CONSTRAINT-BASED SIMULATION OF OUTFITTING PROCESSES IN BUILDING ENGINEERING

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ABSTRACT: Execution planning of building projects is very time-consuming. A multitude of requirements such as local, technical and specific project ones have to be considered. This results in a wide choice of possible schedules including the assignment of employees and equipment. Often these different solutions are not sufficiently analysed in building industry. However, an in-depth investigation of different solutions is very useful not to overrun the projected costs and scheduled time. This paper focuses on using a constraint-based simulation model to detail construction tasks and their corresponding prerequisites such as constructional dependencies between tasks, necessary resources or availability of working space to execute a given task. Adjustable simulation components are developed to be combined to a thorough simulation model. By using the composed simulation model practical schedules can be generated and evaluated in terms of work flow organisation, utilisation of space and worker's efficiency as well as process costs.

KEYWORDS: constraint-based simulation, outfitting processes, construction schedules, resource assignment.

1 INTRODUCTION

The estimation of a successful building realisation is often linked to the project criteria quality, time and costs. Often it is not possible to find optimum solutions for all criteria. For example, an exceeding quality leads to higher costs as normal. Thus, a well-elaborated project organisation that focuses on a steady work flow and an efficient capacity utilisation is necessary to realise a building project successfully. Hence, high competence and extensive project experience are essential.

Currently, execution planning of outfitting processes is not sufficiently considered. In praxis, processes proceed uncoordinated. Consequently, outfitting processes are characterized by interferences and disturbances, and are planned independently without feedback to the responsible companies. This affects adversely the execution. Generally, outfitting processes are characterized by a great dependency among each other and different surrounding area requirements. These circumstances require an extensive planning and coordination effort.

The quantity of possible execution solutions is limited by requirements. These are, for example, constructional dependencies between the execution work steps, the assignment of employees and equipment and the availability of working space to execute a given work step. If sufficient working space is not available, workers' productivity will be reduced, in consequence projected execution time and calculated costs will rise (e.g., Akinci et al. 2002, Mallasi 2004). Also the local and specific project requirements must be carefully pointed out, because they might also reduce the quantity of possible execution solutions. The application of simulation models is a promising approach to support the planners.

This paper focuses on using a constraint-based simulation model to detail construction tasks and their corresponding prerequisites. Adjustable simulation components are developed which can be combined to a thorough simulation model. By means of the composed simulation model practical schedules can be generated and evaluated in terms of work flow organisation, utilisation of space and worker's efficiency as well as process costs, afterwards. This simulation approach is developed within the cooperation SIMoFIT - Simulation of Outfitting Processes in Shipbuilding and Civil Engineering.

2 CONSTRAINT-BASED SIMULATION

Using simulation models has several advantages. Simulation models enable users, for example, to visualise material flows, to localize manpower bottlenecks or to run experiments and what-if scenarios. In manufacturing industry simulation applications are often used to optimize production processes. The applications provide the opportunity to model global production facilities, local plants or specific lines. Modelling of construction sites is quite different from modelling of production plants. The construction site layout, for instance, changes during the processing, following transport ways and material flows have to be adapted. Due to the fact that simulation applications in manufacturing industry only support static layouts, another simulation approach to describe construction processes has to be used.

The constraint-based simulation approach guarantees a high flexibility of modelling processes. Attributes of simulation objects and their relations are described by constraints. If additions or new prerequisites occur, an adaptation can be achieved easily by defining or removing certain constraints. If only a few constraints are defined, the solution space will be huge. The more constraints are specified the more the solution space is restricted (e.g., Fox and Smith 1984, van Hentenryck et al. 1996). Thus, the planning problem is to find a practical work flow schedule, where all constraints are fulfilled.

According to Sriprasert and Dawood (2002) three different types of constraints are classified to describe the execution of building projects. These types and some important constraints are shown in table 1.

Table 1. Important Constraints in Construction (according to Sriprasert and Dawood 2002).

Physical Constraints	Contract Constraints	Enabler Constraints
- Technological dependencies - Space - Safety - Environment	- Time - Cost - Quality - Special agreement	- Resources - Requirement - Availability - Capacity - Perfection - Continuity - Information - Requirement - Availability - Perfection

Some of these constraints are binding. Others may be bypassed for the sake of an increase in cost, time or risk (Sriprasert and Dawood 2002, Sriprasert and Dawood 2003). Within this approach only physical and enabler constraints like technological dependencies, space and resource requirements are considered.

Using constraint-based simulation to solve job-shop scheduling problems has been analyzed by Sauer (1998), Fox and Smith (1984) and Beck and Fox (1998). It is shown, that two types of constraints should be distinguished, so-called hard constraints and soft constraints. Hard constraints define stringent conditions in construction processes and have to be fulfilled before a work step can be started. Essential technological dependencies and resource capacities are defined as hard constraints. Soft constraints characterize appropriate dependencies (Sauer 1998). A complete fulfilment is not necessary. Uncertain planning parameters, for example, an indefinite starting time of work steps can be described by soft constraints. Soft constraints can be relaxed on a limited scale to find variable configurations, which solve all constraints (Fox and Smith 1984, Beck and Fox 1994). They might be helpful, if no solution is detectable. However, soft constraints make the modelling of systems more realistic.

3 OUTFITTING PROCESS CONSTRAINTS

For every outfitting work step different hard and soft constraints are defined (table 2). The beginning of a work step is bound to some global hard constraints (Sauer 1998). The work step has to be executed without any interruption. Each work step has to be realized by its required amount of employees, which cannot be deducted before finishing the work step. Furthermore, each work step will be executed without a change of the working position of employees or equipments.

Technological dependencies

Technological dependencies specify definite sequences between processes, outfitting tasks or work steps. Both constructional aspects and formal aspects are considered. Constructional aspects have to be respected. Otherwise bearing capacity might be influenced and cannot be guaranteed respectively. Formal aspects describe a practical performance of processes, tasks and work steps. For example, it is a common practice to first lay the cornerstones before building the intermediate wall sections to achieve dimensional accuracy of a brick wall.

Table 2. Implemented Outfitting Process Constraints.

Constraint		Examples
Hard Constraints	Global constraints	Complete execution of a work step without interruption
		Work steps have to be executed at least by the defined amount of employees
		Work steps have to be executed without changes of the positions of employee and equipment
	Technological dependencies	Attending stringent rules at execution - constructional and formal aspects are implemented
	Strategies	Attending predefined execution rules - proven formal aspects are implemented
	Capacity	Appointing the amount, qualification and productivity of employees and equipment
	Availability	Limitation of material
	Safety Criteria	Criteria of employment and equipment protection
Soft Constraints	Productivity	Functional bench mark: relations between workers productivity and offered working space

Strategies

Strategies are predefined execution rules, which extend the technological dependencies. Established process sequences can be simulated and analysed. For example, assembling strategies of partition walls can be modelled to assist the user on deciding which assembling order is most useful. The best execution solution can be found by means of a closer inspection of the construction site layout (e.g., Riley and Sanvido 1995). For instance, based on the current layout the following work order strategies can be beneficial to realize an undisturbed execution (figure 1):

- in vertical or horizontal ascending order
- in vertical or horizontal descending order
- according to the length of walls (a)
- the shortest walls first
- longest distance between the working groups (b)
- using cyclic work patterns

Figure 1. Outfitting Work Order Strategies.

Capacity

Resource capacity describes the amount of serviceable employees and equipment. Their quantity is finite. If the capacity is exhausted, no more work step can be started. The capacity specifies for example skills, productivity of employees and equipments output. For different work steps various skilled employees can be required.

Availability

The availability of material is a constraint to control material flows. Close to a working place the space to store required material often is limited. Thus, storage areas near by the working place have to be found. Otherwise in-time delivery has to be disposed. The unavailability of material corresponds to the possibility of supply bottlenecks in production.

Safety criteria

To protect employees and to assure the right exposure to the equipment, safety criteria have to be considered. If prescribed safety criteria cannot be obeyed, work steps cannot start. Typical safety criteria are distances between persons and machines, maximum working time for equipment and personnel or essential needed working space (e.g., Akinci et al. 2002).

Productivity

As explained it is possible to relax soft constraints within a limited scale. A fulfilment is expedient and for that reason to aspire. Currently, within this approach, one soft constraint is implemented: worker's productivity (Beck and Fox 1994, Mallasi 2004). An employee only achieves 100 percent productivity, if required work space is offered. Productiveness will rapidly fall, if this operating range cannot be guaranteed. The complex coherence between free working space and productivity of employees needs to be simplified. Currently, the worker's productivity value is described by a linear function.

4 CONSTRAINT-BASED SIMULATION OF OUTFITTING PROCESSES

Outfitting processes of building projects consist in several construction tasks. Each outfitting task, like erecting a partition wall, is decomposed into work steps like plastering or installing a stub. This simulation approach focuses on simulating each single work step. Each work step has a current state – not started, started and finished – and requires a certain execution time. Before a simulation run can start, all work steps, hard and soft constraints, material elements, the construction site and resources like employees and equipment have to be defined.

The following procedure describes the detection of work steps that can be started at the current simulation time:

1. A work step can be executed, if all associated hard constraints are fulfilled. All not started work steps are checked up on satisfying these criteria. These work steps are stored in a special set of executable work steps.
2. Further, the fulfilment of soft constraints has to be checked for all executable work steps. Executable work steps have to be ordered by the percentage of their soft constraints fulfilment. Only the first work step of this list can be started. If several work steps fulfil their constraints in equal measure one of them is chosen randomly.
3. After starting a work step, its state changes from "not started" to "started". Work steps' presupposed objects like certain material, resources, equipment and working space are locked during its execution. Following locked objects cannot be used by other work steps. Subsequently, all "not started" work steps have to be checked up again on fulfilment of their hard and soft constraints by going to step one.

The simulation time is continuously checked during a simulation run. Every started work step has a certain remaining time. If the remaining time of a work step is expired, the work step has to be stopped by the following sequence:

1. The state of a stopped work step has to be set to "finished".
2. All locked material, resources, equipments and working spaces have to be unlocked and therefore can be used by other work steps.

The simulation will be repeated until all work steps are finished. Starting and finishing a work step as well as locking and unlocking material, resources, equipment and working space are documented. In result one simulation run calculates one practical execution schedule, one material flow as well as utilisation of employees and equipment. A quantifying of simulated solutions is not intended by the simulation itself. The overall goal is to simulate different practical solutions for execution, which can be analysed regarding principal guidelines such as time, cost and quality afterwards.

5 DISCRETE-EVENT SIMULATION FRAMEWORK

The presented constraint-based simulation approach was implemented by using the discrete-event simulation program Plant Simulation from Tecnomatix Technologies Ltd. Within a simulation run a discrete-event simulation program only inspects points in time, at which events occur. Typical events are, for example, a work step is starting or a material element is entering a certain storage area. The time between two succeeding events is not considered. A discrete-event simulation program calculates the time from starting a work step until it is finished. The calculated end of term is stored as an event into a list of scheduled events. Thus, the simulation time leaps from event to event. To build up a constraint-based simulation model for outfitting processes in building engineering, a simulation framework was developed. The simulation framework consists of different re-usable components, for example, to generate data, to check constraints, to lock work spaces, to manage resources or material and to control work steps. The simulation toolkit for shipbuilding of the "Simulation Cooperation in the Maritime Industries" community (SimCoMar) is used to implement this framework for outfitting processes.

Data generation

The manual definition of all required data for a special construction project is very time-consuming. Therefore, some components and interfaces to support the data generation were implemented. For each outfitting process a separate data generator has to be defined using a special data generator interface. This interface provides methods to create material sheets, work steps and work step constraints for a certain outfitting component (figure 2). Before the defined data generators can be used, they have to be registered to a central data generation component. Currently, a drywall data generator is implemented.

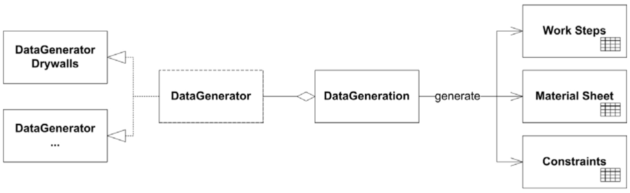

Figure 2. Data Generation Concept.

Work step container

Generated work steps are stored in a work step container. Each work step has a unique identifier, associated outfitting components and a current state. The work step container records every modification of a work step state. Thus, an associated work schedule can be created.

Material administration

The material administration component defines several material elements belonging to a work step based on its generated material sheet. Using the material administration all required material elements of an active work step can be requested. Furthermore, some statistical evaluations of material availability and material storage are supported by the material administration.

Resource administration

The resource administration component was implemented to assign and to release required resources of a work step. Resources are, as per description, employees or work equipment. All these resources have to be specified by the user manually. To analyze the resources workloads, each access to an employee or work equipment is recorded. Currently, only employees and their technical skills are implemented.

Constraint management

The constraint management component consists of different sub-components. For each constraint type a separate component was implemented (figure 3). The generated constraints are assigned to their corresponding constraint type components. Each sub-component provides a method to check the related constraints of a denoted work step. The constraint management component tests all work steps to get the next executable work steps.

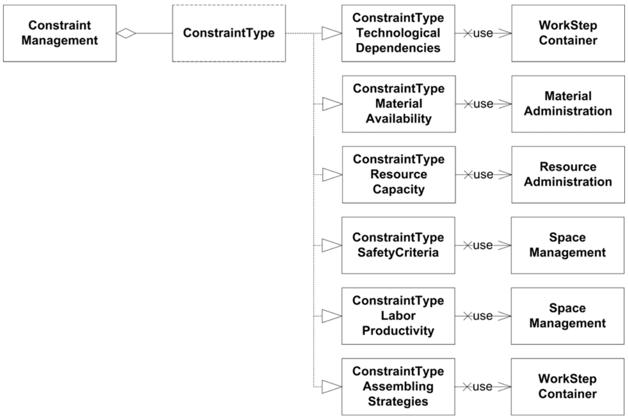

Figure 3. Constraint Management Concept.

Space management

An important objective of this simulation approach is the consideration of required work spaces as constraints. A special grid component was developed to lock and unlock work areas.

Workflow control

Every outfitting simulation model contains a workflow component to control different work steps and to generate their events. An essential function of the workflow control is to start the next executable work steps randomly. Appropriate methods were implemented to inquire necessary material elements or resources from the material or resource administration. Furthermore, methods to lock or unlock work spaces to provide safety criteria were added.

6 EXAMPLE: ASSEMBLING DRYWALLS

Within this research activity assembling drywalls of a building storey is the first implemented outfitting process. In this example thirteen drywalls have to be installed (figure 4). The material sheet of these drywalls includes the number of intumescent strip rolls, U-channels, C-studs, plasterboards, loft insulating rolls and plaster bags. Depending on drywall lengths and a desired distance between the C-studs, material sheets can be generated by using the implemented drywall data generator.

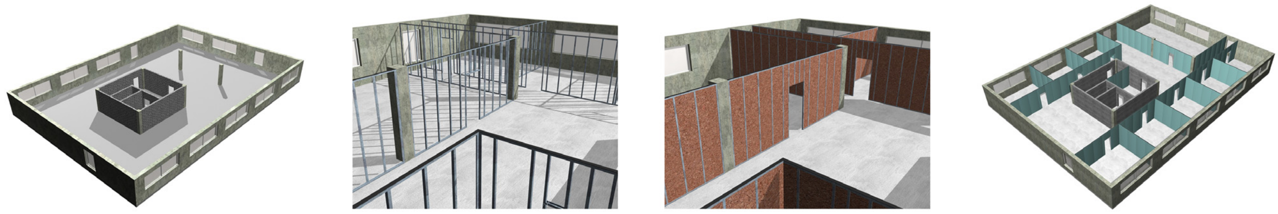

Figure 4. Building Storey with thirteen Drywalls.

6.1 *Drywall work steps*

The assembling process of a drywall consists of eight work step types: calibrating the wall, sticking intumescent strips and U-channels together, fixing U-channels at ceiling or floor, installing C-studs, fixing plasterboards first side, filling loft insulation material, fixing plasterboards second side and plastering drywall. Currently, work steps like cutting material and mixing plaster are not considered. For each material element, separate work steps and their execution positions have to be calculated based on these eight work step types. For example assembling a drywall of length 4 m and distance of 0.625 m between the C-studs consists of seven work steps installing C-studs and eight work steps fixing plasterboards. Each work step was generated and passed to the workflow control. The execution time of each work step was calculated based on well-known working time standard values (e.g., IZB 2002). For example, generally a worker needs about 0.1 h/m2 to fill insulation material.

6.2 *Drywall constraints*

In the next generation step constraints for assembling a drywall have to be specified. Within the drywall generator the technological dependencies are defined, as shown in figure 5. Sticking an intumescent strip and a U-channel together, for example, needs as finishing work step a calibration of the drywall. Another example, before a worker can fix a plasterboard element at a certain position, all C-studs in the range have to be installed.

Generally, certain material and resources are required to execute a drywall work step. For example, to execute the work step “sticking strip and U-channel together”, an employee with the skill “drywall constructing”, an intumescent strip roll and a U-channel element is needed. For each drywall work step type a procedure to generate the constraints was implemented.

Due to safety at work aspects it is reasonable to ensure a minimum of work space to execute a work step. For this example, at least a free operating range of one meter is necessary to execute a work step. This requirement can be described by a safety criteria constraint. Furthermore, labor productivity constraints are defined to consider different worker’s productivity levels depending on the available operating range. It will be set to 100 percent if an operating range of three meter is available. The calculation between one and three meter available operating range is simplified as a linear function.

6.3 *Resource definition*

For each simulation run resources have to be defined manually. In the presented example only technical skills and workers are specified. To execute all drywall work steps the following skills are required: calibrating, drywall constructing, filling insulation material and plastering. Based on these skills different types of employees are defined:

- foreman: all skills
- drywall worker: drywall constructing, filling insulation material and plastering
- laborer: filling insulation material and plastering skill

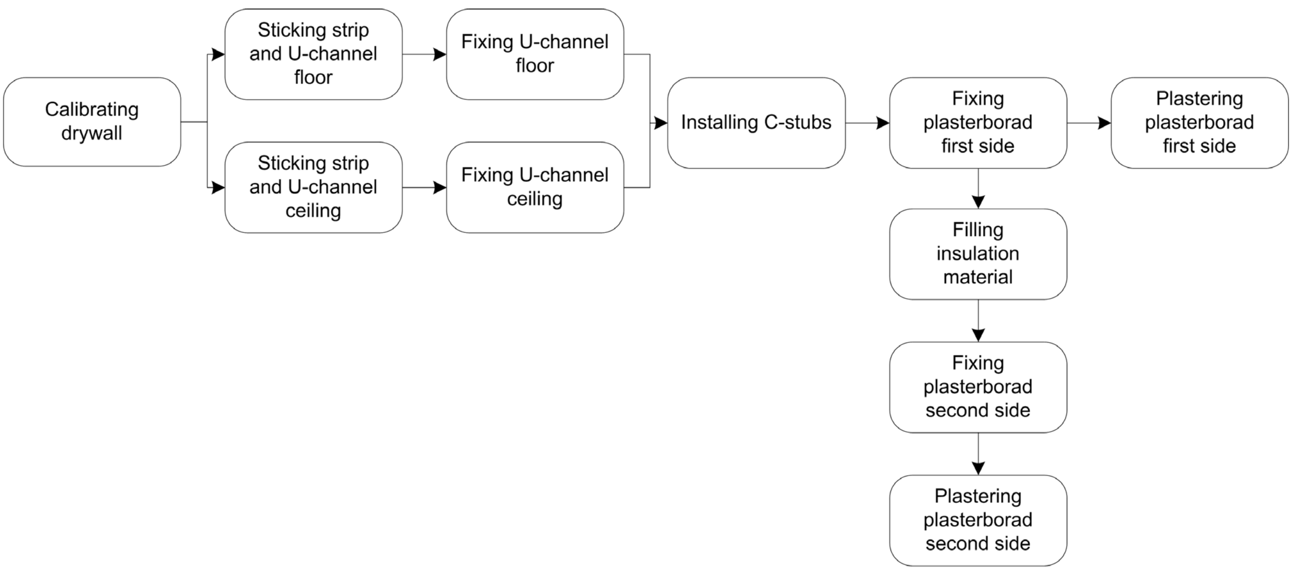

Figure 5. Technological Dependencies between Drywall Work Steps.

6.4 *Simulation and evaluation*

Simulation results of the visualized drywall example are as follows. Four possible employee variations were determined. The different employee variations of foremen, drywall workers and laborers are shown in table 3.

Table 3. Employee variations in 4 experiments.

Employees / Experiment No.	Number of Foremen	Number of Drywall Workers	Number of Laborers
Experiment 1	1	1	2
Experiment 2	1	3	2
Experiment 3	1	4	3
Experiment 4	2	4	4

For each employee variation 1000 simulation runs have been performed randomly. Within these simulation runs the same drywall work steps, constraints and material sheets are generated. For each simulation run the work step schedule and the workload of employees was recorded and can be evaluated afterwards. Furthermore, every simulation run can be animated using the discrete-event simulation program and be used for visual control of the simulation progress. The implemented simulation model and a snapshot of a simulation step are shown in figure 6.

At this stage only results of net working time are evaluated. Minimum and maximum net working time as well as average and standard deviation are shown in table 4. In this example the shortest net working time is given for the assignment of two foremen, four drywall workers and four laborers (experiment 4).

Not only net working times are important but also costs and workloads have to be observed. In this case, the following wages per hour are assumed: foreman 28 EURO/h, drywall worker 21 EURO/h and laborer 11 EURO/h. Workers costs and average workloads of the defined employee types are shown in table 5. Costs and workloads are calculated based on the shortest simulation run of each experiment.

Table 4. Working Time Results from experiments.

Net Working Time / Experiment No.	Minimum [min]	Maximum [min]	Average [min]	Std. Deviation [min]
Experiment 1	12462	14047	13096	295
Experiment 2	6078	9222	6743	492
Experiment 3	5040	7667	5943	587
Experiment 4	4150	5635	4579	297

Table 5. Costs and Workload Results from experiments.

Costs & Workloads / Experiment No.	Worker Costs [EURO]	Av. Workload Foremen	Av. Workload Drywall Worker	Av. Workload Laborer
Experiment 1	14747	99%	97%	17%
Experiment 2	11447	99%	89%	49%
Experiment 3	12180	99%	88%	48%
Experiment 4	12727	94%	88%	34%

Table 5 shows the calculated results. In experiment 4 the shortest net working time was attained. This experiment proves to be at the same time inappropriate in consideration of costs and workers' workload. Workers, especially laborers, but also the foremen and drywall workers are not used to full capacity, which causes additional costs for idleness. An advanced utilization to lower costs is shown in experiment 3. The needed execution time is about 20 percent higher. Considering principal guidelines, the project planners have to appoint a number of employees, which solves the project management criteria for a steady work flow and an efficient capacity utilisation. The application of Monte-Carlo Simulation cannot guarantee to find the optimum solution. However, this approach generates a multitude of practical schedules that can be analyzed and visualized to define an optimized solution manually.

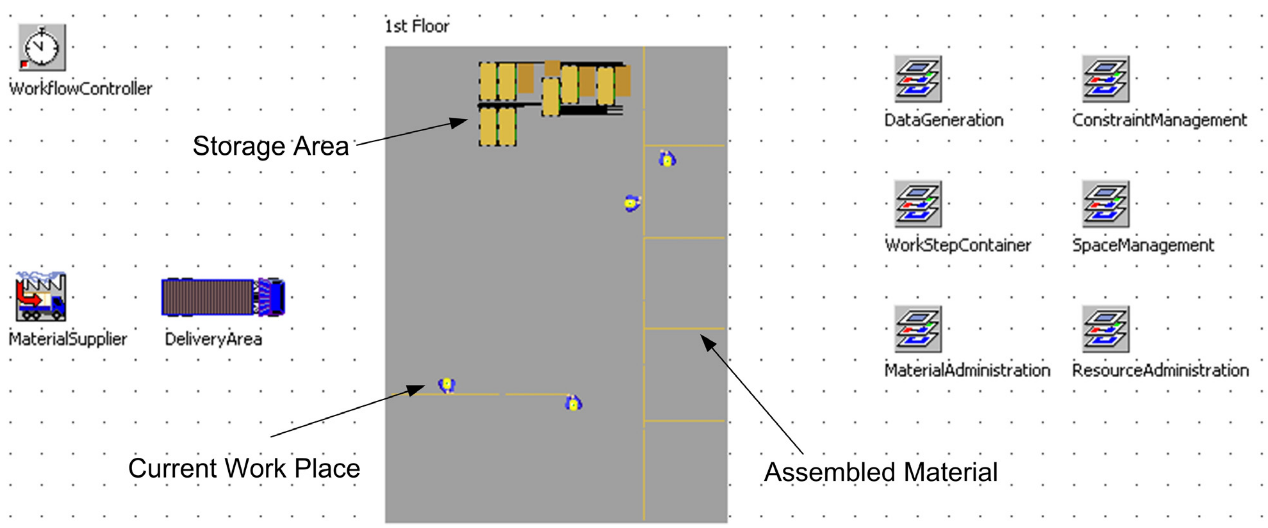

Figure 6. Animation Snapshot of a Simulation Step.

7 CONCLUSIONS

Execution processes of building projects are very complex. Thus, in execution planning a multitude of requirements like technological dependencies and safety criteria have to be considered as well as principal guidelines, such as time, cost and quality. A high competence is demanded by the planners to take all these different influences into account. This paper introduces simulation as an appropriate instrument to support the planning process. Constraint-based simulation models are highlighted since they allow modelling dynamic structures. Requirements can be easily defined or adapted by adding or removing constraints.

Currently, in order to model outfitting processes, the following constraints have been considered: global hard constraints, technological dependencies, strategies, capacity, availability, safety criteria and productivity. To implement this approach, a discrete-event simulation framework has been chosen and a lab tested research is presented. The result is, that practical schedules can be generated to evaluate worker's efficiency, utilisation of space as well as process costs by using a constraint based simulation model (e. g., Zhang et al. 2005, Mallasi 2004).

In future work, the defined drywall data generator component has to be enhanced and completed respectively. Constraints like assembling or production control strategies have to be added to offer the opportunity to analyze certain scenarios. A further component is projected and has to be implemented to broaden the models' realistic behaviour: a storage area control component. The projected component estimates the storey area regarding execution processing in order to find certain storage areas. The area is divided into sub-areas, which are valued regarding their suitability for storage. Adequate storage areas are important to guarantee an undisturbed execution flow. If sufficient storage area cannot be offered, further attention should be paid to supply of material and equipments' disposability in the planning process. Further implementation of fuzzy-techniques to describe soft constraints is on the research agenda. Actually, the complex coherence between free working space and productivity of employees is described by a linear function, which is a simplified representation. By implementing fuzzy-techniques, the relaxing character of soft constraints could be better delineated.

In addition, further components, like transport processes, have to be modelled and implemented. These components can be combined to a thorough simulation model. Therefore, special global constraints have to be considered, for example, to connect outfitting and transport processes. Besides supporting the planning process, another application for this composed simulation model is to draw prognoses. Based on the actual execution status, the further execution can be simulated. Thus, the simulation model enables a steady control of fulfilment of the execution and planning guidelines.

REFERENCES

Akinci, B., Fischer, M., Levitt, R., and Carlson, R. (2002). "Formalization and Automation of Time-Space Conflicts Analysis", Journal of Computing in Civil Engineering, 16(2), 124-134.

Akinci, B., Fischer, M., and Kunz, J. (2002). "Automated Generation of Work Spaces Required by Construction Activities", Journal of Construction Engineering and Management, 128(4), 306-315.

Beck, J.C., and Fox, M.S., (1994). "Supply Chain Coordination Via Mediated Constraint Relaxation", Proceedings of the First Canadian Workshop on Distributed Artificial Intelligence, Banff, Alberta.

Beck, J.C., and Fox, M.S. (1998). "A Generic Framework for Constraint-Directed Search and Scheduling", AI Magazine, Winter 1998, 103-132.

Fox, M.S., and Smith, S.F. (1984). "ISIS – a knowledge-based system for factory scheduling", Expert Systems Journal, 1(1), 25-49.

IZB - Institut für Zeitwirtschaft und Betriebsberatung Bau (2002). "Trockenbau-Planzeiten Wände : methodisch ermittelte Zeitwerte für die Planung, Ausführung und Entlohnung", Neu-Isenburg - Zeittechnik-Verlag, Karlsruhe.

Mallasi, Z. (2004). "Identification, and Visualisation of Construction Activities' Workspace Conflicts Utilizing 4D CAD/VR Tools", 1st ASCAAD International Conferend, e-Design in Architecture, KFUPM, Dhahran, Saudi Arabia, 235-253.

Riley, D.R., and Sanvido, V.E. (1995). "Patterns of construction-space use in multistory buildings", Journal of Construction Engineering and Management, 121(4), 464-473.

Riley, D.R., and Sanvido, V.E. (1997). "Space planning method for multistory building construction", Journal of Construction Engineering and Management, 123(2), 171-180.

Sauer, J. (1998). "A Multi-Site Scheduling System", Proc. Artificial Intelligence and Manufacturing – Research Planning Workshop – State of the Art and State of the Practice, Albuquerque, AAAI-Press, 161-168.

Sriprasert, E., and Dawood, N. (2002). "Requirements identification for 4D constraint-based construction planning and control systems", International Council for Research and Innovation in Building and Construction – CIB w78 conference, Construction Informatics Digital Library (available at http://itc.scix.net/paper w78-2002-90.content).

Sriprasert, E., and Dawood, N. (2003). "Genetic Algorithms For Multi-Constraint Scheduling: An Application for the Construction Industry", International Council for Research and Innovation in Building and Construction – CIB w78 conference, Construction Informatics Digital Library (available at http://itc.scix.net/paper w78-2003-341.content).

van Hentenryck, P., Saraswat, V., et al. (1996). "Strategic Directions in Constraint Programming", ACM Computing in constraint programming, 28(4), 701-726.

Zhang, C., Hammad, A., Zayed, T.M., and Wainer, G. (2005). "Representation and Analysis of Spatial Resources in Construction Simulation", Proceedings of the 2005 Winter Simulation Conference, 1541-1548.