A SIMULATION APPROACH TO INTEGRATE THE WEATHER IMPACT INTO THE EXECUTION PLANNING

Hong Ha Le, Master of Science , hong-ha.le@uni-weimar.de
Hans-Joachim Bargstaedt, Professor and Department Head, hans-joachim.bargstaedt@uni-weimar.de
Chair of Construction Engineering and Management, Bauhaus University Weimar, Weimar, Germany

ABSTRACT

The construction planning is complex because of many uncertainties occurring during the execution process. One of them is bad weather conditions, because most of the activities in construction are exposed to weather and sensitive to some of its features. Therefore, in the executing stage, the short term weather forecast should be considered to make the execution plan for the upcoming days more realistic. This paper presents a simulation approach to incorporate the impact of weather factors into the constraint-based simulation of construction processes, where weather effects are described as constraints. The data of reliable 5-day weather forecast retrieved from public sources is utilized, where it is updated every 3 hours daily. Then the non-weather- and weather-related construction processes for the next 5 days are modeled and experimented. The benefits of the experiment's results are supports in analyzing the impact of weather on execution processes, in preparing practicable execution schedules, and in making construction claims.

Keywords: Weather impact, construction planning, constraint-based simulation

1. INTRODUCTION

The construction planning is complex because of many uncertainties occurring during the execution process. One of the uncertainties, which clearly affects construction activities, is bad weather conditions. The uncertainties caused by weather can significantly affect a project's schedule, resulting in significant variations as compared to the baseline schedule (Shahin et al. 2007). A number of studies have been researched on the impacts of weather on construction labour productivity and activities' duration. Koehn and Brown established two functions between labour productivity and weather factors for general construction (Koehn and Brown 1985). A factor model of construction productivity was developed by Thomas and Yiakoumis who investigated the relationship between air temperature, relative humidity and productivity (Thomas and Yiakoumis 1987). Others showed systems which discuss rainfall events and the activities' associated time lost due to the precipitation event (Smith and Hancher 1989; El-Rayes and Moselhi 2001). In a further research, Moselhi, Gong and El-Rayes (1997) provided an automated decision support system to estimate the effects of reduced labour productivity and work stoppage caused by adverse weather conditions on construction sites. Related to the impacts of bad weather conditions on productivity and duration of construction activities, some other researchers have pointed out how these impacts affect baseline schedule and also analyzed weather-related construction claims (Moselhi and El-Rayes 2002; Hyun-Soo et al. 2005; Shahin et al. 2007). These researches have usually studied the influences of weather on the whole construction scheduling in planning stage based on historical weather data or typical weather patterns of local areas. However, the variation of weather conditions is often complex and not always the same as how it used to be. Therefore, in the executing stage, the actual on site weather forecast should be considered to make the execution plan for the next days more realistic. In other words, the as-planned schedule may be subject to changes during the executing stage in order to reduce serious consequences caused by bad weather conditions.

It is clear that simulation has found its effectiveness in performing construction processes. Also construction problems can be investigated conveniently through simulation models. In the research project “Simulation of Outfitting Processes in Shipbuilding and Civil Engineering” (SIMoFIT) performed by the Bauhaus-University Weimar and Flensburger shipyard company, a constraint-based simulation approach was developed to improve the construction planning in civil engineering (Beißert, König and Bargstädt 2008b). This approach was implemented by using the discrete-event simulation program Plant Simulation from Tecnomatix Technologies Ltd.

This paper presents an approach to incorporate the impact of weather factors into the constraint-based simulation of construction processes, where the weather effects are described as constraints. In this research, the data of 5-day weather forecast retrieved from public sources is utilized, where it is updated every 3 hours daily. Therefore, the execution plan for the next 5 days can be experimented based on actual weather data. The proposed model attempts to produce a simulation environment, which helps in managing the construction plan regarding to the effect of weather conditions. This research focuses on the influence of weather conditions on the construction of a fiber cement façade system. Based on this framework, other types of construction activities can be similarly investigated.

2. THE IMPACT OF WEATHER ON CONSTRUCTION PROCESSES

Construction activities are usually executed in an outdoor environment, hence they are often sensitive to weather parameters such as temperature, humidity, wind, rainfall and snow. The degree of sensitivity to these parameters varies significantly from one construction operation to another because of the specific nature of these operations and the methods used in their execution (Moselhi and El-Rayes 2002). In practice, the effects of weather conditions on on-site activities are diverse. The most common effects of the weather conditions can be categorized into three different cases:

(1) temporarily prevent workers from working, shut-down of operations,
(2) affect the delivery of material by preventing certain equipment from operating,
(3) reduce labour productivity causing the extension of activities’ construction duration.

Case (1) is the clearest seen case of interruptions due to weather conditions: in severe weather conditions, certain activities, and sometimes the whole project, must be halted (Shahin et al. 2007). The weather conditions, which cause temporarily stop working, are usually related to heavy rain, snow, extremely strong wind and the adverse conditions of temperature and humidity. Studies indicate that temperature above +43^{o}C and below -23^{o}C with humidity above 50% are intolerable, and workers should cease working (Koehn and Brown 1985). Extremely hot weather can cause injuries, heat exhaustion and heat stroke; whereas working in extremely cold weather may lead to freezing involving the fingers, hands, toes, feet, ears and nose (Koehn and Brown 1985). Heavy rainfall and snow are also reasons which interrupt the execution processes. It is very obvious, that how rainfall or snow affects the construction processes depends on the type of construction activities as well as on the intensity of the weather event. For example, exterior insulation installation should not be performed while it is raining because of the nature of the insulation material, which might get soaked with water. However, façade element installation can be performed under light rain. Cutting elements can be performed without any interruptions of heavy rain or snow if the work is carried out in sheltered spaces.

Case (2), which may be a long or short shut down of the delivery process, is not so clearly indicated on site. For example, strong wind can affect the operation of cranes, so that material cannot be hoisted, even if there still seems to be enough supply at the moment. Following an instruction of crane operation, it is suggested that the maximal permissible wind velocity to operate a crane is about 20 m/s. However, the instruction also mentions that, if wind velocity is around 13m/s, a gust of wind may suddenly appear with the velocity of 20 m/s. Hence the wind velocity of 13 m/s should be estimated for the maximal wind velocity of crane operation permission. Therefore, the delivery of material to high levels can be interrupted if cranes cannot be operated, which obviously affects the execution schedule.

Case (3) leads to the most difficult situation to identify on site. In a bad weather scenario, the conditions can reduce the labor productivity, hence the activities’ duration have to be extended. For an operation in an open area, the productivity achieved in poor weather conditions is considerably lower than that achieved in favorable weather conditions (Song, Al-Battaineh and AbouRizk 2005). The problem is that this reduction is not obvious at first glance.

Reduced labor productivity is generally attributed to reduced human performance due to heat or cold stresses resulting from the combined effect of temperature, humidity and wind velocity (Moselhi, Gong and El-Rayes 1997). Some studies have been conducted to establish the relationship between labor productivity and weather factors as reviewed in Section 1. In this paper, the outcomes of the research conducted by Koehn and Brown (1985) are utilized. Thereby the functions between productivity, temperature and relative humidity for general construction were established using regression analysis based on historical data, which are shown below as Eqs. (1) and (2). Eq. (1) is applicable from -20^{o}F to 50^{o}F (-28,9^{o}C to 10^{o}C), whereas Eq. (2) is applied for temperature from 70^{o}F to 120^{o}F (21,1^{o}C to 48,9^{o}C) (Koehn and Brown 1985)

$$P_C = 0.0144T - 0.00313H - 0.000107T^2 - 0.000029H^2 - 0.0000357TxH + 0.647 \quad (1)$$
$$P_W = 0.0517T + 0.0173H - 0.00032T^2 - 0.0000985H^2 - 0.0000911TxH - 1.459 \quad (2)$$

where:
P_C = productivity factor for cool or cold weather;
P_W = productivity factor for warm or hot weather;
T = temperature in Fahrenheit;
H = relative humidity as a percentage.

To obtain a smooth transition between the two curves, productivity at 60 ^{o}F (15,6 ^{o}C) and 70 ^{o}F (21,1 ^{o}C) were arbitrarily taken as 100 %. Then Koehn and Brown developed a table, which illustrates the relationship between productivity P_{TH} and temperature for various values of relative humidity. In this research, this table is represented as a contouring map shown in Figure 1, so that it is easier to imagine the change trend of productivity factors. Also the temperature in Fahrenheit is converted into Celsius degree. Productivity factors in this case represent the percentage of standard efficient operation.

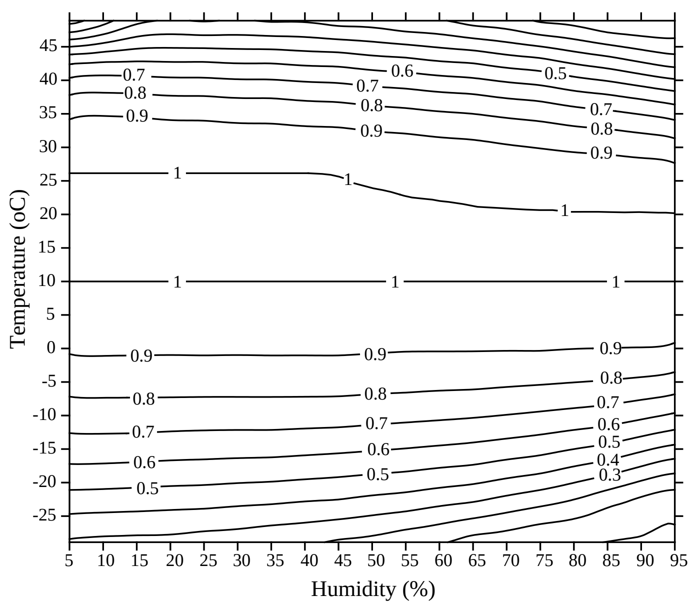

Figure 1: Construction productivity factor as function of temperature and relative humidity (Koehn and Brown 1985)

With this result, the productivity can be estimated for a wide range of weather conditions. This result is reliable because it was estimated based on a large set of historical construction productivity data. However it is the shortcoming of this result that it was developed without wind velocity consideration. In other words, wind velocity is considered as comfortable or light wind, which doesn't affect the above productivity factor. By the result of a questionnaire with experts and the classification of beaufort wind scale, the authors find that wind scale smaller than or equal to 2 ($v \leq 3,3$ m/s) is considered light wind and has almost no effects on the working performance. If wind scale is bigger than 7 ($v > 17,1$ m/s), people should stop working. Using sets of data points retrieved from interviewing with experts, the relationship between wind velocity and productivity factor P_{WC} is estimated by means of a polynomial regression analysis technique. Eq. (3) is derived with the wind velocity ranging from 3,4 m/s to 17,1 m/s. The coefficient of determination (R^2) obtained from the regression analysis is 0,83. This indicates that 83% of the variation in the productivity may be explained by the change in wind velocity. It should be noted that maximum productivity values, which are calculated by this equation, should not exceed 1. That means that if the calculated P_{WC} is bigger than 1, then the value of 1 is used.

$$P_{WC} = - 0,000252W^3 + 0,003286W^2 – 0,038148W + 1,09 \qquad (3)$$

The final productivity factor which is affected by temperature, humidity and wind velocity is calculated using Eq.(4). By using this equation, productivity factors for a wide range value of wind velocity, temperature, relative humidity are obtained, which helps in pointing out, how main weather parameters affect the working performance.

$$P = P_{WC} \times P_{TH} \qquad (4)$$

where:
P_{TH} : Productivity factor retrieved from Figure 1;
P_{WC} : Productivity factor related to wind velocity;
P : Productivity factor related to wind velocity, temperature, humidity.

3. SIMULATION CONCEPT

The constraint-based concept is developed using discrete-event simulation. That means, only points of time, at which events occur, are inspected. At the point of time when an event occurs, it should be investigated, if new events need to be generated or time points of existing events need to be moved. Thus, the simulation time leaps from event to event (König, Beißert and Bargstädt 2007). There are two types of constraints in the constraint-based approach, namely hard and soft constraints. Hard constraints define stringent conditions in construction processes and must be fulfilled before work steps can be started. Soft constraints are used to describe appropriate dependencies, which are not necessary to be completely fulfilled.

Within this approach, construction processes are broken down into construction tasks. Each construction task, for example, erecting a façade element, is decomposed into single work steps, such as measuring, fixing. Each work step requires time to execute and has its current state, which should be “not started”, “started” or “finished”. When a new event occurs, all not started work steps need to be checked for the fulfillment of their hard constraints. If all associated hard constraints are fulfilled, these work steps are listed as executable. The next simulation step is ordering these executable steps based on the percentage of the fulfilment of their soft constraints. Only the first work step in the list can be executed. In case several steps fulfil their soft constraints in equal measure, one of them is chosen randomly. Each work step requires certain material, resources and working space. These required objects are locked during the work step’s execution duration and can be unlocked after this work step is finished. That means the other work steps can only use these objects after this step is finished. After locking all required objects, the work step’s state changes from “not started” to “started”. When its execution time is expired, its state changes to “finished”. These simulation steps will be repeated until all work steps are finished. The overall aim is to simulate different practicable solutions that can be visualized and analyzed regarding principal guidelines such as time, cost and quality (König, Beißert and Bargstädt 2007).

Based on the concept of constraint-based simulation, the authors develop a simulation model, which provides an approach to integrate the weather impact into the execution processes; where they are described as hard and soft constraints. This simulation model focuses on the impact of weather on the scheduling in executing stage and uses the current 5-day weather forecast data. Hence, every 5-day period of both non-weather- and weather-related construction scheduling are achieved, so that the disturbances due to weather can be forecasted. Furthermore, experiments of weather-related execution flows can be made, so that many possibilities of practicable schedules are provided. By using this model, the construction schedule can be revised frequently during the execution process, which helps in avoiding serious consequences caused by bad weather conditions. Figure 2 describes the integrated weather construction model, which is composed of a number of components. These components will be explained in detail in the following sections.

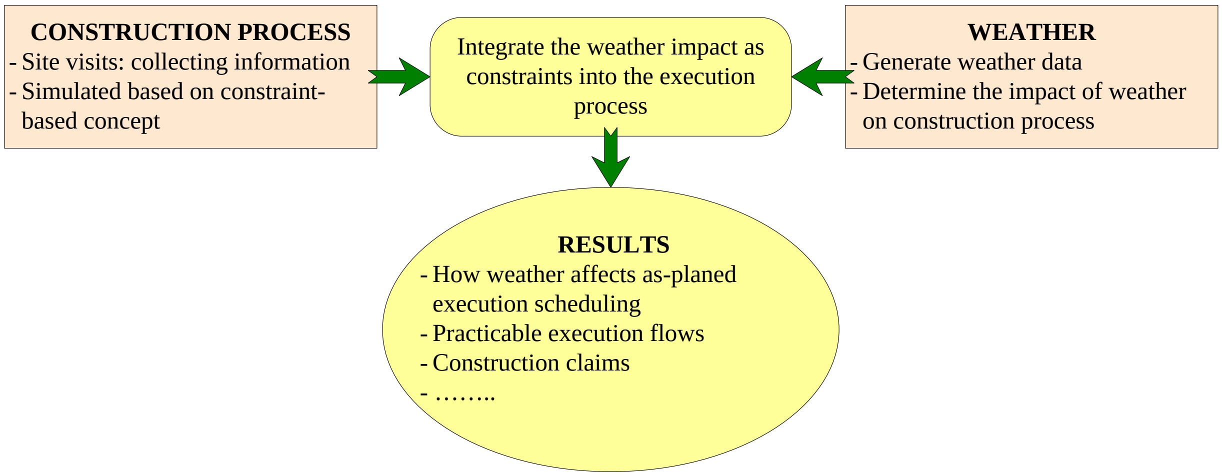

Figure 2: Weather-construction processes integrated model

3.1. Constraint-based simulation of construction processes

The first step of building this model is to analyze construction process in order to understand it in more details. At this stage, the impact of weather on the construction process will be overlooked. The processes should be visited on site and useful information are collected, which should include (Shahin et al. 2007):

- work breakdown structure of the process,
- the construction sequences of tasks, their technological dependencies or any other process constraints,
- the resource requirements of each activity: type and required level of resources,
- data collection about the activity durations based on historical data, experts' knowledge or standard estimating manuals.

The more accurate this information is, the more reliable the results will be. The next step is simulating the construction process using the constraint-based concept. Weather conditions are also not yet considered in this step. In order to simulate the construction processes, all simulation objects such as tasks, resources, material, equipment are represented as variables. Stringent relationships between these variables like execution sequences, resources or material requirements are defined as hard constraints (Beißert, König and Bargstädt 2009). Some construction hard constraints are listed in Table 1.

Table 1: Construction hard constraints (Beißert, König and Bargstädt 2008a)

Name of hard constraints	**Description and examples**
Technological dependencies	Construction and formal aspects *"work step A before work step B" means work step A has to be completed before work step B can be started*
Capacity	Resource boundaries *Amount, qualification of workmen; amount and capacity of equipment*
Availability	Material flow restriction *Supply of material linked to the requirement of storage area*
Safety criteria	Workmen and equipment protection

As described above, construction activities will be decomposed into single work steps. Execution flows are estimated based on the relationships between work steps, which are called technological dependencies. For example, the insulation elements can be installed only when the wall angles have been installed completely. Furthermore, the construction strategies are also flexibly simulated. Strategies are predefined execution rules, which extend the technological dependencies (Beißert, König and Bargstädt 2007). For example, erecting strategies of façade elements can be from left to right, from top to bottom of a building or vice versa.

Work steps' ideal construction duration is predefined as input data, then the total construction time will be automatically calculated by a simulation clock. The required material, workers to execute each work step are also predefined, which are generated by the material and personnel administration of the simulation model, respectively. The simulation model runs from the first work step to the final one following the concept described previously. Consequently, the construction processes are abstracted as it should be operated on site.

3.2. WEATHER

WEATHER is a model's component which is developed to generate weather conditions during the execution processes and determines the impact of weather on every work step. Figure 3 shows the assignments of WEATHER component. When a new work step is started, a simulation clock should record the point of time and give it to WEATHER. Based on the time and the weather input data, WEATHER generates the weather conditions. The main weather characteristics such as temperature, relative humidity, wind velocity and precipitation are considered. Furthermore, work steps which are sensitive to weather factors are identified by WEATHER.

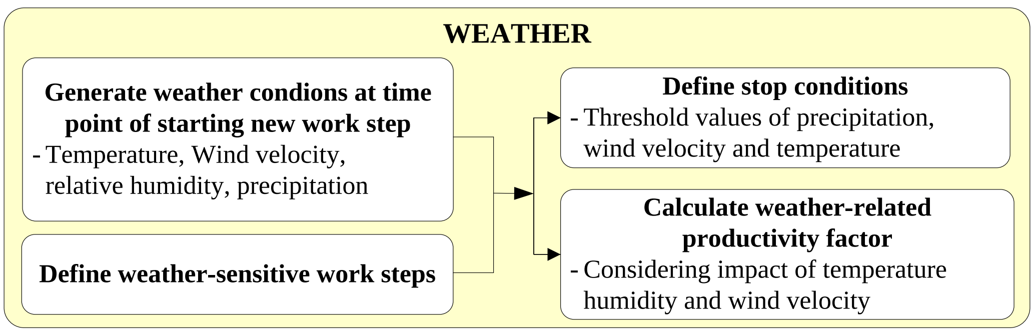

Figure 3: WEATHER component description

Case (1) and (3) of the weather impacts on construction processes discussed in section 2 are implemented in WEATHER. Case (2), the impact of wind velocity on the operation of cranes, leading to the effect on the delivery of material to high levels, will be considered in next research steps. That means, material can be transported to the different levels without interruption due to weather. Based on the identification of the weather-sensitive work steps, their influencing weather factors and the generated weather conditions, WEATHER determines the stoppage conditions of the current work step or calculates the weather-related labor productivity factor. Threshold values of precipitation, wind velocity, temperature are defined to specify the conditions of temporarily stop working. For example, whenever wind velocity is stronger than 17,1 m/s (wind scale is 8) people should stop working. In order for WEATHER to calculate the weather-related productivity factor, Figure 1 and Eqs (3),(4) are utilized. This productivity factor represents the percentage of efficient working performance, then its value is less than or equal to 1. If it is equal to 1 then the working performance is not affected; in other words, the activity's duration is not changed. If the productivity factor is less than 1 then the activity's duration is extended because the standard working performance can't be achieved due to bad weather. Thus, the weather-related duration of each work step is calculated using Eq. (5): $D_W = D / P$. In this equation, D_W is the weather-related duration; D is the ideal duration, which is estimated based on historical data, experts' knowledge or standard estimating manuals; P is the productivity factor calculated by Eq. (4).

3.3. Integrating the weather impact into the execution processes

The final step is integrating the weather impact into the execution process, see Fig. 4. The stoppage conditions are described as hard constraints, whereas the productivity of the work steps is described as a soft constraint. When a new event occurs, after all hard constraints of the processes have been fulfilled, all weather-sensitive work steps are checked for their weather stoppage conditions. It should be reminded that, at this point of time, WEATHER generates the weather factors based on the time given by the simulation clock. If the weather factors are not beyond the threshold values, then work steps can be listed as being executable. Conversely, weather-sensitive work steps should be stopped. Then WEATHER calculates weather-related productivity factors for all executable weather-sensitive steps. The next simulation step is ordering these executable steps randomly or by the percentage of the fulfilment of their soft constraints. Only the first work step in the list can be executed. In case several steps fulfil their soft constraints in equal measure, one of them is chosen randomly. Besides, executable steps can be arranged in descending order of work step's productivity. That means the work steps with higher productivity are listed above in the list and will be executed first. After a work step is chosen, it can be started with its weather-related duration. The simulation runs until there are no more unfinished work steps.

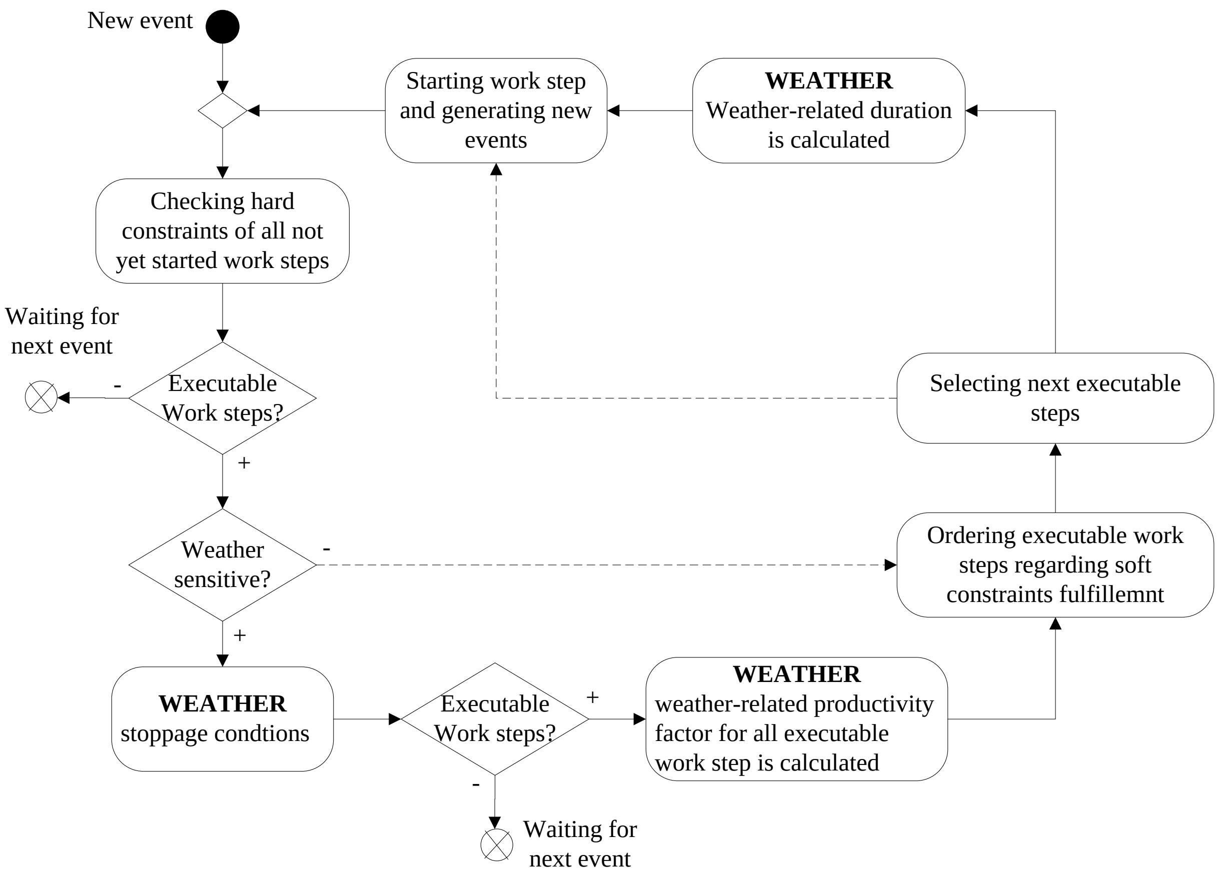

Figure 4: Weather-construction processes integrated diagram

4. EXAMPLE

An application example of a fiber cement façade construction is applied to illustrate the proposed approach and demonstrate its capabilities in: (1) analyzing the impact of weather on the execution process through comparing the non-weather and weather execution processes; (2) supporting the preparation of realistic execution planning by performing many simulation experiments; (3) helping in analyzing and estimating weather-related construction claims.

The construction site of the façade system of a 5-story building in Schwarzenberg, Germany was visited in order to collect necessary data. The erecting process of a fiber cement façade system consists of the assembling of four main components: wall angle, insulation, aluminum profile and fiber cement façade element. The installation of these four main components is decomposed into ten work steps: measuring the position, fixing wall angles to the building's structure; measuring the position and dimension of elements, cutting, fixing insulation elements to wall angles and building structure; measuring position and dimension, cutting aluminum profiles, installing aluminum profiles; measuring position, installing façade element. The execution duration of each type of work step was determined based on expert's knowledge, which is shown in Fig. 5.

In order to simulate the execution process, the constraints for assembling the façade system need to be specified. The technological dependencies are represented in Figure 5. 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 (Beißert, König and Bargstädt 2007). 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 17:30 pm including a pause of an hour at noon.

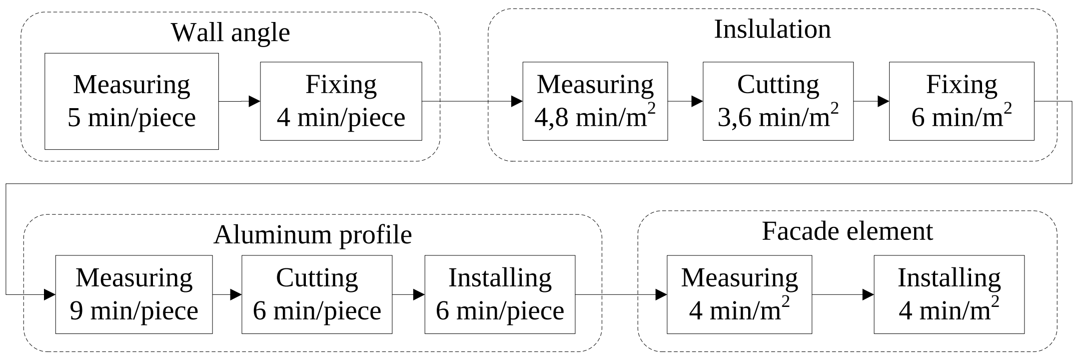

Figure 5: Technological dependencies between work steps and their non-weather-related execution duration

For each simulation run, the whole project or its certain parts, which need to be constructed, are defined manually. The information about these construction assignments such as the position or the construction starting time of the project's part is defined in a construction assignment container. Besides, the work steps, work steps' constraints and material are also defined in containers and generated by some data generators. To learn in more detail about the components of discrete-event simulation framework, which help in simulating a construction process, please refer to the research of Beißert, König and Bargstädt (2007).

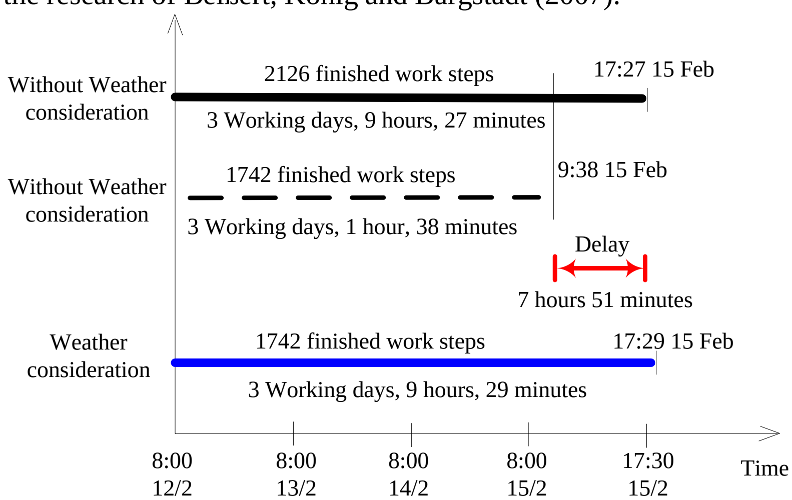

Figure 6: Simulation results of construction duration and number of finished work steps

With this model, both non-weather- and weather-related execution schedules can be simulated and experimented. The non-weather-related schedule is considered as the as-planned schedule in the preconstruction stage. The weather-related schedule is the actual schedule on site in the executing stage. The weather parameters are temperature (^{o}C), wind velocity (m/s), relative humidity (%), precipitation (mm). If the model considers weather forecast data, then it runs in every period of 5 days. In this example, the contract specifies a start construction date of February 12, 2008. The results of the model for the non-weather and weather-related schedule are shown in Figure 6.

The results consist of number of work steps, which are finished in a period of 5 days; and the construction duration needed to finish these work steps. 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. As shown in Figure 6, in 4 working days, there should be 2126 finished work steps and the finish time date is at 17:27 on Feb 15. However, during these 4 working days, construction operations experience delays and work steps' extended working duration due to bad weather. On the first 3 days, there is heavy rain in 2 hours every day. Thus the construction site is temporarily shut-down during raining. Besides, the productivity factor is reduced due to uncomfortable conditions of temperature, humidity and wind velocity. Therefore the work steps' execution duration is extended. The output of the model shows that in 4 working days, there are only 1742 finished work steps. In a different scenario, the construction delay is estimated based on the results of the simulation model. It is shown in Fig. 6 that 1742 work steps should be finished at 9:38 on Feb 15 without considering weather conditions, whereas these number of work steps can actually be finished at 17:29 Feb 15. That means that the construction delay is 7 hours and 51 minutes due to the impact of weather.

These results support to analyze and quantify the impact of bad weather on the execution processes of a façade system. Furthermore, the simulation experiments can be made to help in preparing practicable weather-related execution schedules. Table 2 represents the results of 4 simulation runs, which are performed randomly. These experiments have the same weather conditions, construction assignments, work steps, constraints, workers. In every simulation run, the next started work step is chosen randomly from the list of next executable steps. Therefore, the final results of every simulation run are different from each other. Each simulation run demonstrates a possibility of executable schedule with different execution duration and the number of finished work steps. Results of the number of finished work steps clearly show the consequence of the weather impact on the execution process. Instead of 2126 work steps which should be finished in 4 working days, less than 1800 work steps can be finished. The experiment results show that the schedule achieved from experiment 2 has the most number of finished work steps, then it may be a good choice.

Table 2: Results of construction duration and number of finished work steps from experiments

Experiment No.	Weather-related execution schedule	
	Number of finished Work steps	Duration (dd: hh: mm: ss.ssss)
1	1742	3:09:29:06.3419
2	1753	3:09:29:24.2820
3	1733	3:09:29:35.4949
4	1740	3:09:28:28.1313

5. CONCLUSION

Weather clearly has a major impact on construction processes, leading to the extension of construction duration and cost overruns. Reducing the disturbances caused by bad weather during the execution processes is normally based on the engineer's experience. The need to know how bad weather conditions can affect the execution processes as well as how to reduce the consequences is obvious.

The presented approach showed a method how to include weather criteria into the construction planning in order to avoid the unexpected disturbances. It presented a model which integrates the impact of weather as constraints into the simulation of construction processes. This approach guarantees a flexible way to consider weather conditions; where on one hand the model can be easily adapted by adding or removing constraints, on the other hand the weather parameters can be adjusted regularly as necessary. The approach concentrated on the modeling of the working process of each construction activity by decomposing it into single work steps. Thus the impacts of weather can more precisely be allocated to the different activities of a construction process.

This model focused presently on the impact of weather in the executing stage, using a 5 day forecast period. As a result, non-weather-related and weather-related execution processes of every 5-day period can be experimented. Based on the results of the forecast experiments, the effect of actual on-site weather conditions on the operative execution process can be identified. Thus different options can be taken to resolve or reduce the possible consequences due to unexpected bad weather conditions in the short term execution duration, which obviously affects the whole construction time. For example, different practical execution strategies can be investigated to find appropriate execution sequences on site. The possibly extended duration due to bad weather can be optimized.

Based on this simulation approach, the historical weather data can also be considered in next research steps. Therefore the possibility to investigate the whole construction duration is provided, which help in preparing construction planning. Furthermore, based on the impact of typical weather pattern in the year, the forecast of manpower utilization during project time is analysed. Thus, the presented approach can be applied in order to utilize manpower more effectively, which will help in increasing the overall construction productivity and in reducing the non-working or unproductive working time especially for medium specialized construction companies, who have some operative construction sites in different regions.

REFERENCE

"Beaufort scale", from http://www.nzz.ch/nachrichten/wetter/beaufortskala.

"Krane (Hilfe zur Erstellung einer Betriebsanweisung)", from http://www.eval.at/evalflash/pdf_betriebsanweisungen/Betriebsanw_Kran.pdf.

Beißert, U., König, M. and Bargstädt, H.-J. (2007). "Constraint-Based Simulation of outfitting processes in Building Engineering". *CIB 24th W78 Conference*, Maribor, Slovenia

Beißert, U., König, M. and Bargstädt, H.-J. (2008a). "Execution Strategy Investigation Using Soft Constraint-Based Simulation". *IABSE ICT Conference*, Helsinki, Finland.

Beißert, U., König, M. and Bargstädt, H.-J. (2008b). "Generation and Local Improvement of Execution Schedules Using Constraint-Based Simulation". *ICCCBE-XII & Incite*, Beijing, China.

Beißert, U., König, M. and Bargstädt, H.-J. (2009). "Considering quality aspects for construction scheduling using Constraint-Based Simulation". *CIB W078 & MC4T - Managing IT in Construction*, Istanbul, Turkey, A.A. Balkema.

El-Rayes, K. and Moselhi, O. (2001). "Impact of Rainfall on the Productivity of Highway Construction". *Journal of Construction Engineering and Management*, 127(2), 125-131.

Hyun-Soo, L. et al. (2005). "Method for Calculating Schedule Delay Considering Lost Productivity". *Journal of Construction Engineering and Management*, 131(11), 1147-1154.

Koehn, E. and Brown, G. (1985). "Climatic Effects on Construction". *Journal of Construction Engineering and Management*, 111(2), 129-137.

König, M., Beißert, U. and Bargstädt, H.-J. (2007). "Visual Simulation - An Appropriate approach to support execution planning in building engineering". *Proc. of the 7th International Conference on Construction Applications of Virtual Reality (ConVR)*, Pennsylvania State University, USA.

Moselhi, O. and El-Rayes, K. (2002). "Analyzing Weather-Related Construction Claims". *Cost Engineering* 44/No.8.

Moselhi, O., Gong, D. and El-Rayes, K. (1997). "Estimating weather impact on the duration of construction activities". *Canadian Journal of Civil Engineering*, 24(3), 359-366.

Shahin, A. et al. (2007). "A simulation-based framework for quantifying the cold regions weather impacts on construction schedules". *Proceedings of the 39th conference on Winter simulation*, Washington D.C., IEEE Press.

Smith, G. R. and Hancher, D. E. (1989). "Estimating Precipitation Impacts for Scheduling". *Journal of Construction Engineering and Management*, 115(4), 552-566.

Song, L., Al-Battaineh, H. T. and AbouRizk, S. M. (2005). "Modeling uncertainty with an integrated simulation system". *Canadian Journal of Civil Engineering*, 32, 533-542.

Thomas, H. R. and Yiakoumis, I. (1987). "Factor Model of Construction Productivity". *Journal of Construction Engineering and Management*, 113(4), 623-639.