In the case presented in Figure 3, the “Construct Basement” pattern includes the work packages “Construct Formwork”, “Tier Rebar”, “Fill Concrete” and “Remove Formwork” as well as the corresponding precedence relationships. Besides being employed at numerous subsequent stages in the activity generation, activity sequencing, schedule generation and cost analysis processes, the information on - and relationship between - different activities, resources and product models in the pattern, can also be reused later on in other similar construction projects.

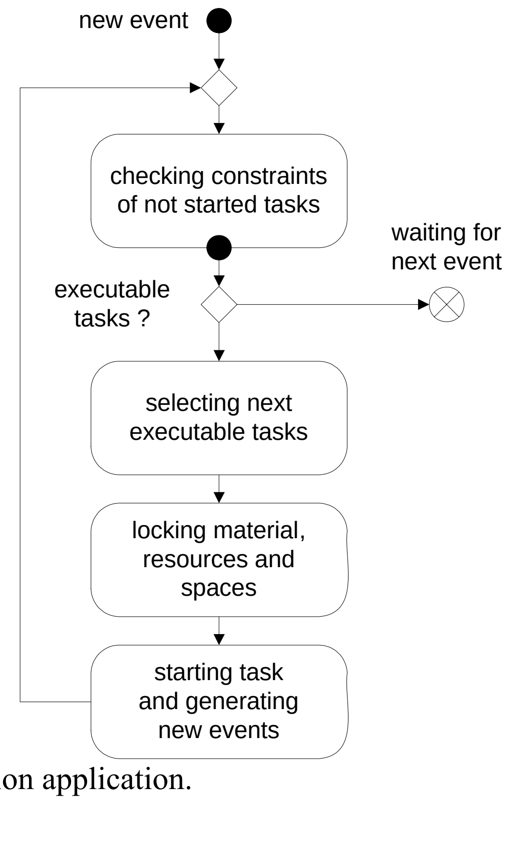
3 CONSTRAINT-BASED SIMULATION

3.1 *Overview*

In bridge construction projects, the possibilities of scheduling are manifold. A multitude of requirements, such as technological dependencies, material delivery dates or storage areas have to be taken into account. So determining an efficient construction schedule is a complex and time-consuming task. To facilitate it, this paper proposes a combination the constraint-based simulation approach (Beißert et al., 2007 & 2008) with a pattern-based method for the product model-based preparation of the input data.

Within the SIMoFIT cooperation (*Simulation of Outfitting Processes in Shipbuilding and Civil Engineering*) a constraint-based simulation approach has been developed to improve execution planning (Beißert et al., 2007). Construction scheduling problems can be described by *Constraint Satisfaction,* which is a powerful paradigm for modeling complex combinatorial problems (Blazewicz et al., 2007). Classical constraint satisfaction problems are defined by sets of variables, domains and constraints (Rossi et al., 2006). Accordingly, modeling the construction scheduling problems as constraint satisfaction problems, the construction tasks, materials, work force, equipment, and construction site layout are represented by variables. Different scheduling constraints can be specified between these variables. Typical *stringent constraints* of construction processes are technological dependencies between execution activities, certain equipment and manpower requirements, availability of materials and safety aspects, such as specific working areas or maximum time allowances (Beißert et al., 2007).

The solutions to constraint satisfaction problems are valid execution orders for the construction tasks where all associated constraints are fulfilled. The constraint-based approach guarantees a high flexibility of modeling construction processes. If additions or new prerequisites occur, the model can easily be adapted by adding or removing certain constraints. Normally, solving complex constraint satisfaction problems analytically is extremely time-consuming. By contrast, simulation methods can be used to investigate and evaluate different scenarios very quickly. Thus, the constraint satisfaction approach was incorporated into a discrete event



simulation application.

Figure 4: UML diagram of starting tasks

The simulation concept enables the generation of different events during the discrete simulation by the procedures *Starting Tasks* and *Stopping Tasks*. A task can only be executed if all its associated constraints are fulfilled. Figure 4 depicts the procedure of starting tasks. If a new event occurs, all tasks not yet started are checked on fulfillment of their associated stringent constraints. This leads to a set of next executable tasks. In the next step one of these executable tasks is selected for starting. Its presupposed objects, like material resources or employees, are locked during its execution and cannot be used by other tasks. This procedure is repeated until no more tasks can be started at the current time step. Once the remaining time allocated for a certain work step has expired, the task is marked as finished. The specifically reserved work force and materials are unlocked and can be employed for other construction tasks.

3.2 *Implemented Constraints*

In construction projects, constraints can be understood as restrictions that control or regulate the commencement or progress of work sequences or operations in order to complete construction tasks within the agreed time and budget, and to the required standards (Sriprasert, 2002 and Beißert, 2007). The research presented in this paper made use of the following constraints:

Contract Constraints

The realistic construction schedule is bound by several contract constraints. A construction schedule should include the commencement date, completion date and imposed milestones, while simultaneously generating the corresponding costs involved. The finished product should accordingly be completed within that time line and budget.

Technological Dependencies Constraints

Technological dependencies define stringent conditions in construction processes and have to be fulfilled before a task can be started. Technological dependencies specify different types of physical relationships. They not only define the sequence of the tasks connected with a certain activity, such as putting “Construct Formwork” before “Fill Concrete”, but also dependencies between building components, such as “Piers have to be finished before the superstructure can be created”.

Availability Constraints

Availability constraints control the material flows. Thus, the materials required for a certain task have to be available before that task can be started, which means that the materials should be deposited alongside the location of the designated operations. This includes arranging just-in-time deliveries if it is not possible to provide the required storage area. Delays in transportation lead to hold-ups in the performance of the task concerned.

Capacity Constraints

The capacity constraint refers to resources such as a stipulated number of workers or a certain set of equipment. If the capacity is exhausted, no further tasks can be started. It is also possible to determine the quality and quantity of resources by specifying certain skilled laborers, for example, where the nature of individual operations requires special skills.

Continuity Constraints

One of the main objectives of scheduling is to maintain the continuity of resources and consequently to minimize idle time. The continuity constraint helps to ensure a steady implementation of all available resources. This means that resources are preferably assigned to tasks on the basis of the longest waiting time between the two succeeding assignments. This paper only deals with continuity constraints in terms of worker utilization.

4 EXAMPLE: A SIMPLE SUBSTRUCTURE BRIDGE

A simple substructure bridge project was used as an example to demonstrate the achievements of this approach. This example is presented in two parts according to the software tools employed: the “Preparator” and the “Constraint-based Simulation”. The “Preparator” is responsible for generating activities and relevant resources using a 3D model. Figure 5 shows the main graphical user interface of the “Preparator”. The top menu bar contains menu items for quick access to the functions of the “Preparator”. The right-hand window is used separately to manage various pattern data, such as activities, resources, models, etc. The left-hand window is used to display the entire project data and the current status of the building components reserved for certain processes. The middle section serves to depict the 3D model and the project settings. The workflow sequence for generating activities and preparing data for the constraint-based simulation is as follows:

1. First, the user needs to specify the basic bridge information to generate activities connected with the bridge construction project. This includes the construction method employed, the number of piers, the number of segments, and so on.

2. Next, the "Preparator" will generate the preliminary activities according to the project settings and the predefined patterns. This data is described and stored in the aforementioned pattern-based construction models.

3. Once the activities have been generated, the user can edit and modify the relevant activities and resources to adapt them to the particular project.

4. The user links the 3D model with the activities using the drag-and-drop technique. At the same time the volume and the surface area are calculated and stored within the resultant work package. Later on, these quantities are multiplied by the diverse performance factors to calculate the required time and the associated costs.

5. Finally, the user exports data (a set of work packages) for constraint-based simulation, which includes activities, resources and quantities.

The "Constraint-based Simulation" is implemented to check the fulfillment of a task associated constraints and to select the next executable tasks. Based on this information successively a valid work schedule is generated. The simulation is performed using the input data from the "Preparator". The following steps are required:

6. The Constraint-based Simulation approach is integrated in commercial discrete-event simulation software. Starting the program, the user imports the required data generated by the "Preparator", as shown in Figure 6.

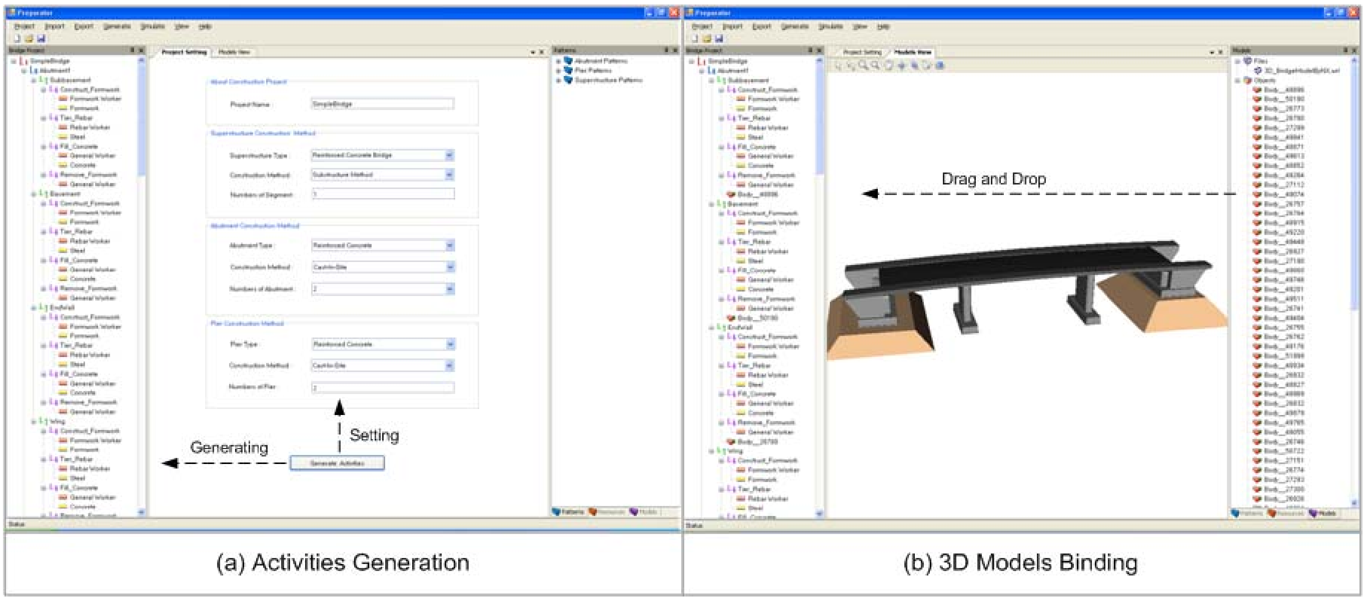


Figure 5. The main Graphical User Interface of Preparator

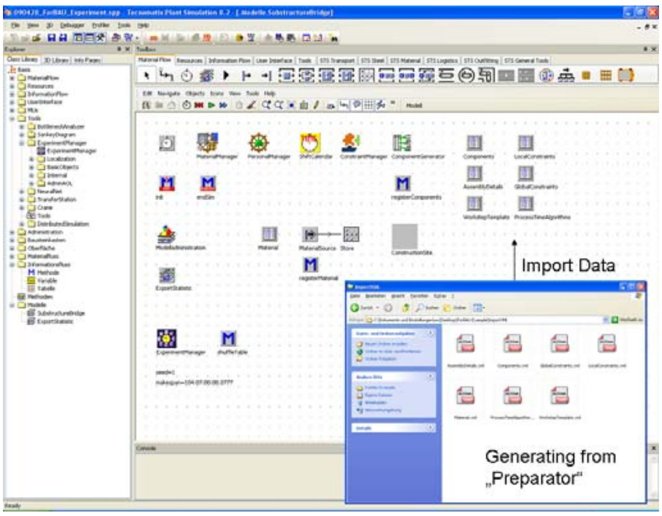


Figure 6. Constraint-based simulation

Process	StartDate	EndDate
Construct_Formwork_Subbasement_StartedAbutment	2007/06/01 00:00:00.0010	2007/06/01 09:00:00.0010
Construct_Formwork_Subbasement_EndedAbutment	2007/06/01 00:00:00.0010	2007/06/04 07:00:00.0021
Tier_Rebar_Subbasement_StartedAbutment	2007/06/01 09:00:00.0010	2007/06/04 09:00:00.0021
Tier_Rebar_Subbasement_EndedAbutment	2007/06/04 07:00:00.0021	2007/06/06 12:00:00.0042
Fill_Concrete_Subbasement_StartedAbutment	2007/06/04 09:00:00.0021	2007/06/05 09:00:00.0032
Remove_Formwork_Subbasement_StartedAbutment	2007/06/05 09:00:00.0032	2007/06/06 14:00:00.0043
Fill_Concrete_Subbasement_EndedAbutment	2007/06/06 12:00:00.0042	2007/06/08 07:00:00.0063
Construct_Formwork_Basement_StartedAbutment	2007/06/06 14:00:00.0043	2007/06/08 14:00:00.0064
Remove_Formwork_Subbasement_EndedAbutment	2007/06/08 07:00:00.0063	2007/06/15 07:00:00.0114
Tier_Rebar_Basement_StartedAbutment	2007/06/08 14:00:00.0064	2007/06/13 14:00:00.0095
Fill_Concrete_Basement_StartedAbutment	2007/06/13 14:00:00.0095	2007/06/14 12:00:00.0106
Remove_Formwork_Basement_StartedAbutment	2007/06/14 12:00:00.0106	2007/06/21 07:00:00.0157
Construct_Formwork_Basement_EndedAbutment	2007/06/15 07:00:00.0114	2007/06/20 07:00:00.0145
Tier_Rebar_Basement_EndedAbutment	2007/06/20 07:00:00.0145	2007/06/22 07:00:00.0166
Construct_Formwork_EndWall_StartedAbutment	2007/06/21 07:00:00.0157	2007/06/27 07:00:00.0198
Fill_Concrete_Basement_EndedAbutment	2007/06/22 07:00:00.0166	2007/06/28 12:00:00.0207
Tier_Rebar_EndWall_StartedAbutment	2007/06/27 07:00:00.0198	2007/07/02 12:00:00.0229
Remove_Formwork_Basement_EndedAbutment	2007/06/28 12:00:00.0207	2007/07/04 12:00:00.0248
Fill_Concrete_EndWall_StartedAbutment	2007/07/02 12:00:00.0229	2007/07/02 13:00:00.0229
Remove_Formwork_EndWall_StartedAbutment	2007/07/02 13:00:00.0229	2007/07/03 08:00:00.0240
Construct_Formwork_Wing_StartedAbutment	2007/07/03 08:00:00.0240	2007/07/04 08:00:00.0251

Figure 7. The output of the realistic construction schedule

7. The user specifies the quantity of the available resources, including laborers and their qualifications, the machines and the auxiliary construction equipment, such as form work panels, for example.

8. The user executes the constraint-based simulation.

9. A construction schedule is generated (Figure 7).

Our approach is semi-automatic. The required basic bridge information, the resources quantities and the constraints are assigned manually by the planner. From this information, the system generates a realistic construction schedule.

5 CONCLUSION

Execution processes for building projects are extremely complex. This means that a multitude of requirements like technological dependencies and resource capacities have to be taken into account in execution planning, as well as the principal guidelines, such as time and costs. Using the constraint-based simulation technique is a good way to generate a feasible schedule, but creating the necessary input data manually is tedious and time-consuming. To overcome this problem, we have developed a software tool called "Preparator" which assists the scheduler in creating the required input data. The tool allows the user to assign process patterns to individual elements of a 3D building model. A process pattern represents a certain construction method the user has decided to apply. It consists of a number of work packages and describes their precedence relationships.

A work package combines an atomic activity with the required material, the resources and the information on the activities that need to be accomplished beforehand. To determine the material quantities the "Preparator" automatically deducts the quantity required for each process (quantity take-off) on the basis of the 3D building model. The entire set of generated work packages forms the input for the constraint-based simulation of the construction process. The constraint-based simulation technique has been chosen since it makes it possible to model the highly dynamic processes encountered in the construction industry. Requirements can be easily defined or adapted by adding or removing constraints. The final outcome is a practical work schedule for executing the construction project.

Ongoing development work envisages incorporating Soft Constraints into our simulation approach (Beißert et al., 2007). Soft Constraints represent conditions derived from execution strategies, for example. When selecting the next task for execution, the constraint module takes soft constraints into account by ranking all executable tasks by their degree of Soft Constraint fulfilment. Absolute compliance is not essential, but they will make schedule generation more realistic.

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