VISUAL SIMULATION - AN APPROPRIATE APPROACH TO SUPPORT EXECUTION PLANNING IN BUILDING ENGINEERING

M. König, Prof. Dr.-Ing.,
Bauhaus-University Weimar Germany;
markus.koenig@uni-weimar.de

U. Beißert, Dipl.-Ing.,
Bauhaus-University Weimar Germany;
ulrike.beissert@uni-weimar.de

H.-J. Bargstädt, Prof. Dr.-Ing.,
Bauhaus-University Weimar Germany;
hans-joachim.bargstaedt@uni-weimar.de

ABSTRACT: This paper focuses on a simulation concept to visualize and to analyze outfitting processes in building engineering. A constraint-based simulation model is used to specify dependencies between outfitting tasks, availability of resources and required work spaces. Further, the model is used to specify conditions of transport processes, delivery dates as well as time and cost restrictions. By using a constraint-based simulation model practicable schedules can be generated and visualized simultaneously. For example, execution conflicts such as restricted work spaces are highlighted. Afterwards, the simulated and visualized results can be evaluated in terms of work and material flow organization, utilization of space and worker's efficiency. This constraint-based simulation approach guarantees a high flexibility. Thus, if additions or new prerequisites, for example, during project meetings are suggested, they could be easily implemented by defining or removing certain constraints such as requirements or production strategies. In the same manner, the current project status could be entered. Adjustable simulation components for transport control, spatial management, material management and assembling control as well as for visualization and animation are developed.

KEYWORDS: visual simulation, constraint-based modeling, planning support, outfitting processes.

1. INTRODUCTION

Successful project realization is linked to detailed and flexible project planning. Thereby, a multitude of restrictions and requirements has to be considered to find practicable and efficient execution solutions. Consideration of all requirements including the assignment of resources and spaces, results in a wide choice of possible solutions for execution. An in-depth investigation of these different solutions is essential not to overrun the projected costs and time. However, currently planning of outfitting processes is not sufficiently considered in civil engineering. That is quite surprising, due to the fact that building installation and outfitting processes represent about 38% of the construction volume in building industry in Germany in the year 2005 (IBW 2006). The main problem of outfitting planning is that each company plans its own processes, independent from other executers. But outfitting processes are very complex and a lot of interdependencies between workers of different trades have to be considered. Thus, outfitting processes are mostly distinguished by interferences. In consequence, on production site an extensive coordination effort is necessary to handle these difficulties. A realistic planning and detailed analysis will help to reduce these problems. Visual simulation can be used to deliver the necessary data for such an analysis.

Visual Simulation is an appropriate application to support execution planning in building engineering (e.g., Hanff 2007, Bargstädt and Blickling 2006, Mallasi and Dawood 2004). The simulation and visualization of projected execution solutions offer the opportunity to detect manpower bottlenecks as well as inefficient equipment or worker utilization. Furthermore, the practicable process visualization assists the know-how exchange within a company and between partners respectively. For example, an appropriate animation of execution sequences is a valuable communication basis for planners and executers. Especially, to see construction processes from a different angle may help to improve projected execution strategies. In addition, using visualization to depict problems might be helpful to argue for exceptional facilities and extraordinary expenses.

Within the cooperation SIMoFIT (Simulation of Outfitting Processes in Shipbuilding and Civil Engineering - http://www.simofit.com) a constraint-based simulation approach is developing (e.g., Beißert et al. 2007; König et al. 2007). The SIMoFIT cooperation was established between Bauhaus-University Weimar and Flensburger Shipyard. Outfitting construction processes in shipbuilding and building industry are highly comparable to each other. Dependencies between outfitting tasks, availability of resources such as equipment or workers, required work spaces and transport processes as well as delivery dates and time and cost restrictions have to be considered in planning processes of both trades (e.g., Beißert et al. 2007; König et al. 2007). To simulate outfitting processes the successfully used in practice Simulation Toolkit Shipbuilding (STS) of the SimCoMar community (Simulation Cooperation in the Maritime Industries community - http://www.simcomar.com) is adapting (e.g., Steinhauer and Heinemann 2004). Flensburger Shipyard and their partners of the SimCoMar community are developing the Simulation Toolkit Shipbuilding since 2000.

In this paper, the application of a discrete-event simulation is presented to find practicable construction schedules considering different project-specific constraints. The results of each simulation run can be analyzed afterwards to detect potential improvements. However, the use of simulation applications provides a multitude of advantages, for example, the opportunity to visualize and to animate work as well as material flows and using results as a co-operative basis for decision-making. In addition, it offers the opportunity to integrate current production states and to draw prognoses of the further progress.

2. CONSTRAINT SATISFACTION

Constraint satisfaction is a powerful paradigm for modeling combinatorial search problems such as scheduling construction tasks (e.g., Rossi et al. 2006, Beck and Fox 1998, Goltz 1995). Constraints specify conditions or restrictions of variable values. The problem consists in finding a value combination for all variables, where their associated constraints are fulfilled. The more constraints are specified to describe a task, the more the solution space is restricted and following the more the multitude of possible solutions for execution is deducted (e.g., van Hentenryck et al. 1996, Sauer 1998). Normally, a constraint solver is used to find an optimal assignment of the variables to a given problem that satisfies the constraints (Rossi et al. 2006). However, realistic problem modeling leads to a multitude of variables and associated constraints. In this case, the use of a constraint solver such as a backtracking search algorithm to find optimal solutions is very time-consuming.

Often in construction practice, it is not necessary to find an optimal solution. Considering the facts that project constraints are changing rapidly and often defined construction schedules are valid only some days, it is adequate to search or to compute only a few practicable schedules and decide on these solutions. Thus, it is more important, to generate and to adapt practicable schedules very fast. Hence, one advantage of using the constraint satisfaction approach for generating and analyzing construction processes is an easy adaptation by defining or removing certain constraints, if additions or new prerequisites occur. In the same manner, actual project data can be integrated as constraints to provide detailed forecasts.

To secure a realistic schedule the constraints have to be classified into hard and soft constraints (e.g., Sauer 1998, Rossi et al. 2006). Hard constraints define stringent conditions. They have to be fulfilled in any case. These are, for example, necessary technological dependencies of tasks or required equipment. Soft constraints characterize appropriate characteristics of variables, for example, an indefinite starting time or overlapping workspaces (e.g., Zhang et al. 2005, Akinci et al. 2002b, Riley and Sanvido 1997). Their complete fulfillment is not necessary. Thus, soft constraints can be relaxed on a definite scale to find variable configurations to solve all constraints. This might be helpful, if no solution is detectable (e.g. Fox and Smith 1984; Beck and Fox 1994). The fulfillment rate of soft constraints can be a decisive factor not to overrun the projected costs and time as well to achieve an efficient utilization of employees or equipment. An important step of further research work is looking for solutions that fulfill all hard constraints and violate the soft constraints as little as possible.

3. CONSTRUCTION TASKS CONSTRAINTS

Within our research activity a constraint-based approach is used to describe restrictions and requirements of outfitting processes. Currently, only physical constraints and some enabler constraints emphasized by Sriprasert and Dawood are considered (e.g., Sriprasert and Dawood 2002; Sriprasert and Dawood 2003). According to Sauer the regarded outfitting constraints were structured into hard and soft constraints (Sauer 1998). An overview of the defined outfitting constraints is given in table 1. A detailed representation of the constraint approach and the specified outfitting constraint types is shown in Beißert et al. 2007; König et al. 2007.

TAB. 1 Outfitting Constraints

Hard Constraints		Soft Constraints	
Technological dependencies	Stringent rules of execution processes, for example, definite sequences between construction tasks or work steps	Productivity	Relation between workers' productivity and provided work space (e.g., Akinci et al. 2002a; Mallasi 2004)
Capacity	Amount and qualification of employees and equipment	Strategies	Predefined execution orders and established process sequences
Availability	Supply of material linked to the requirement of storage area		
Safety Criteria	Employees' and equipments' criteria of protection		

4. SIMULATION CONCEPT

The constraint-based concept is implemented using discrete-event simulation. That means, only points in time are inspected at which certain events occur. Typical events are, for example, a work step is completed or a material element is entering a storage area. Upon occurring events it has to be investigated, whether new events have to be generated or time points of existing events have to be moved. Thus, the simulation time leaps from event to event.

This presented discrete-event simulation approach focuses on simulating single work steps. Each outfitting task, for instance, erecting a partition wall, is decomposed into single work steps, such as plastering or installing a stub. Each work step has a current state – "not started", "started" and "finished" – and requires a determined execution time. If a new event occurs, first all not started work steps have to be checked up on fulfillment of their hard constraints. A work step can be executed, if its associated hard constraints are fulfilled. Further, all executable work steps are controlled on fulfillment of their soft constraints. Hereunto applying work steps are ordered by their percentage of soft constraints' fulfillment. Only the first of the listed executable work step can be started. If several work steps fulfill their soft constraints in equal measure one of them is chosen randomly.

Each started work step presupposes certain material, resources and working space. The required objects have to be locked during its execution. That means material, resources, equipment and working spaces cannot be used by other work steps. After locking all required objects the work step state changes from "not started" to "started". Subsequently, the set of "not started" work steps is checked up again on fulfillment of their hard and soft constraints by going to step one until no more work steps can be started at the current time.

The simulation time is continuously checked during a simulation run. Every started work step exhibits a determined execution time. Thus, if the remaining time is expired, the work step is marked as finished. Its locked resources, equipments and working spaces will be unlocked and can be used by other work steps. Both simulation steps will be repeated until all work steps are finished. Events such as starting and finishing of work steps as well as locking and unlocking of material, resources, equipment and working space are recorded. Thus, the simulation run can be investigated afterwards. One simulation run calculates exactly one practical execution schedule, one material flow as well as the utilization of employees and equipment. The overall aim is to simulate different practicable solutions that can be visualized and analyzed regarding principal guidelines such as time, cost and quality.

5. IMPLEMENTATION

The presented constraint-based simulation approach is implemented by extending the Simulation Toolkit Shipbuilding (STS) of the SimCoMar community. The STS uses the discrete-event simulation program Plant Simulation provided by UGS Tecnomatix (http://www.ugs.com/products/tecnomatix/). This popular simulation framework already enables modeling, simulating and visualizing of production systems and processes. To generate constraint-based simulation models for outfitting planning, as shown in figure 1, the following simulation components are extended or implemented.

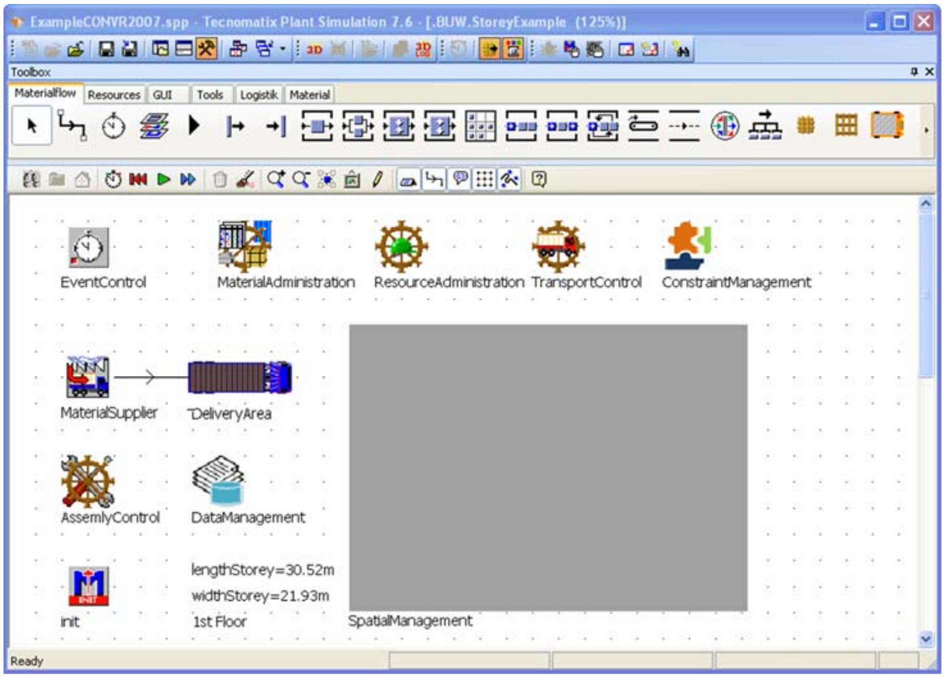

FIG. 1: Implementation of a constraint-based Simulation Model using Tecnomatix Plant Simulation.

5.1 Material Administration

The material administration manages the material elements of all outfitting work steps. Based on a material sheet all material elements are generated by a special supplier component implemented in the STS. The material sheet contains information about physical dimensions of material, its needed storage area and transportation supporting equipment as well as materials' delivery dates. Each material element such as a panel, plate or plasterboard is registered at the material administration component by committing its current storage position. Thus, if a work step requests a certain material element, the material administration reports whether the requested element is available or not. Its current storage position is submitted and following the beginning of needed transport processes can be marked.

5.2 Resource Administration

The resource administration component was implemented to manage, assign and release the required resources of work steps. Therefore, the administration records each access to an employee or work equipment. Resources are, as per description, employees and work equipment. Currently, only employees and their technical skills are considered. Movable equipment such as welding apparatus or erecting scaffoldings to broaden models' realistic will be implemented next. The current assignment of resources of a started work step is recorded by the administration component. Thus, utilization diagrams can be generated, visualized and evaluated.

5.3 Spatial Management

An important objective of this simulation approach is the consideration of required work and storage spaces as well as transport ways. Therefore, a special cell-based spatial component is developing to manage the available, required and locked spaces on production sites. The concept is to divide each production site into levels. An expedient partition, for example, is to describe each building storey as a production level. At present, all production levels have to be defined manually. A level is modeled by a regular rectangular grid. Each cell of the grid takes a certain state – "unlocked" or "locked" – and special attributes such as "generally locked for storage" or "generally locked for transportation" (e.g. figure 2).

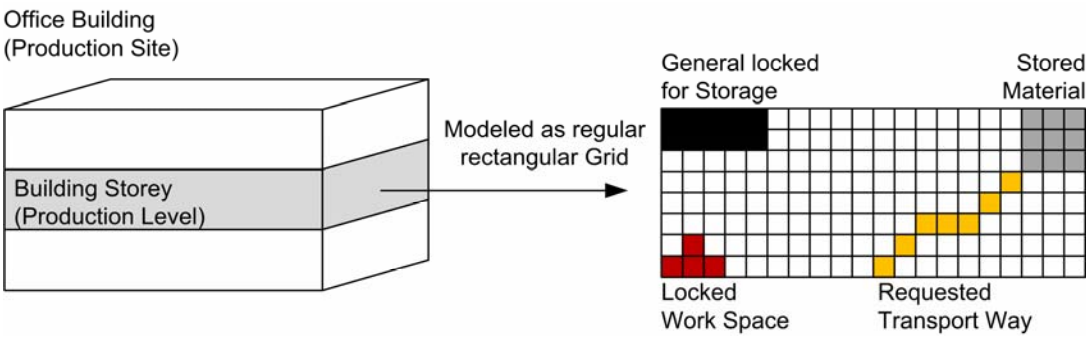

FIG. 2: Production Site, Production Levels, cell-based spatial Component and locked Cells.

5.4 Transport Control

The transport control component of the STS manages the transport requests and transport equipments. Typical equipments are cranes or lift trucks. If a transport job is requested, the transport control component provides a method to assign appropriate transport equipment and to find possible transport ways. Possible transport ways are detected by using graph search algorithms (e.g., Dechter and Pearl 1985, Cormen et al. 2001). Whenever a transport job is requested, the transport component locks the required equipment and the calculated transport way. Hence, before a work step can be started the corresponding transport processes of the requested material and requested equipment have to be finished.

5.5 Constraint Management

The constraint management component stores all outfitting work steps and their associated hard and soft constraints. Work steps as well as the technological dependency, capacity, availability and strategy constraints are generated by using predefined templates. For instance, a typical template of a technological dependency in assembling drywalls is: U-channels on floor and ceiling have to be fixed, before C-stubs can be installed. Presently, for several execution options of assembling drywalls several templates are specified manually. Advantageously, the defined templates can be used in other models as well.

If a new simulation event occurs, all currently not started work steps are checked up on fulfillment of their constraints. First the hard constraints are controlled on fulfillment, in result a list of next executable work steps is generated. Second the listed steps are checked up on fulfillment of their soft constraints and ordered by their degree of performance. The first of the listed work steps is chosen to be executed next. Following, the first work step is submitted to the assembly control component. According to the specified constraint types, such as technological dependency or capacity, different framework components are used to check the constraints' fulfillment. For example, the fulfillment of availability constraints only can be checked by using the material administration.

5.6 Assembly Control

Starting and stopping of work steps is an essential function of the assembly control component. Primarily, after receiving a next executable work step from the constraint management component the assembly control checks the current storage position of presupposed material and equipment. If the current storage position of work steps needed material or equipment is differing from the working place, appropriate transport jobs have to be started by the transport control component. Anymore, the required material is marked as used. The associated executing resources as well as the work area are locked. Work steps' start is suspended until all material elements and needed equipment were transported to the working place. Finishing transport jobs and work steps, respectively, generate new simulation events. If an event occurs, the component controls which resources and spaces have to be unlocked. Thus, unlocked objects can be used by other work steps. Further the assembly control requests a new executable work step. The relations between the assembly control component and the other simulation components such as constraint management and transport control are shown in figure 3.

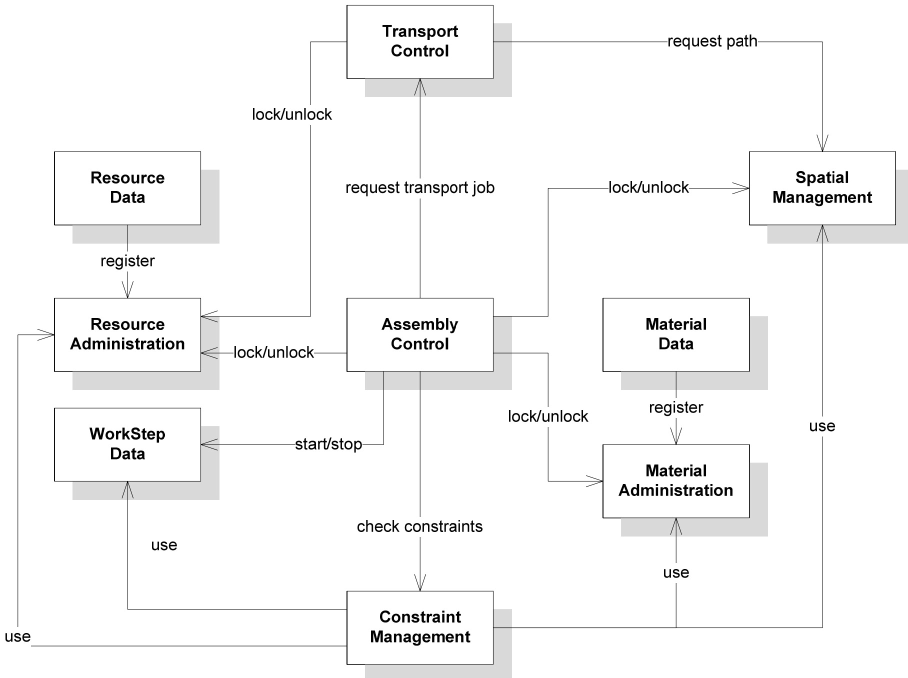

FIG. 3: Relation Concept between Assembly Control and other Simulation Components.

5.7 Visualization and animation

The 2D visualization and animation concept of the used simulation application is based on icons for static and moveable objects as well as animation points. Every simulation object has a special icon representation. During a simulation run objects can change their positions, for example, employees are working at certain places or material elements are assembled at certain positions. To assign a new position to an object its associated animation point has to be moved. This only can be done, during events' processing. Appropriate animation polygons can be specified to implement continuous transport animations between two successive events. In addition, a simplified 3D visualization is possible. Each 2D icon can be linked to 3D visualization objects described in VRML. For the 3D animation the same animation points are used. In figure 4 a transport of an outfitting material by a tower crane to a certain storage location is shown (a) as well as the work positions of workers during drywall assembling (b).

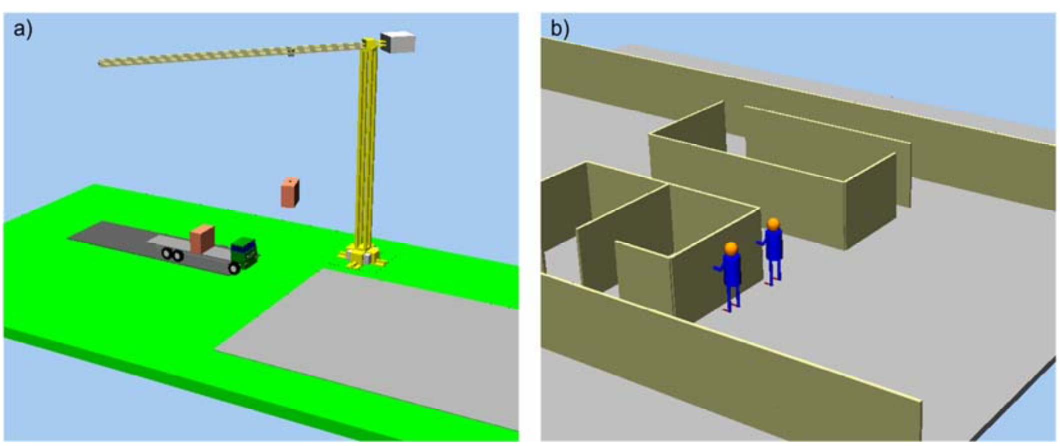

FIG. 4: 3D Visualization of Outfitting Material Transport a) and Drywall Assembling b)

The increasingly use of visualization and animation during the planning of execution processes assists to improve the know-how exchange within a company and between partners, respectively. Following, this is also a convincing argument to focus on using visualization in outfitting planning. The interdependencies between different assembly sections and their resulting interferences are comprehensible shown via visualization and animation. Therefore, a detailed visualization and animation of execution sequences is a valuable communication basis for planners and executers. Especially, to see construction processes from a different angle may help to improve projected execution strategies. Furthermore, an objective evaluation of different execution circumstances enhances its usefulness in praxis. For example, on the management level using visualization to depict problems might be helpful to argue for exceptional facilities and extraordinary expenses.

5.8 Data Management

A practicable simulation model is heavily dependent on the input data quality. Though, the definition of input data on an adequate detailed level is very time-consuming. Work steps and their execution times have to be specified as well as their associated work spaces relative to production levels. Furthermore, production levels with spatial restrictions, material sheets and detailed assembling positions have to be modeled. Some of these input data can be transferred directly or simply adapted from CAD-systems; others have to be defined manually.

Currently, the major problem consists in: data of available CAD-systems often do not contain the required details for simulation models. Typically, in building industry production objects such as drywalls are specified by a boundary representation model. But for a detailed assembly simulation the construction details such as channel, stud or plasterboard objects are needed. A practical solution is to implement special purpose data generators. Such data generators define all required input data of a certain outfitting process. Within this research activity a first prototype of a drywall generator is implemented. Depending on the length of drywalls and the desired distance between C-studs the prototype generates all work steps, material sheets and assembly positions.

6. EXAMPLE: DRYWALL ASSEMBLING

Currently, within the presented research activity drywall assembling processes are modeled by using the developed simulation framework. The modeled drywall processes consist in different work steps types for assembling U-channels and C-studs, filling loft insulating material and fixing plasterboards (figure 5). Each drywall and drywall section, respectively, is build up by these defined work step types. Each work step, for example, assembling U-channel requires certain material elements, a work positions and resources. All these requirements are specified as work steps' associated constraints by using the implemented drywall data generator. Within this generator all technological dependencies are defined generally as a drywall template. Sticking an intumescent strip and a U-channel together, for example, needs drywall calibration as finishing work step. Within the resource administration component only workers and their skills are considered at the moment.

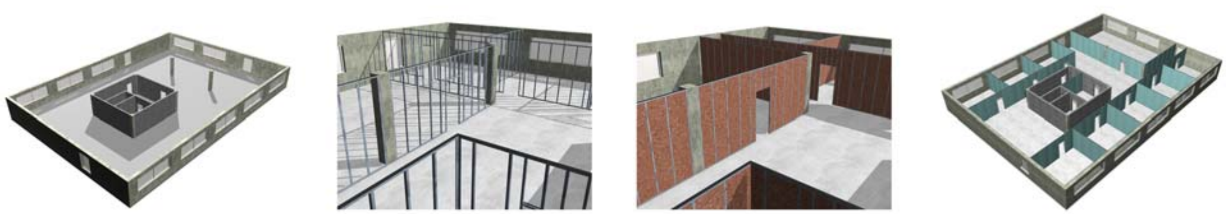

FIG. 5: Building Storey with Drywalls

The scenario of an outfitting process can be visualized within a simulation run. Transport jobs as well as positions of assembled material, resources and work spaces are animated for each simulation time step. Work spaces of employees and their overlapping are depicted as shown in figure 6. An overlapping of work areas results from the soft constraint productivity that considers the coherence between workers' productivity and provided work space.

Each simulation run can be repeated by using identical simulation input parameters. Furthermore, the processing of a simulation run can be stopped to investigate the current simulation state. Advantageously, the current visualization can be discussed and possible improvements for outfitting execution can be tested by adapting or adding outfitting hard and soft constraints. The generated execution times for each simulated work step can be exported as XML. The XML data contain all starting and finishing time as well as the looked resources. Afterwards, the data can be imported by using Microsoft Project to represent the schedule, for example, as a Gantt chart.

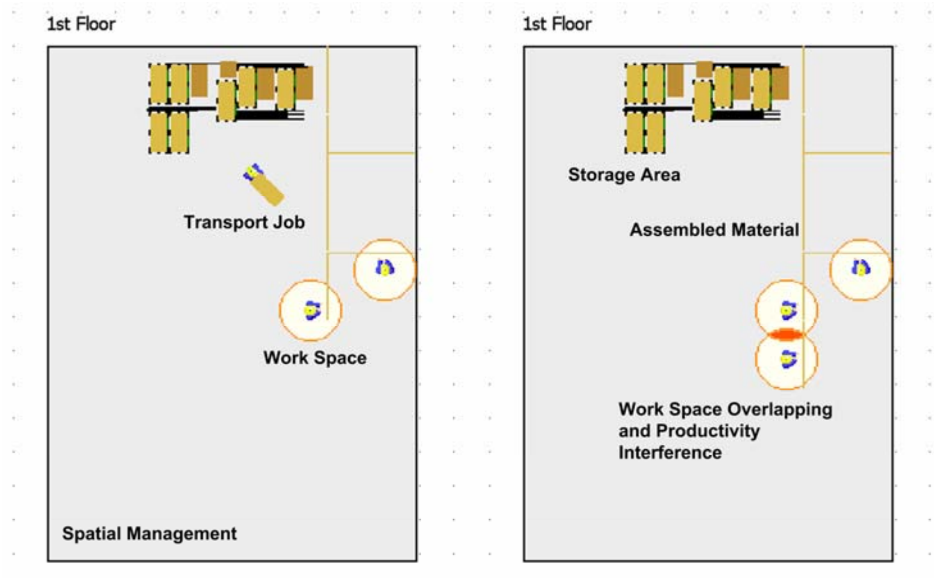

FIG. 6: 2D Visualization of two Simulation Steps.

7. CONCLUSION AND OUTLOOK

Definitely, it is very time-consuming to generate and analyze practicable outfitting schedules manually where equipment and employees are sufficiently utilized. This paper introduces visual simulation as an appropriate instrument to support the planning process. A constraint-based simulation framework is developing to assist the outfitting planning. In result, different practicable schedules for execution can be generated. The simulated schedules can be visualized and evaluated regarding worker's efficiency, utilization of space as well as process costs, afterwards.

Future works concentrate on defining further outfitting constraints. Appropriate methods especially to describe soft constraints have to be researched. Definitions of the highlighted constraints safety criteria, productivity and strategies are still in progress. Some of the considered soft constraints like strategies can be violated infinite. Others like capacity or productivity constraints affect work steps' execution times. Currently, the ability of several methods to describe various constraint types like fuzzy, weighted or semiring-based constraints is investigating.

In addition, simulation components are projected, for example, an extended storage area control component. The projected component estimates production sites regarding outfitting execution in order to find suitable storage areas. Adequate storage areas are important to guarantee an undisturbed execution flow. The investigation and implementation of suitable constraint visualizations especially the fulfillment of soft constraints is another main part of the presented research activity. Currently, only a rudimental circular 2D visualization of work spaces and safety areas is possible. In the next step, this soft constraint presentation will be detailed and visualized in 3D. Furthermore, the fulfillment of strategy constraints will be recorded and adequate illustrated to support the decision for a certain outfitting strategy.

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