CONSTRAINT-BASED SIMULATION OF OUTFITTING PROCESSES IN SHIPBUILDING AND CIVIL ENGINEERING

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Abstract

Currently, in shipbuilding as well as in civil engineering outfitting planning is not sufficiently investigated. A multitude of requirements such as technological dependencies, resource and work space assignment have to be considered. Outfitting processes in both domains are distinguished by interferences, disturbances, great interdependencies and different surrounding area requirements. In consequence, on production site an extensive coordination effort is necessary to handle these problems. A realistic planning and detailed analysis will help to reduce the on-site coordination effort and not to overrun the projected costs and time. Appropriate tools have to be implemented to support planners and improve the outfitting planning. Within the cooperation SIMoFIT (Simulation of Outfitting Processes in Shipbuilding and Civil Engineering) a discrete-event simulation framework is developing to support outfitting planning in shipbuilding and civil engineering. This paper focuses on using a constraint-based simulation approach to detail outfitting tasks and their corresponding restrictions and requirements. Typical outfitting restrictions and requirements are specified as hard and soft constraints. This approach guarantees a high flexibility in modeling processes. Further, outfitting processes can be specified more realistically. Thus, different practical schedules can be simulated and evaluated in terms of work and material flow organization, utilization of space and worker's efficiency as well as process costs. The framework was lab tested by both cooperation partners and proves its suitability to support the outfitting planning process in shipbuilding and civil engineering.

Keywords: constraint satisfaction, discrete-event simulation, outfitting processes, shipbuilding and civil engineering

Presenting Author's biography

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1 Introduction

Successful project realization is linked to quality, time and cost criteria. Often in project planning process it is not possible to find optimum solutions to satisfy all three criteria in equal measure. For example, an exceeding quality leads to higher costs as normal. Thus, thorough and exact planning is necessary to realize ship and building projects successfully.

Currently, in shipbuilding as well as in civil engineering the planning of outfitting processes is not sufficiently considered. 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 (2005) while the main construction trade represents only about 30% [1]. Outfitting processes in both domains are distinguished by interferences, disturbances, great interdependencies and different surrounding area requirements. In consequence, on production site an extensive coordination effort is necessary to handle these problems. A realistic planning and detailed analysis will help to reduce the on-site coordination effort. The question is: what can be done to improve the planning of outfitting process? Appropriate tools have to be found.

A multitude of requirements such as local, technical and project-specific have to be considered in outfitting planning. In addition, the assignments of employees and equipment have to be regarded as well. Consideration of all these different restrictions and requirements result in a wide choice of practicable outfitting schedules. Often these different solutions are not sufficiently analyzed. However, an in-depth investigation of the various solutions is very useful not to overrun the principal guidelines regarding costs and time.

In manufacturing industry such as steel prefabrication and ship assembling simulations are used successfully to improve production processes. These processes and hence their related simulation models are characterized by static layouts, well-known and limited process variations. Due to the fact that outfitting processes are more complex and dynamic, a flexible simulation framework has to be developed.

This paper highlights on a constraint-based simulation framework to model outfitting processes in shipbuilding and building engineering. The constraint-based approach is proved to be appropriate to define outfitting tasks and their corresponding restrictions and requirements. Using this constraint-based simulation approach different practical outfitting schedules can be generated and evaluated in terms of work and material flow organization, utilization of space and worker's efficiency as well as process costs.

Within the cooperation SIMoFIT (Simulation of Outfitting Processes in Shipbuilding and Civil Engineering) a discrete-event simulation framework is developing to support outfitting planning. SIMoFIT was established between Bauhaus-University Weimar and Flensburger Shipyard [2]. Outfitting processes in shipbuilding and building industry bear a high resemblance to each other. The same circumstances have to be considered such as dependencies between outfitting tasks, availability of resources and required work spaces as well as changing transport ways and delivery dates. In addition the planners have to answer the same questions: find a practicable schedule with sufficiently utilized equipment and employees that satisfies principal guidelines.

Therefore, a modular simulation toolkit is used and adapted for outfitting processes. Flensburgers and their partners of the SimCoMar (Simulation Cooperation in the Maritime Industries) community are developing the STS (Simulation Toolkit Shipbuilding) [3], [4]. The STS contains several simulation components, for example, to model steel-prefabrication lines as well as material and assembling control components. These adjustable components can be combined to a complete simulation model. Within the SIMoFIT cooperation the existing simulation experience of Flensburgers and the construction know-how of Bauhaus-University Weimar are combined to define and to develop further components to model outfitting processes [5].

2 Constraint Satisfaction

Constraint satisfaction is a powerful paradigm for modeling combinatorial search problems [6]. Conditions or restrictions of variables are dedicated as their constraints. The problem consists in finding a value combination for all variables, where all constraints are fulfilled [7], [8]. In this case, simulation objects such as outfitting tasks are described by a set of variables. Relations between these variables like execution sequences or resource requirements are described by constraints. Consequently, the constraint-based approach guarantees a high flexibility of modeling outfitting processes, if additions or new prerequisites in processing occur. The model can be easily adapted by simply adding or removing certain constraints. The more constraints are specified, the more the solution space is restricted (e.g., [9], [10]) and, consequently, the more the multitude of possible schedules is deducted.

Constraint satisfaction can be used effectively to model many forms of reasoning (e.g. temporal reasoning) and applied to many problem domains (e.g. scheduling) [6], [11]. The classifying of constraints into hard and soft constraints adds to models' realistic [12]. Hard constraints define stringent conditions in construction processes. They must be fulfilled before a work can be started. Essential technological dependencies and needed resource capacities to execute a work are defined as hard constraint. Usually, there are many requirements and preferences like functional or appropriate dependencies in outfitting execution processes that have to be considered in the planning process. As they don't have to be fulfilled completely they can be described by soft constraints (e.g. [9], [13]). Consequently, the soft constraints can be violated to find possible variable configurations [14]. Extending the model on soft constraints allows for discrimination among all the solutions which satisfy the hard constraints [6].

Looking for solutions that fulfill all hard constraints and violate the soft constraints as little as possible is known as Constraints Satisfaction Problems (CSP). In this case, Monte-Carlo simulation is used to solve the CSP: one simulation run calculates one possible value combination [7]. Allowing for search spaces' dimension an adequate amount of simulation runs has to be performed in order to provide a significant set of solutions for the following investigation.

Looking for optimal solutions is known as Constraint Optimization Problems (COP). Usually, the model allows only "hard" Boolean-valued constraints but adds a cost function over the variables that must be minimized. A constraint solver is used to find an optimal assignment to all problem variables that satisfies the constraints [6]. Using a constraint solver such as a backtracking search algorithm to find optimal solutions is very time-consuming. In construction practice, an optimal solution often is not necessary. In fact, it is adequate to search or to compute a few practicable schedules, reminding that project constraints are changing rapidly and often defined construction schedules are valid only a couple of days. Thus, it is more important to generate alternative practicable schedules fast to adjust occurring disturbances than to optimize an implausible execution flow.

The simulation runs can be analyzed afterwards with regard to different criteria. Preferred solutions can be visualized based on the simulation documentation. Visualization increases the possibility to detect potential improvements of the execution. Further, current production states can be easily integrated into the model. Based on the current execution state some prognoses can be drawn.

3 Outfitting Task Constraints

The constraint-based approach is used to describe the outfitting tasks. Attributes of simulation objects and their relations are described by hard and soft constraints. An overview of the defined outfitting constraints is given in table 1.

Table 1 Outfitting Process Constraints

Hard Constraints	
Technological dependencies	Constructional and formal aspects
Capacity	Amount and qualification of employees and equipment
Availability	Supply of material linked to the requirement of storage area
Safety Criteria	Employees' and equipments' protection
Soft Constraints	
Productivity	Relation between workers' productivity and provided working space (e.g., [15], [16])
Strategies	Predefined execution orders and established process sequences

Currently, only physical constraints and some enabler constraints emphasized by Sriprasert and Dawood [17], [18] are considered in the presented approach.

3.1 Technological dependencies

Technological dependencies define stringent rules for execution process, for example, definite sequences between construction tasks or work steps. Thus, technological dependencies are specified as hard constraints. For instance, the technological constraint "work step A before work step B" means that work step A has to be completed before work step B can be started. Also practical aspects can be described by technological dependency constraints. For example, it is a good practice to achieve dimensional accuracy of a brick wall to first lay the cornerstones before building the intermediate wall sections.

3.2 Capacity

The capacity constraint considers resource boundaries like a limited amount of serviceable employees and equipment. Their quantity is finite. If the capacity is exhausted, no more work step can be started. Furthermore, the quality and quantity of resources can be determined. For example different skilled employees can be specified, if execution of different work steps requires various skilled employees.

3.3 Availability

Availability represents material flows. For example limited supply of material can be considered as well as the herewith linked requirement of storage area. Following, availability is also defined as hard constraint. The unavailability of material corresponds to the possibility of supply bottlenecks in production. Further, if suitable storage areas cannot be offered, more attention has to be paid to supply of material and equipments' disposability.

3.4 Safety Criteria

Safety criteria are protection criteria. Durations or distances to protect employees and to assure the right exposure to the equipment are specified. Safety criteria are specifying as hard constraints. Thus, 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., [15], [18]).

3.5 Productivity

The productivity constraint is a functional bench mark. It will be defined as a soft constraint. The complex coherence between free working space and productivity of employees needs to be considered. For example, an employee only achieves 100 percent productivity, if required work space is provided. Productiveness will rapidly fall, if this operating range cannot be guaranteed [13], [16].

3.6 Strategies

Strategies are proven formal aspects and are defined as soft constraints. Predefined execution orders and established process sequences can be simulated and analyzed. They can extend the technological dependencies but are not binding. For example, execution according to the length of walls or according to the longest distance between the working groups can be modeled to assist the user on deciding which assembling order is most useful (figure 1).

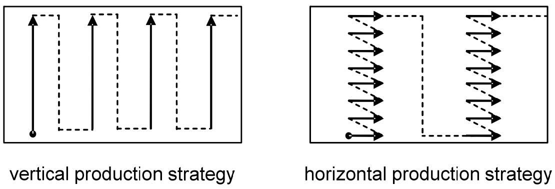

Figure 1 Examples of working strategies

4 Simulation Concept

The constraint-based approach is used within a discrete-event simulation concept. That means, only points in time are inspected at which events occur. Typical events are, for example, a work step is completed or a material element is entering a storage area. After an event occurs, it has to be investigated, if new time points have to be generated or existing time points have to be moved. Thus, the simulation time leaps from event to event.

This presented discrete simulation approach focuses on simulating single work steps. Each task, e.g. erecting a partition wall, is decomposed into work steps such as plastering or installing a stub. A work step has a current state – "not started", "started" and "finished" – and requires a certain execution time. The execution of a work step is bound to some general restrictions:

- Each 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
- Each work step will be executed without a change of the working position of employees or equipments

If a new event occurs, all not started work steps have to be checked. A work step can be executed, if all associated hard constraints are fulfilled. Further, for all executable work steps the fulfillment of soft constraints has to be checked up. The executable work steps are ordered by their percentage of soft constraints' fulfillment. Only the first in the list of executable work steps 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 material, resources and spaces the work step state changes from "not started" to "started". Subsequently, all "not started" work steps have to be 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 (figure 2).

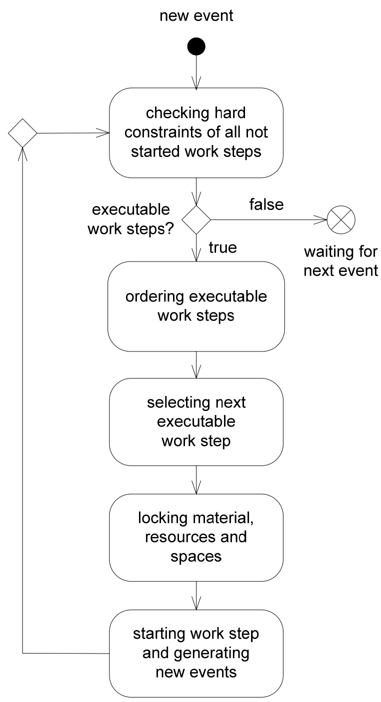

Figure 2 UML activity diagram for starting a new work step

The simulation time is continuously checked during the simulation run. Every started work step exhibits a determined execution time. 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.

The simulation 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 one practical execution schedule, one material flow as well as utilization of employees and equipment. The quantifying of simulated solutions is not intended by the simulation itself. The overall goal is to simulate different practicable solutions, which can be 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 [20]. This simulation framework enables modeling, simulating and visualizing of production systems and processes. Some important features are [20]:

- object-oriented, hierarchical models of logistic and production processes
- graphs and charts for analysis of throughput, resources and bottlenecks
- comprehensive analysis tools, including automatic bottleneck analyzer, sankey diagrams and Gantt charts
- 3D online visualization and animation
- open system architecture supporting multiple interfaces and integration capacities (CAD, Oracle, SQL, XML, etc.)

To generate project-specific constraint-based simulation models for outfitting processes in shipbuilding and civil engineering the following simulation components are extended or implemented.

5.1 Material Administration

The material administration component of the simulation model manages the material elements of all outfitting work steps. All material elements are generated by a special supplier component of the STS based on a material sheet. Every outfitting 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 and submits its current storage position.

5.2 Resource Administration

The resource administration component was implemented to manage, assign and release the required resources of work steps. Further, the administration records each access to an employee or work equipment. Resources are, as per description, employees or work equipment. Currently, only employees and their technical skills are considered. Movable equipment such as welding apparatus or erecting scaffoldings will be implemented next.

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 available, required and locked spaces on production sites. Each production site, such as buildings or ships, is divided into levels. A production level describes, for example, building storeys or fire zones of ships. Currently, all production levels have to be defined manually. Each level is modelled by a regular rectangular grid (e.g. [21]). The cells of the grid have a certain state – “unlocked” or “locked” – and special attributes such as “generally locked for storage” or “generally locked for transportation” (figure 3).

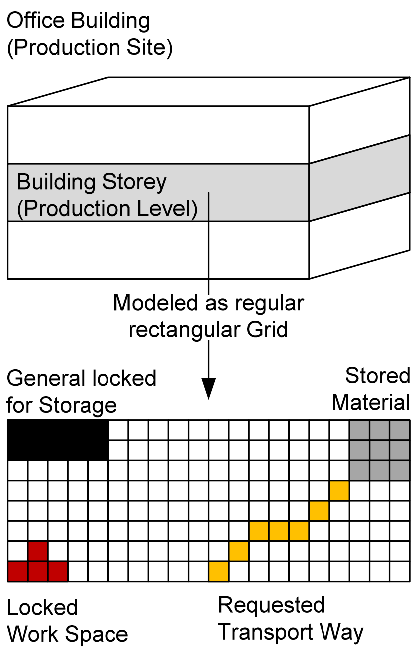

Figure 3 Production site, production levels, cell-based spatial component and locked cells

5.4 Transport Control

The transport control component of the STS manages transport equipments and transport requests. Typical equipments are cranes or lift trucks. If a transport job is requested, the transport control component provides a method to find and lock required transport equipment and possible transport ways considering current available spaces. Possible transport ways are detected by using graph search algorithms. Currently, an A* search algorithm (e.g. [22]) or a Dijkstra algorithm (e.g. [23]) can be used to calculate shortest paths. Before a work step can be started, corresponding transport processes of requested material or equipment have to be initiated.

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 example, a typical template for technological dependency in drywall assembling is: U-channels on floor and ceiling have to be fixed, before C-stubs can be installed. These templates are specified manually.

If a new simulation event occurs, all currently not started work steps have to be checked up on fulfillment of their constraints. Subsequently, a list of next executable work steps is generated, ordered by the percentage of their soft constraints fulfillment. Now, the first work step in the list is submitted to the assembly control component.

According to the specified constraint types different framework components are used. For example, the fulfillment of availability constraints only can be checked by using the material administration. The relations between different constraint types and the implemented components are shown in figure 4.

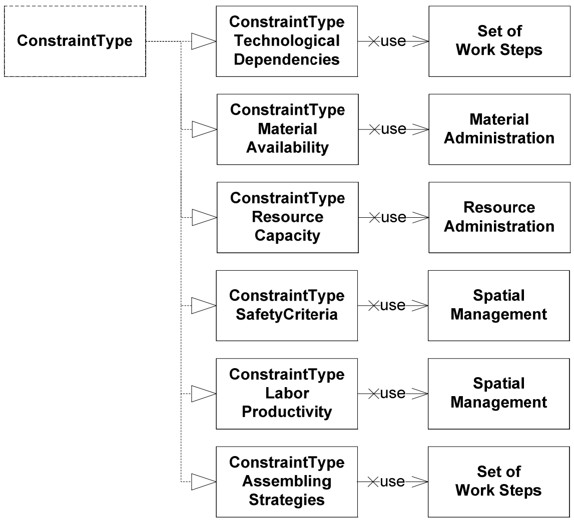

Figure 4 Relations between constraint types and simulation components

5.6 Assembly Control

Starting and stopping of work steps is the essential function of the assembly control component. Primarily, after receiving the next executable work step from the constraint management component the assembling control checks the current storage position of the presupposed material and equipment. If the material or equipment is not located nearby the associated work area, appropriate transport jobs have to be assigned. The material is marked as used. The resources as well as the work area are locked. Work steps' start is suspended until all material and equipment were transported. Finishing transport jobs and work steps, respectively, generate new simulation events. If a new event occurs, the assembling component controls which resources and spaces have to be unlocked and further requests a new executable work step.

5.7 Data Management

For building up a practicable simulation model the definition of input data is very time-consuming. The work steps and their execution times have to be specified as well as work spaces relative to production areas, site layout with spatial restrictions, material sheets and detailed assembling positions. Some input data can be transferred directly or simply adapted from CAD-systems; other data 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 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, all work steps, material sheets and assembly positions can be generated. Currently, Flensburger Shipyard is developing an appropriate data structure to manage simulation input data in shipbuilding.

5.8 Visualization and Animation

Know-how exchange assistance within a company and between partners respectively is a convincing argument for using visualisation in outfitting planning. A detailed visualisation 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, using visualisation to depict problems might be helpful to argue for exceptional facilities and extraordinary expenses.

The 2D visualization and animation concept of the used simulation application is based on icons for static and moveable object 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. To implement continuous transport animations between two successive events appropriate animation polygons can be specified. In addition, a simplified 3D visualization also is possible. Each 2D icon can be linked to some 3D visualization objects implemented as cuboids. For the 3D animation the same animation points are used.

6 Examples

The research approach and the implemented simulation components are validated by the cooperating partners in both industrial sectors.

6.1 Example 1: Assembling drywalls

The Bauhaus-University Weimar investigates drywall construction processes in office buildings using the developed framework. In this example thirteen drywalls have to be installed (figure 5). The material sheet of a drywall includes the number of intumescent strip rolls, U-channels, C-studs, plasterboards, loft insulating rolls and plaster bags.

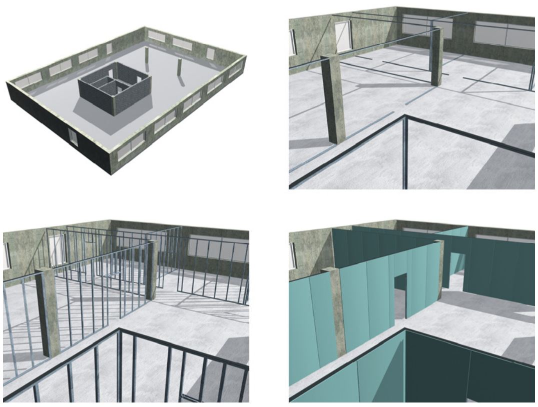

Figure 5 Building storey with drywalls

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 and 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, single 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, amongst others. The execution time for each work step is calculated based on well-known working time standard values (e.g., [24]). For example, generally a worker needs about 0.1 h/m² to fill insulation material.

Drywall Constraints

Constraints for assembling a drywall have to be specified in the next definition step. Within a drywall template technological dependencies are defined generally, as shown in figure 6. Sticking an intumescent strip and a U-channel together, for example, needs drywall calibration as finishing work step.

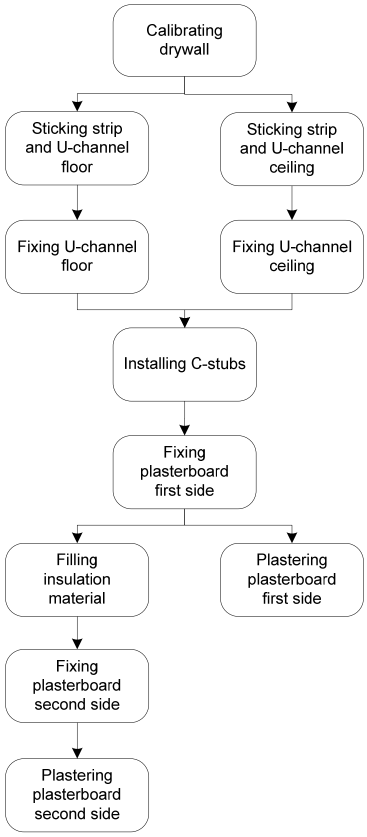

Figure 6 General technological dependencies between drywall work step types

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 are needed. For each drywall work step type the corresponding availability and capacity constraints have to be specified.

Resource definition

Resources have to be defined manually for each simulation experiment. In the presented example only technical skills and workers are specified. To execute drywall work steps the following skills are specified: calibrating, drywall constructing, filling insulation material and plastering. Based on these skills different types of employees are defined: foreman (all skills), worker (all skills excluded calibrating) and laborer (filling insulation material and plastering skill).

Strategy constraints

Within this example two different global execution strategies are specified as soft constraints manually. The first global strategy combines certain drywalls execution groups ordered by priority. Drywalls within a group are assembled randomly. The second strategy sorts all drywalls relative to their wall length in descending order.

Simulation and Evaluation

Three employee variations were simulated for each global execution strategy. The different employee variations of foremen, workers and laborers are shown in table 2.

Table 2 Employee variations

Employees → / Variation ↓	Number of foremen	Number of workers	Number of laborers
Variation 1	1	1	1
Variation 2	1	2	1
Variation 3	1	2	2

Different simulation runs were performed for each employee variation and global execution strategy. Within these simulation runs the identical drywall work steps, hard constraints and material sheets are used. For each simulation run the work step schedule and the workload of employees are recorded to evaluate them afterwards. Furthermore, every simulation run was animated using the discrete-event simulation framework and can be used for visual control of the execution progress. Some parts of the simulation model and a snapshot of a simulation step are shown in figure 7.

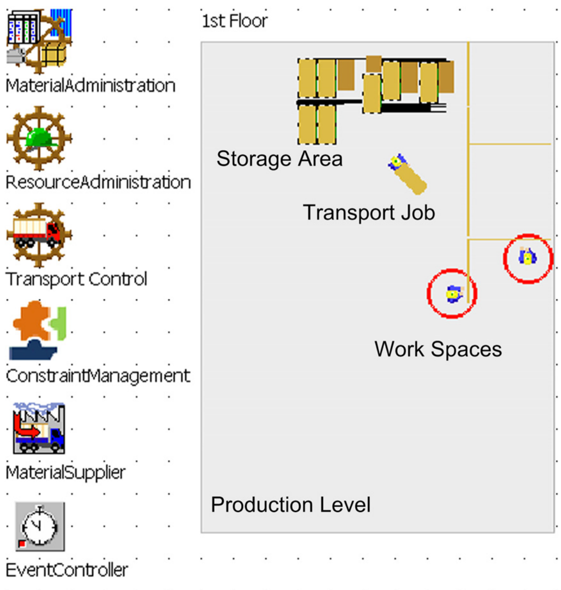

Figure 7 Snapshot of a simulation step

After running all experiments the minimal working time and labor costs are evaluated as shown in table 3. In this scenario, the following wages per hour are assumed: foreman 28 EURO/h, worker 21 EURO/h and laborer 11 EURO/h. The shortest working time is given for the assignment of one foreman, two workers and two laborers by using the drywall group strategy (i.e. experiment 3).

Table 3 Working time and labor costs results of drywall execution experiments

Results →	Min. time [h]	Costs [€]
Drywall group strategy		
Experiment 1 (Variation 1)	152	9120
Experiment 2 (Variation 2)	120	9720
Experiment 3 (Variation 3)	112	10304
Drywall length strategy		
Experiment 4 (Variation 1)	144	8640
Experiment 5 (Variation 2)	136	11016
Experiment 6 (Variation 3)	128	11776

To find a suitable group combination, not only working times and costs are important but also workloads have to be regarded. The workloads of the defined employees are shown in table 4.

Table 4: Workload results of all experiments

Workloads [%] →	Foreman	Workers		Laborers	
Drywall group strategy					
Experiment 1	73	95		24	
Experiment 2	46	94	78	24	
Experiment 3	52	98	82	26	12
Drywall length strategy					
Experiment 4	79	90		34	
Experiment 5	42	73	16	16	
Experiment 6	44	78	16	17	4

The results of this simple drywall example illustrate that working times, labor costs and utilization vary

ISBN 978-3-901608-32-2

according to the number of appointed employees and used strategy. Now, considering project-specific time and costs restrictions the planner can choose one of these employee and strategy combinations or define new constraints and resources to find other solutions with more steady work flows or more efficient employee utilizations. Currently, this constraint-based simulation approach cannot guarantee to find optimum solutions. However, a multitude of practical schedules can be generated to find an optimized solution manually.

6.2 Example 2: Ferry outfitting

Currently Flensburger Shipyard is building so-called RoPax ferries for cars, trucks and passengers. More than ten years ago the production of deckhouses was outsourced. Therefore, experience to control outfitting processes in passenger or crew areas are marginal. Thus, there is an increasing requirement for a tool to evaluate these complex production flows.

Simulation has been established at Flensburger as a practicable tool for production development and production planning in steel production, already. Several simulation-based applications support the daily work of planners and foremen. However, outfitting processes, particularly in passenger areas, have not been analyzed sufficiently yet. A prototypic simulation model of a passenger cabin area, developed some years ago, turned out to be not sustainable to model outfitting tasks. Though, it provided interesting cognitions for the further research.

Flensburger Shipyard uses the adjustable components developing in the SIMoFIT cooperation to build-up simulation models of ferry outfitting. One fire zone of a ferry that is erected currently on the slipway is specified as a prototype simulation model. Fire zones are compartments of a ship in a passenger deck separated by fire protection doors and walls. A fire zone contains several rooms and is also planning unit for outfitting activities. In the presented example the fire zone contains a snack bar, lounge areas and restrooms. Thus, many different aspects of outfitting and furnishing have to be considered. Logistic processes were not taken into account because they were analyzed in an earlier simulation project, intensively.

The product data for the simulation model was generated from drawings and part lists. In future research activities will focus on suitable tools in order to provide the required data and the as-is state in time to reduce the data mining work to a minimum.

In the first step three different types of outfitting processes with different requirements are analyzed: drywall, ground floor and ceiling construction. Processes and outfitting sequences were derived from manual scheduled activities. Sequences were transformed into technological dependency constraints associated to the outfitting work steps. Thus, a practicable execution order within the fire zone rooms is guaranteed (figure 8).

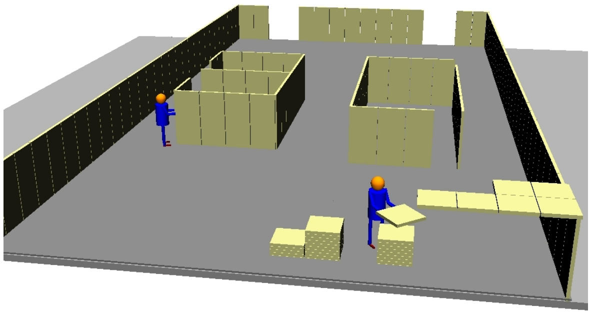

Figure 8 Visualization of the fire zone

Global constraints between fire zones consider the dependencies between neighboring compartments. For example, ceiling outfitting in a fire zone cannot start before floor straightening work in the zone above is not completed. Another example, floor pavement only can be floated after ships' launching due to the inclination angle of the slipway. These global constraints are defined generically as dependencies between work steps of assembly tasks in different fire zones.

By using simulation models different assembling strategies can be analyzed regarding the required execution time, workers efficiency and space utilization. In future, constraint-based outfitting simulation is planned to be used for production planning of further passenger ferry projects.

7 Conclusion

Outfitting execution processes are very complex. A multitude of requirements such as technological dependencies and safety criteria have to be considered The planners must exhibit high competence in order to take all different effects on execution into account. Definitely, it is very time-consuming to find practicable schedules manually where equipment and employees are sufficiently utilized. This paper introduces simulation as an appropriate instrument to support the planning process. Constraint-based simulation models are highlighted due to the fact that they allow modeling dynamic structures. Therefore, requirements can be easily defined or adapted by adding or removing constraints.

Currently, in order to model outfitting processes, the following constraints have to be considered: technological dependencies, capacity, availability, safety criteria, productivity and strategies.

Within the cooperation SIMoFIT a constraint-based simulation framework is developing to assist the outfitting planning. Therefore, a modular discrete-event simulation toolkit is used. In result, different practicable schedules for execution can be generated. The simulated schedules can be evaluated regarding worker's efficiency, utilization of space as well as process costs, afterwards. Lab tested outfitting applications of both partners are presented.

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 productivity constraints describe previous sections to what it is satisfied [14]. Currently, the ability of several methods to describe various constraints types like fuzzy, weighted or semiring-based constraints is investigating.

Further simulation components are projected, for example, an extended storage area control component to broaden the models' realistic behavior. 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.

8 References

[1] IBW – Deutsches Institut für Wirtschafts-forschung. Strukturdaten zur Produktion und Beschäftigung im Baugewerbe – Berechnungen für das Jahr 2005, http://www.bmvbs.de, 2006.

[2] http://www.simofit.com.

[3] http://www.simcomar.com.

[4] D. Steinhauer. Simulation in Shipbuilding – Supporting Shipyard Planning, Production Planning and Product Development. 12. ASIM Fachtagung Simulation in Produktion und Logistik - Sigrid Wenzel (Hrsg.), Society for Modeling and Simulation International and SCS Publishing House e.V., San Diego/Erlangen, pp. 1-14, 2006.

[5] U. Beißert, M. König and H.-J. Bargstädt. Constraint-Based Simulation of Outfitting Processes in Building Engineering. CIB 24th W78 Conference, Maribor, Slovenia, 2007.

[6] F. Rossi, P. van Beek and T. Walsh. Handbook of Constraint Programming, Foundations of *Artificial Intelligence*, Elsevier, Amsterdam, 2006.

[7] V. Kumar. Algorithms for Constraint Satifcation Problems: A Survey. *AI Magazine*, spring 1992, pp. 32-43, 1992.

[8] E. C. Freuder and R. Wallace. Partial constraint satisfaction. *Artificial Intelligence*, 58:21–70, 1992.

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

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

[11] J. C. Beck and M. S. Fox. A Generic Framework for Constraint-Directed Search and Scheduling, *AI Magazine*, winter 1998, pp. 103-132, 1998.

[12] J. Sauer. 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, pp. 161-168, 1998.

[13] J. C. Beck and M. S. Fox. Supply Chain Coordination via Mediated Constraint Relaxation. Proceedings of the First Canadian Workshop on Distributed Artificial Intelligence, Banff, Alberta, 1994.

[14] H. Fargier, J. Lang, R. Martin-Clouaire and T. Schiex. A constraint satisfaction framework for decision under uncertainty. Proceedings of the 11th International Conference on Uncertainty in Artificial Intelligence, Montreal, Canada, 1995.

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

[16] Z. Mallasi. Identification and Visualization of Construction Activities' Workspace Conflicts Utilizing 4D CAD/VR Tools. 1st ASCAAD International Conference e-Design in Architecture, Dhahran, Saudi Arabia, pp. 235-253, 2004.

[17] E. Sriprasert and N. Dawood. 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), 2003.

[18] E. Sriprasert and N. Dawood. 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), 2002.

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

[20] http://www.ugs.com/products/Tecnomatix.

[21] S. Wolfram. A new kind of science. Wolfram Media, Section 5: Two Dimensions and Beyond, pp. 169-221, 2002.

[22] R. Dechter and J. Pearl. Generalized best-first search strategies and the optimality of A*". *Journal of the ACM,* 32 (3), pp. 505 – 536, 1985.

[23] T. H. Cormen, C. E. Leiserson, R. L. Rivest, and C. Stein. Introduction to Algorithms, MIT Press and McGraw-Hill, Section 24.3: Dijkstra's algorithm, pp.595–601, 2001.

[24] IZB - Institut für Zeitwirtschaft und Betriebs-beratung Bau. Trockenbau-Planzeiten Wände: methodisch ermittelte Zeitwerte für die Planung, Ausführung und Entlohnung, Neu-Isenburg - Zeittechnik-Verlag, Karlsruhe, 2002.