A Multi-Layer Constraint and Decision Support System for Construction Operation

A simulation framework for the exterior construction works in high rise building

Amir Elmahdi, Hong-Ha Le, Hans-Joachim Bargstädt
Institute for Construction Engineering and Management
Bauhaus Universität Weimar, Germany
emails: amir.elmahdi@uni-weimar.de, hong-ha.le@uni-weimar.de, hans-joachim.bargstaedt@uni-weimar.de

***Abstract*—Up till now, traditional methods of planning construction projects such as 2D technologies including bar charts, network diagrams and other scheduling tools, which are typical methods for modeling the progress of a project, have been the only methods considered. These planning tools are incapable of acknowledging different aspects of construction projects, that it to say, they ignore the space requirements, in which activities are executed and the impact of weather on construction processes. This leads to drawbacks during the execution of these tasks such as work area overlapping, reduction in productivity, safety hazards, long hauling paths and poor quality of work. Therefore, the objective of this paper is to acknowledge the requirements of spatial aspects and the impact of weather, and to integrate these requirements into one simulation framework model. We propose a constraints-based simulation framework. That is to say, the simulation framework executes only tasks, which satisfy the requirement of the space availability and sensitivity towards weather conditions. The implementation of the multi-layer decision support system for construction operations was carried out in Plant Simulation environment and the Simulation Toolkit Shipbuilding (STS) Tool Box Component. This concept will assist site managers in planning and updating the near-term activities for the exterior construction work of high rise buildings. This is on-going research; therefore, other aspects such as execution strategies for different tasks will be developed in a future approach. This research contributes a new approach to integrating different construction problems in one simulation model, which have not been much considered in previous work.**

Keywords-Weather impact; spatial constraints; construction operation; plant simulation.

I. INTRODUCTION

Construction projects are subject to quite a number of influencing factors and are characterized by many unavoidable disturbances. Typical influencing factors in the construction processes are workspace overlapping, missing material and poor quality of work or delays caused by workspace congestion and/or bad weather conditions. They are difficult to predict beforehand and their impact is difficult to evaluate by using the current traditional planning tools due to their complexity [1]. Usually, project managers deal with these disturbances and uncertainties mainly as they happen, using their experiences, historical data and “gut engineering feeling”. However, the stochastic nature of construction processes, the principles superintended in the intervention of each resource as well as the respective interaction between the resources and the associated workspace requirements for the different trades cannot be managed efficiently using traditional planning tools, such as 2D technologies including bar charts, network diagrams and other scheduling tools [2]. These methods are not capable of considering the different influencing parameters of construction operations such as the attributes of component installation and their spatial information as well as the impact of weather [3]. This leads to drawbacks during the execution of these tasks such as overlapping of work areas, reduction in productivity, safety hazards, and poor quality of work. Traditional measures such as working on weekends or increasing the number of workers have been applied to overcome these disturbances. However, they are often used without detailed analysis and so they do not give the desired effect or are oversized. Therefore, project managers are in need of new and more innovative *decision support tools* that extend the use of traditional planning tools from the planning phase to assist them at the construction phase in order to deliver the end product of the project on time and on budget.

Simulation models have been used to examine the impact of possible disturbances of construction processes and to compare all possible strategies and methodologies for task execution so that project managers identify the actual encountered problems and analyze their impact [4]. Thus they can undertake appropriate measures and identify the most appropriate and cost effective solutions. However, simulation models lack the development of an integrated system, which incorporates different construction aspects such as technology, space, logistics, or weather conditions, etc. in one simulation model.

The paper is structured as follows: first, we summarize previous work on workspace modeling and the impact of weather on construction activities. Then, we introduce the research work at the Institute for Construction Engineering and Management at Bauhaus University. Next, we describe our methodology to address the proposed objective of this paper. Lastly, we summarize our conclusion and future work.

II. MOTIVATION

The exterior construction work phase is shaped by the involvement of many individual trades, or rather companies. That is to say, there are many different activity fields. Thus, there are a variety of construction processes, material properties and storage methods, equipment, and different workspace needs. These trades are restricted to perform their job in limited workspaces. Moreover, the type of work focuses mainly on manual assembly, adjustment, and some awkward positioning in operations such as on scaffolding, ceiling and wall surfaces [5]. Furthermore, there is a high degree of interdependencies and technological dependencies of the individual trades.

In another scenario, weather conditions are also a factor, which affect the exterior construction work phase. Benjamin and Greenwald suggest that 50% of construction activities are sensitive to weather conditions [6]. The final product of construction operations is a collection of different interactions between materials, multiple pieces of equipment and crew members, which are completely dependent on the weather status. Therefore the impact of weather is an important factor, which should be seriously considered in estimating construction time. Project planners normally prepare for additional time in the construction schedule to consider delays due to bad weather conditions. However, the buffer time is used without exact analysis and is based on the experience of project managers.

This paper proposes a multi-layer decision support system. We have developed our system in a constrained-based simulation framework environment, which includes an integration of technological dependencies, the dynamic nature of workspace management and the impact of weather on construction operations at the project level. Then, the fulfillment of the constraints at the construction site can be checked and verified. The developed system has been implemented for trades in the exterior construction work of high rise buildings.

III. LITERATURE REVIEW

In the following subsections, we highlight the previous work related to the research areas of workspace problems, weather impact and some main researches at Bauhaus Universität Weimar.

A. *Related work on workspace modeling*

Workspace is conventionally addressed solely by different researchers. For instance, Riley and Sanvido develop a methodology to constrict workspace by the actual work in place and the amount of space available [7][8]. They extended their previous proposal by defining various space patterns for different trades based on selected methods of working. Akinci et al. developed a methodology to model construction activities in 4D CAD models, by formalizing the general description of space requirements through a computer system. By using 4D CAD a user can automatically generate the project-specific workspaces according to schedule information and represent the workspaces in four dimensions with their relationships to construction methods [9]. Akbas proposes a geometry-based process model (GPM) that uses geometric models to create and simulate workflows and work locations. This method provides spatial insight into the planning of workspaces and space buffers for repetitive crew activities [10].

B. *Related work on weather impact*

Similarly, the impact of weather on construction activities has also been set to different studies to determine their severity on construction operations. Some studies estimate the relationship between weather parameters and productivity or task duration using regression analysis or neural networks [11][12]. Related to the impact of bad weather conditions on productivity and the duration of construction activities, some other researchers have pointed out how these impacts affect baseline schedules and have also analyzed weather-related construction claims [13][14][15]. These researches provide a decision support framework to analyze the impact of weather on the whole schedule, where the input data is construction processes, weather historical data, and the impacts of weather, whereas the output is the final schedule with a weather-related delay duration. Some construction types have been researched concerning how weather impacts different construction types such as masonry, highway construction, general construction, transportation construction [16], wind turbine construction [17], and earthwork [18].

C. *Research at the Bauhaus Universität Weimar*

At Bauhaus-Universität Weimar, the Institute for Construction Engineering and Management researches on different aspects of modeling construction and manufacturing processes. For instance, Beißert et al. propose a Constraint-based Simulation for modeling construction processes [19][20]. Thereby, the construction tasks and their constraints for production such as technological dependencies, availability and capacity can be specified, and valid execution schedules can be generated. Further work developed by Voigtmann et al. concern construction site logistics between construction sites and work locations [21][22].

Le and Bargstädt have developed a simulation model to acknowledge the impact of weather on construction processes [23][24]. They developed a network component "WEATHER" within the software Plant Simulation. This network generates weather data and makes decisions on how weather may impact construction processes. The impact of weather has been divided into 3 cases: (1) temporarily prevents workers from working, (2) affects the delivery of material by preventing cranes from operating, (3) reduces labour productivity causing the extension of activities' construction duration [23]. Thereby weather thresholds such as wind velocity, temperature, humidity and precipitation for the first and second cases need to be decided. Besides, relationships between productivity and weather parameters need to be estimated for the third case. The weather impact decisions made by the "WEATHER" component are finally integrated into the construction processes as weather constraints. Thus, the weather-related schedule is provided with the estimated delays.

Similarly, Elmahdi and Bargstädt acknowledge the workspace requirements within the schedule plan for good workmanship. Based on literature and site observations, they classified the different required areas in large scale building projects [1]. With this they propose a semi-automatic methodology to generate the required areas for the scheduled project activities [3]. The acknowledgement of workspace requirements are developed in a new network component "SpatialNetwork". Furthermore, the "SpatialNetwork" is embedded as an additional constraint component within the software Plant Simulation. Thus the fulfillment of spatial constraints at the construction site can be checked and verified.

However, all these advanced works have been considered in separate models. That is to say, there is no interaction between the "WEATHER", "SpatialNetwork" and the site logistic components. Therefore, the objective of this paper is to combine three aspects within one simulation framework. To achieve this goal we have to acknowledge technological dependencies with individual trades, workspace requirements and the impact of weather. Furthermore, we integrate these requirements as additional constraints. Then, the fulfillment of these constraints at the construction site can be checked in a hierarchical structure and verified.

IV. MULTI-LAYER CONSTRAINT AND DECISION SIMULATION FRAMEWORK

We propose a constraint-based simulation to achieve the objective of this paper. Therefore, in the following subsections, the fundamental idea of the constraint-based simulation concept is introduced and the framework of the multilayer simulation framework is described.

A. Constraint-based simulation

The proposed multi-layer simulation framework to acknowledge the technological and spatial constraints as well as the impact of weather on construction processes is a constraint based simulation environment. Spriprasert and Dawood define constraint in the context of construction as "one that restricts, limits or regulates commencement or progress of work-face operations to achieve construction products within agreed time, cost and quality [25]". They classify the different types of constraints into three major groups: physical, contract and enabler constraints [25]. Koenig et al formalize two characteristics for the constraints: hard constraints and soft constraints [26]. Hard constraints define conditions that are embedded with work steps, which must be fulfilled before work steps can be started. Soft constraints describe also conditions that are embedded with work steps. However, these conditions are not necessary to be completely fulfilled. Our framework acknowledges this approach for spatial aspects and the impact of weather.

B. Description of multi-layer constraint and decision simulation framework

Fig. 1 illustrates the concept of the multi-layer simulation framework to investigate the impact of weather conditions and spatial conflicts on construction performance. The framework consists of five layers which represent different types of constraints and decisions.

In this framework, the weather and spatial impacts are represented as hard or soft constraints of the construction processes. For example, safety issues for crane operation such as wind conditions or the required workspaces such as material or equipment are describe as hard constraints. On the other hand, the size of workspace and the labor productivity are described as soft constraints. The three cases of weather impact mentioned in the previous section are considered in this framework. Besides these, the required spaces and space conflicts are also examined.

The first layer describes the technological constraints. The technological constraints include global and local constraints. While global constraints describe the priority of the scheduled works between different trades such as the installation of windows before facade and/or between different objects for one trade (such as window-East before window-West), local constraints describe the sequence of their defined multi work steps for one element within one object or the sequence of work steps between two different elements within one object. The second layer controls the fulfillment of weather impact criteria such as wind velocity for crane operation. Furthermore, it identifies weather-sensitive construction activities. The identification of required space types (material, equipment and laborers) and the availability of the required workspaces are described in the third layer. Finally, decisions concerning weather impact and the spatial constraints are proposed in the last two layers.

This multi-layer framework describes two types of interaction: *horizontal interaction* and *vertical interaction.* Vertical interaction describes the sequences between two processes in two different layers. For example, the crane operation is first checked in the weather layer. This step is achieved by comparing the current wind velocity with wind thresholds [23]. If the crane can be operated then we identify in the spatial layer the required type of defined work steps such as material and equipment spaces. If this constraint is fulfilled then material can be transported by crane to the execution positions, which is performed in the weather layer. Horizontal interaction describes sequences between two processes within one layer. For example, the processes in the last layer interact with each other horizontally. The aim of presenting the layer concept is to show how the sequences of processes within one layer interact with each other. In the same way we can show how these processes interact with different processes in different layers. Thus, different constraints of construction processes are presented as flexible, logical and transparent. The input data of this framework consists of the construction process data, weather data and spatial data. The construction process data include: the hierarchical description of project activities that are required to fulfill the final product, the assembly strategy for the different elements, their technological dependencies (local and global constraints) and date constraint, which allows the specification of the start dates of individual tasks, the required resource such as execution time, the number of workers, and the type and quantity of material. The more accurate this information is, the more reliable the results will be. Weather data is based on historical data or weather forecast data. For making weather-impact decisions, the weather thresholds and a function—which together can determine the relationship between the productivity and weather parameters—are needed. Finally, the spatial data contains the required workspace types, the level of assignment, the orientation, and reference type. Furthermore, we define two strategies in order to resolve workspace conflicts between different workspaces: the spatial adjustment strategy and the productivity adjustment strategy. For the spatial adjustment strategy, we define additional attributes for the different types of workspace such as ability to rotate, resize, and/or relocate workspace. For the productivity adjustment strategy we identify different parameters, such as overlapping areas, quality and quantity of material, actual available number of resources, etc. that affect the performance of workers on a specific task. We integrate these parameters as additional functions for conflict resolution in the simulation framework. Furthermore, these parameters are considered cumulative and so we therefore gave a weight factor for each parameter.

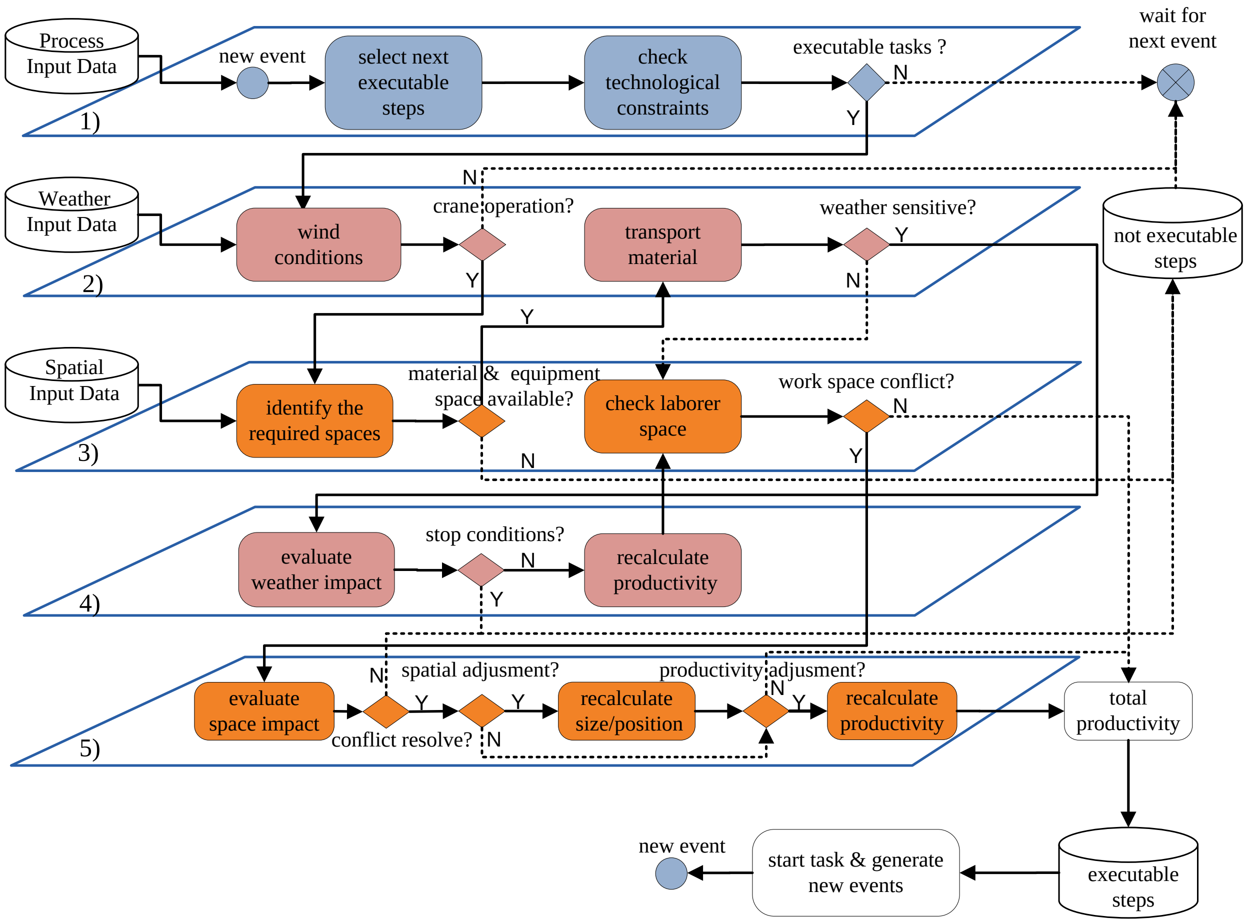

Figure 1. Multi-layer constraint and decision simulation framework

Activities are built within Plant Simulation in a hierarchical structure. The highest level of the activity description is the trade. The lowest level of the activity description is the element or section. For each element or section one or more work steps may be defined [3]. A work step has three states: “not started,” “started” and “finished,” and requires certain execution times, resources and space [19]. The procedure of the constraint-based simulation outlines the search for process steps that can be started for the current simulation time. Upon the occurrence of an event, all process steps do not start with the state of examining the performance of their technological constraints. Those process steps that meet their assigned constraints will be stored as the next executable steps. The next executable steps begin with their status “not started” and will be delivered to the developed weather constraints and spatial constraints. There, they will be checked up on the availability of workspaces and their sensitivity to weather hierarchically to verify their execution possibility to be started for the current simulation time as shown in Fig. 1.

The required resources and workspaces have to be locked during their execution. That means they cannot be used by other work steps. After locking the required resources and workspaces, the work step state changes from “not started” to “started” Subsequently, the set of “not started” work steps is checked to see if the required space and resources are available and if weather conditions

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are favorable 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. If the required time has expired, the work step status changes from "started" to "finished" and is marked as finished. Its locked resources and working spaces will be unlocked and can be used by other work steps.

V. SIMPLE CASE STUDY

We have validated the multi-layer simulation framework concept in a simple case study. The case study is a 5-story school building in Schwarzenberg, Germany. The construction site includes trades at the exterior construction phase. Our investigation is concentrated for trades to install the façade system and the windows.

The fiber cement façade construction is applied. Erecting a fiber cement façade system consists of the assembling of four main components: wall angle, insulation, aluminum profile and the fiber cement façade element. The installation of these four main components is decomposed into ten work steps: (1) measuring the position, (2) fixing wall angles to the building's structure; (3) measuring the position and dimension of elements, (4) cutting, (5) fixing insulation elements to wall angles and building structure; (6) measuring position and dimension, (7) cutting aluminum profiles, (8) installing aluminum profiles; (9) measuring position, (10) installing façade element. The installation of windows consists of two components: window sill and window frame, which includes four work steps: (1) measuring the position, (2) fixing the window sill; (3) leveling, and finally, (4) fixing the window frame. The execution duration of each type of work step was determined based on an expert's knowledge, which is shown in Fig. 2.

The weather input data used in this case study is the local 5-day weather forecast data. That is to say the model runs in every period of 5 days to check for the impact of weather on the construction process. The weather parameters are temperature (^{o}C), wind velocity (m/s), relative humidity (%), and precipitation (mm). The installation of the façade and window is performed through a scaffolding system. Thus the required workspace for laborer is driven due to the installation positions of the unique work steps of the elements and the width of the scaffolding platform. Since the work mainly focuses on assembling, the equipment workspace is modeled within the laborer workspace. Materials are transported from the storage area in small amounts to the installation through a crane. Aligned to the storage area a debris area is defined. An offset distance from the scaffolding is set as a hazard workspace.

In order to simulate the execution process, the constraints for assembling the façade system and windows need to be specified. The technological dependencies are represented in Fig. 2. Fixing the wall angles to the building structure, for example, needs to be finished before the measuring of the position or dimension of insulation elements can be performed. Generally, specific material and workers are required to execute a certain work step. For instance, to execute the work step "fixing wall angle", a highly skilled worker, a semi-skilled worker and a wall angle element are needed. The on-site working time of workers is defined in a simulation calendar. In this example, working days are from Monday to Friday and the daily working time is from 8:00 am to 5:30 pm including a pause of an hour at noon.

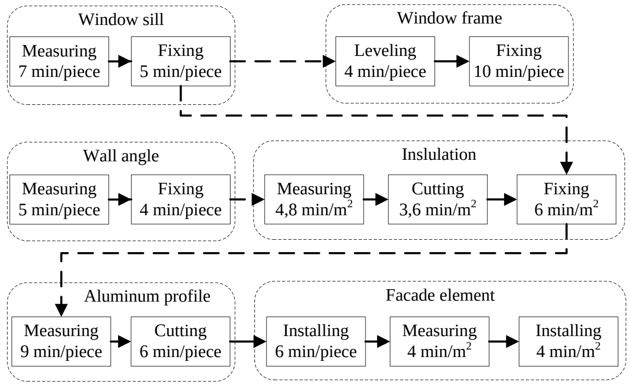


Figure 2. Technological dependencies between work steps and their non-weather-space-related execution duration

Based on the concept represented in Fig. 1, two schedules have been achieved from the simulation model: the as-built schedule and the as-possible schedule. The term "as-built schedule" is used to describe the actual schedule as constructed on site. The "as-possible schedule" expression is used to describe the schedule which considers the technological dependencies as well as the impact of weather conditions and workspace requirements.

In this example, the contract specifies a start construction date of February 12, 2008. The results of the model for the as-planned, as-built and as-possible schedule are shown in Fig. 3. The term "as-planned schedule" mentions the schedule which is prepared in the preconstruction stage.

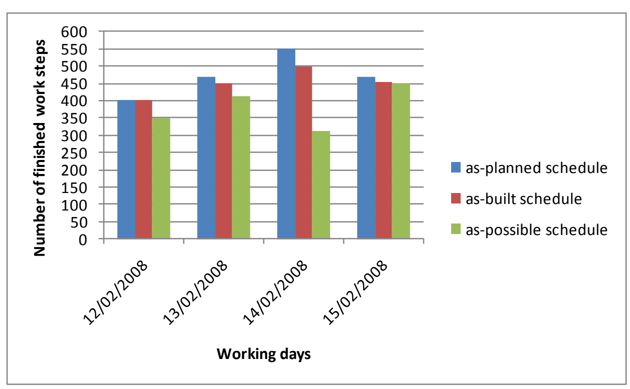
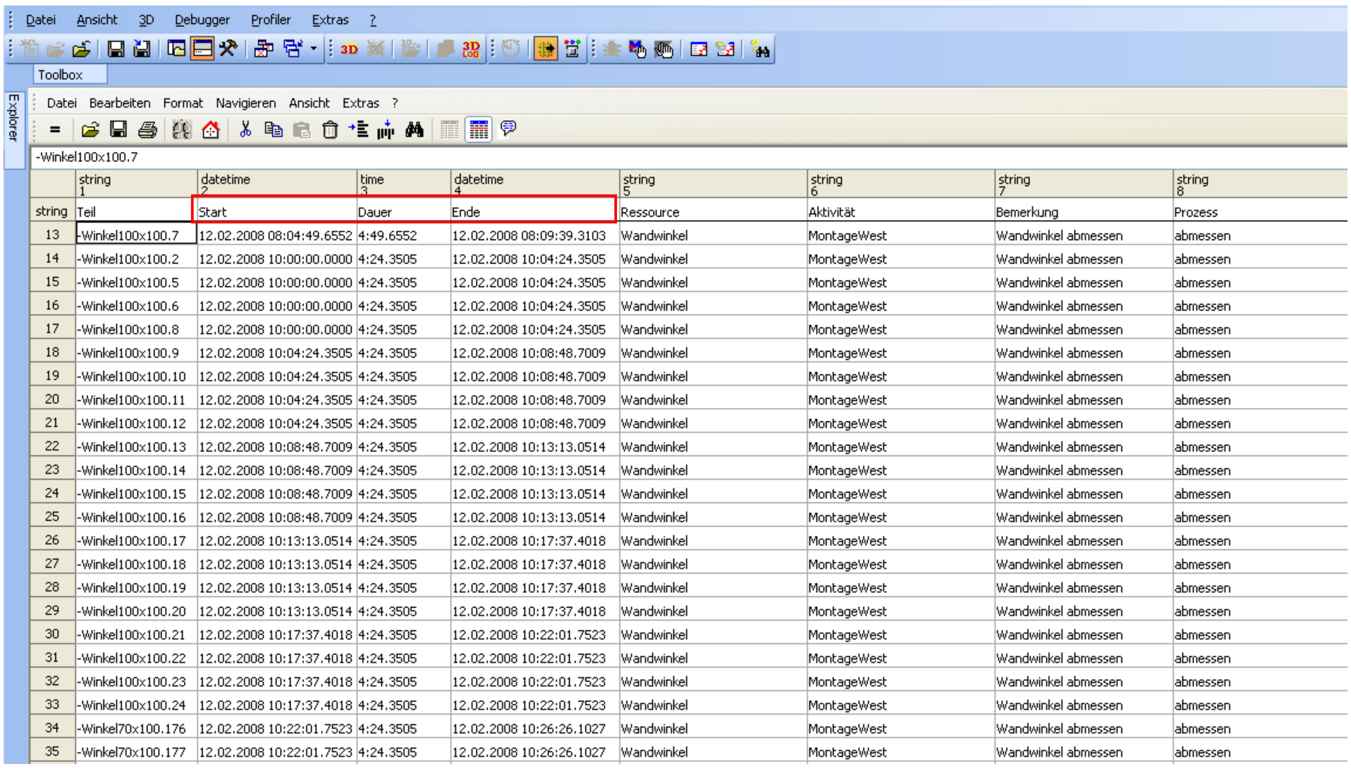


Figure 3. Output of one simulation run

The results consist of the number of work steps, which are finished in a period of 5 days. Because the first day (Feb 12) is Tuesday, the fifth day (Feb 16) is Saturday, which is a non-working day. Thus the schedules from Feb 12 to Feb 15 are achieved. Fig. 3 provides a daily comparison between the finished work steps of the as-possible, as-planned and as-built schedules for the first 4 working days. The number of finished work steps of the as-possible schedule is fewer than that of as-planned or as-built schedules. For example, on the first day, the number of finished work steps of as-planned, as-built, and as-possible schedule are 400, 400, 350 work steps respectively. During these four working days, construction operations experience delays and work steps' duration extended due to bad weather and spatial conflicts. On the first 3 days, there is heavy rain for 2 hours every day. Thus the work on the construction site is temporarily shut-down during the rain storm and the labor productivity is recalculated considering the uncomfortable conditions of temperature, humidity, wind velocity and unavailable workspace. Fig. 4 shows the work steps' execution table, including the start, duration, end point of time and specific information of the corresponding work steps.

One simulation run calculates exactly one practical execution schedule. Thus, project managers can develop different execution strategies and chose the optimal one to reduce the consequences caused by weather and space problems.



	string 1	datetime 2	time 3	datetime 4	string 5	string 6	string 7	string 8
string	Teil	Start	Dauer	Ende	Ressource	Aktivität	Bemerkung	Prozess
13	-Winkel100x100.7	12.02.2008 08:04:49.6552	4:49.6552	12.02.2008 08:09:39.3103	Wandwinkel	MontageWest	Wandwinkel abmessen	abmessen
14	-Winkel100x100.2	12.02.2008 10:00:00.0000	4:24.3505	12.02.2008 10:04:24.3505	Wandwinkel	MontageWest	Wandwinkel abmessen	abmessen
15	-Winkel100x100.5	12.02.2008 10:00:00.0000	4:24.3505	12.02.2008 10:04:24.3505	Wandwinkel	MontageWest	Wandwinkel abmessen	abmessen
16	-Winkel100x100.6	12.02.2008 10:00:00.0000	4:24.3505	12.02.2008 10:04:24.3505	Wandwinkel	MontageWest	Wandwinkel abmessen	abmessen
17	-Winkel100x100.8	12.02.2008 10:00:00.0000	4:24.3505	12.02.2008 10:04:24.3505	Wandwinkel	MontageWest	Wandwinkel abmessen	abmessen
18	-Winkel100x100.9	12.02.2008 10:04:24.3505	4:24.3505	12.02.2008 10:08:48.7009	Wandwinkel	MontageWest	Wandwinkel abmessen	abmessen
19	-Winkel100x100.10	12.02.2008 10:04:24.3505	4:24.3505	12.02.2008 10:08:48.7009	Wandwinkel	MontageWest	Wandwinkel abmessen	abmessen
20	-Winkel100x100.11	12.02.2008 10:04:24.3505	4:24.3505	12.02.2008 10:08:48.7009	Wandwinkel	MontageWest	Wandwinkel abmessen	abmessen
21	-Winkel100x100.12	12.02.2008 10:04:24.3505	4:24.3505	12.02.2008 10:08:48.7009	Wandwinkel	MontageWest	Wandwinkel abmessen	abmessen
22	-Winkel100x100.13	12.02.2008 10:08:48.7009	4:24.3505	12.02.2008 10:13:13.0514	Wandwinkel	MontageWest	Wandwinkel abmessen	abmessen
23	-Winkel100x100.14	12.02.2008 10:08:48.7009	4:24.3505	12.02.2008 10:13:13.0514	Wandwinkel	MontageWest	Wandwinkel abmessen	abmessen
24	-Winkel100x100.15	12.02.2008 10:08:48.7009	4:24.3505	12.02.2008 10:13:13.0514	Wandwinkel	MontageWest	Wandwinkel abmessen	abmessen
25	-Winkel100x100.16	12.02.2008 10:08:48.7009	4:24.3505	12.02.2008 10:13:13.0514	Wandwinkel	MontageWest	Wandwinkel abmessen	abmessen
26	-Winkel100x100.17	12.02.2008 10:13:13.0514	4:24.3505	12.02.2008 10:17:37.4018	Wandwinkel	MontageWest	Wandwinkel abmessen	abmessen
27	-Winkel100x100.18	12.02.2008 10:13:13.0514	4:24.3505	12.02.2008 10:17:37.4018	Wandwinkel	MontageWest	Wandwinkel abmessen	abmessen
28	-Winkel100x100.19	12.02.2008 10:13:13.0514	4:24.3505	12.02.2008 10:17:37.4018	Wandwinkel	MontageWest	Wandwinkel abmessen	abmessen
29	-Winkel100x100.20	12.02.2008 10:13:13.0514	4:24.3505	12.02.2008 10:17:37.4018	Wandwinkel	MontageWest	Wandwinkel abmessen	abmessen
30	-Winkel100x100.21	12.02.2008 10:17:37.4018	4:24.3505	12.02.2008 10:22:01.7523	Wandwinkel	MontageWest	Wandwinkel abmessen	abmessen
31	-Winkel100x100.22	12.02.2008 10:17:37.4018	4:24.3505	12.02.2008 10:22:01.7523	Wandwinkel	MontageWest	Wandwinkel abmessen	abmessen
32	-Winkel100x100.23	12.02.2008 10:17:37.4018	4:24.3505	12.02.2008 10:22:01.7523	Wandwinkel	MontageWest	Wandwinkel abmessen	abmessen
33	-Winkel100x100.24	12.02.2008 10:17:37.4018	4:24.3505	12.02.2008 10:22:01.7523	Wandwinkel	MontageWest	Wandwinkel abmessen	abmessen
34	-Winkel70x100.176	12.02.2008 10:22:01.7523	4:24.3505	12.02.2008 10:26:26.1027	Wandwinkel	MontageWest	Wandwinkel abmessen	abmessen
35	-Winkel70x100.177	12.02.2008 10:22:01.7523	4:24.3505	12.02.2008 10:26:26.1027	Wandwinkel	MontageWest	Wandwinkel abmessen	abmessen

Figure 4. Statistic of the execution process

VI. Conclusion and Future Work

Construction processes are complicated by nature and usually disturbed by many factors. These factors can affect progress individually or simultaneously, in the latter case they can create even worse consequences. The requirement to provide decision support systems to consider simultaneously different affected factors is necessary, which has not been researched enough in previous studies. Using simulation models to research construction problems is proven to be effective and convenient. This paper provides a multi-layer simulation framework which considers technological and spatial constraints as well as the impact of weather for construction planning. These aspects are described as hard and soft constraints in construction processes. This approach provides a flexible way to consider weather and spatial aspects where the model can easily be adapted by adding or removing constraints. Moreover, layers of this framework can interact flexibly with each others to ensure that the impact of spatial conflicts and bad weather conditions can be considered hierarchically. Based on this concept, more different influencing factors of construction processes can be integrated in the same model.

Furthermore, in the next research steps, based on weather-spatial-impacted results, alternative strategies to reduce the consequences can be provided and analyzed using this simulation model. Therefore, it is easier for managers to make the right decisions when encountering weather and spatial problems.

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