Case Study

Impact of Weather Conditions on In Situ Concrete Wall Operations Using a Simulation-Based Approach

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Abstract: The purpose of this research is to study the impact of temperature, precipitation, and wind speed on in situ concrete wall operations, and its combined resulting effect on project duration. The research presented is anchored in the learnings gained through a literature review on weather effects on construction operations, an analysis of weather data with high resolution, and two field studies of in situ concrete wall operations. These learnings are implemented in a discrete event simulation (DES) model for the analysis of weather impact on project duration. The simulation results show that (1) weather greatly impacts project duration and has to be accounted for when planning operations; (2) there are huge differences between weather seasons that could affect the timing of project start-up; and (3) the height of buildings and threshold values for different types of cranes have to be accounted for when planning lifting operations. The main contribution of this paper lies both in the methods, in which high-resolution weather data can be incorporated in DES models to analyze project duration, and in the actual results of the simulation runs, showing to what level weather variables have to be incorporated in the planning of concrete wall construction. **DOI: 10.1061/(ASCE)CO.1943-7862.0001662.** *© 2019 American Society of Civil Engineers.*

Introduction

The productivity of construction operations can be affected by many factors, of which weather is one that may cause disruptions, delays, and cost overruns in construction projects (Christian and Hachey 1995; Thomas and Ellis 2009; Nguyen et al. 2010). Low temperature, rain, etc., hamper the workers' ability to perform optimally, but also other resources, like machinery, may be affected. For example, strong winds may result in that cranes cannot be used for safety reasons. Due to the size of building sites and the fact that they change in layout as the construction evolves, it is not easy to employ measures to shield production against weather. Consequently, weather must always be accounted for when planning construction works and it is necessary to adjust productivity data for specific weather conditions to get reliable project duration and cost estimates.

Previous research studies have focused on how different weather parameters influence productivity, many of them with a focus to establish relationships between weather parameters and labor productivity. Three weather parameters seem to be of main interest: temperature, precipitation, and wind speed, in which the former two have gotten the most attention (e.g., Koehn and Brown 1985; Thomas and Yiakoumis 1987; Thomas et al. 1999). Fewer studies have focused on the effect of wind speed despite the fact that it is pointed out by industry experts as an important factor to consider (Watson 2004). One exception being the study by Moselhi and Khan (2010) analyzing the effects of wind speed on formwork productivity. Based on existing weather–productivity relationships, attempts have also been made to estimate and predict construction project duration under varying contextual conditions see (e.g., Moselhi et al. 1997; Ballesteros-Perez et al. 2015; Shahin et al. 2011; Jung et al. 2016).

However, these projects have addressed weather conditions on a more general level. For instance, the weather data used are based on monthly or, at the best, daily average values. Unfortunately, even a daily aggregate level of data is limited to describing the natural daily variations in weather variables, and how this affects the productivity of construction projects. Temperature is normally lower at night, the intensity of precipitation or wind speeds may vary on an hourly basis, and so forth. Obviously, the most interesting time span to consider weather conditions is during actual working hours and to link current weather conditions with specific work tasks. Today, weather data with higher resolution (hourly basis) can easily be accessed from meteorological databases. This enables to study the effects on a more detailed level (work tasks hour by hour) and thereby provide better predictions.

In this research, a discrete-event simulation-based approach was used to study how weather conditions, on an hourly basis, affect construction operations and project duration. Furthermore, this research focused on construction of in situ concrete walls. Forming and pouring concrete on-site is a frequently used method in many types of construction projects (Illingworth 2000). It is also typically time critical in order to sustain the planned production cycle and it is exposed to all three main weather parameters: temperature, precipitation, and wind speed. Examples being erecting and stripping of formwork, pouring concrete, use of crane for lifting formwork, and the curing process of concrete. Any daily deviation in the construction of the concrete walls may increase the production cycle, and thereby jeopardize the overall project schedule and cost budget.

Hence, the purpose of this research was to study the impact of weather conditions on construction operations using a simulation-based approach. More specifically, the impact of temperature, precipitation, and wind speed on in situ concrete wall operations were studied, and their combined resulting effect on project duration.

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Within this purpose, the following research questions (RQs) are addressed:
- RQ1: How do different weather variables affect construction productivity?
- RQ2: How can the effect of weather variables be described and analyzed using a simulation-based approach?
- RQ3: How is construction productivity (measured as total project duration) affected by different weather conditions and seasonal variations?

The results of this research contribute to the knowledge of how weather conditions affect the duration of construction operations. In contrast to earlier research, the proposed simulation-based approach is more detailed in its description of construction operations, and it also uses combined weather parameters on an hourly basis. This allows for natural daily variations in weather parameters and thus increases the accuracy in estimations of the influence of weather on construction projects. The presentation of the research in this paper is structured in the following way. First, the research process is described presenting in detail the work undertaken. Thereafter, the problem background is presented describing the concept of baseline productivity followed by a review of previous work related to how weather affects construction efficiency. Next, the two field studies are presented in which real process data and knowledge are captured, necessary for model development. This is followed by a detailed description of the simulation model, its components, and how the effect of weather on construction work tasks are considered. Weather data analysis together with input data and simulation model validation are also described. The following two sections describe the work with designing the simulation experiments and the results. The next section is devoted to analyzing and discussing the results. Finally, conclusions, including recommendations for future work, are provided.

Research Approach

The research approach is outlined in Fig. 1. The research process contains five main steps, each described in more detail in this section. Steps 1–3 are used as input to Steps 4 and 5. Steps 1 and 2 are related to RQ1, whereas Step 4 is related to RQ2. Step 4 is used as a basis for the simulation experiments in Step 5, which is used for answering RQ3.

Literature Review, Weather Data, and Field Studies

In the first step, the theory of baseline productivity (Thomas and Zavrski 1999) was studied in order to estimate ideal work productivity (1.1 in Fig. 1), to which the effects of weather parameters could be added. Then, a literature review focusing on studies treating weather-related effects (1.2 in Fig. 1) on construction productivity was conducted, including both scientific papers and technical reports. These two parts formed the theoretical base for how the effects of weather conditions should be treated in this study.

Based on the knowledge gained in Step 1, it was concluded that temperature, wind speed, and precipitation are the most significant parameters affecting construction productivity. However, depending on the geographical location of construction sites, the weather conditions will naturally vary to a great extent. Since the field studies (Step 3) were conducted in Sweden in the northern parts of Europe, cold temperatures and precipitation in terms of snow fall might come into play. Accordingly, in Step 2 climatic data sets including these parameters were obtained from the Swedish Meteorological and Hydrological Institute (SMHI). The data sets covered hourly readings for the last 20 years for the city of Stockholm in Sweden. With the assistance of SMHI, the data sets were statistically analyzed in order to identify the year that could be conceived either as a normal year considering all three weather parameters, or as an extreme year considering one of the parameters at a time. As a final step, each data set was controlled with respect to completeness of data readings and formatting the data so it could be used in a simulation model (Step 5). Using data sets representing Swedish weather conditions naturally limits the generalizability of the study results. However, other climate data sets could be used in the simulation model doing similar analyses for other parts of the world.

Field studies of two projects (A and B) were carried out in Step 3. In both studies, the process of concrete wall construction was documented by on-site observations and from interviews with field experts. The two projects involved construction of multifamily buildings with similar structural design using similar construction

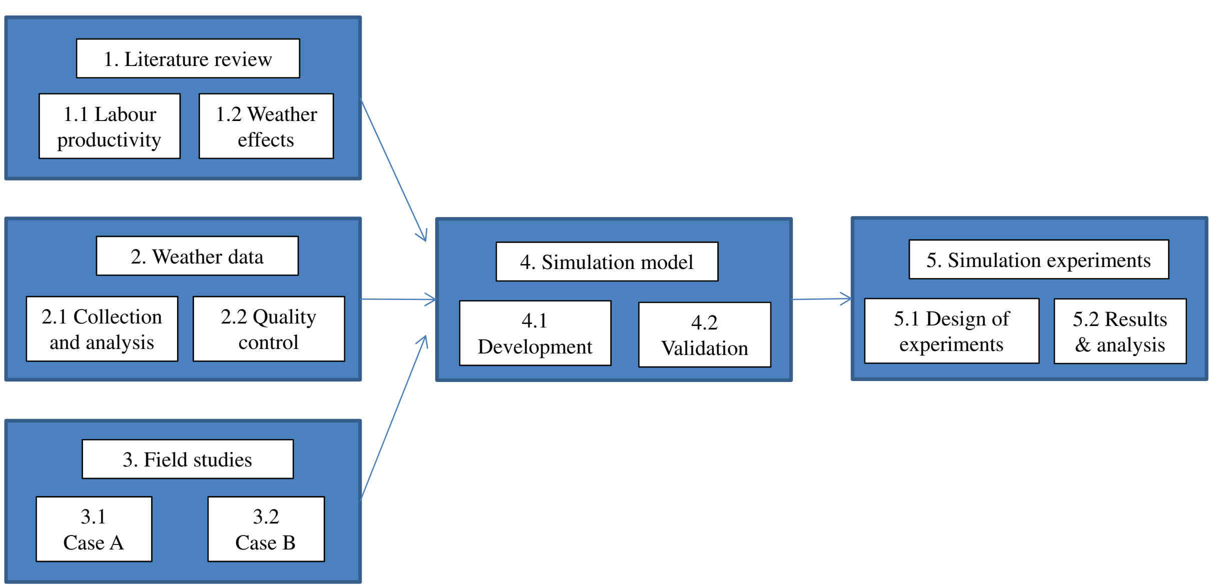

Fig. 1. (Color) Overall research process.

methods, and due to the timing of the field studies the two projects were used slightly differently to get a rich picture of the construction processes and data. For instance, in Project A, handling of formwork panels and details about wall construction sequence and resource usage were documented. In Project B, on-site time studies were carried out to collect work tasks' productivity data. The productivity values from Project B were compared with other similar studies, and also discussed with field experts involved in Project A to confirm the validity of the measured productivity rates. Moreover, Project A was also used for model validation (Step 4) and as a reference case during the simulation experiments (Step 5).

Simulation Model Development and Simulation Experiments

Based on the knowledge gained from Steps 1–3, a simulation model was developed in Step 4. The model contains a detailed description of the construction work tasks and the use of resources, focusing on construction of in situ concrete walls. It also contains specific relationships derived on the basis of productivity study. The relationships were used to determine the effect on work task productivity of varying weather parameters and the overall impact on project duration. Typical methods for verification and validation of the simulation model were employed, e.g., use of the software's integrated functions in order to test the logical behavior. For instance, stepwise animation of logical sequences, and use of embedded blocks to extract critical process data at certain points in the model structure. Finally, the simulated output was compared with the actual process documented in Field Project A.

In Step 5, the effect of weather conditions on work task productivity and total project duration were studied by simulating a number of scenarios. To facilitate a systematic approach, a matrix was developed describing the conditions for each scenario. Based on this matrix, each scenario was simulated separately under highly controlled conditions. The simulated results were compiled and analyzed, leading to conclusions on how weather conditions might impact construction operations, productivity, and project duration.

Reflections on the Research Approach

Discrete-event simulation (DES) was chosen since it offers powerful capabilities to describe and analyze complex systems in a controlled and precise environment (Lucko et al. 2008; AbouRizk et al. 2011). Influencing factors, e.g., weather, can be altered systematically and different scenarios can be studied in a very short time. An important feature of DES is it can perform what-if scenarios on the basis of stochastic input data. In this research, however, the simulation model was run with deterministic inputs. One reason was that the methodology used to calculate the effect of weather in the simulation model was deterministic. Another reason was that climatic data sets based on hourly records were used. It was not possible to create a weather function that could provide hourly values based on a statistical distribution. The research is limited in that it only focus on one project phase (erection of load-bearing concrete walls) using climatic data from one country. However, erection of the load-bearing structure is a crucial part in all building projects, and due to the design of the simulation model, climatic data sets for other countries could easily be incorporated in the simulation model. Hence, the results of the simulation are reasonably general and could be extended with other geographical regions in future studies.

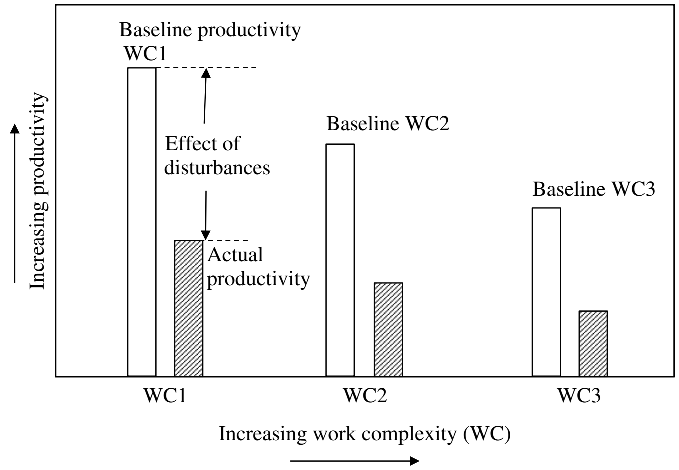

Fig. 2. Illustration of baseline productivity versus actual productivity as a function of work complexity. (Modified from Thomas and Zavrski 1999.)

Problem Background

Baseline Productivity

Productivity is affected by multiple factors simultaneously. Hence, it is difficult to determine the productivity effect of a single input factor. To deal with this problem, Thomas and Zavrski (1999) introduced the concept of baseline theory (Fig. 2). The idea is to determine the ideal productivity (baseline) for a specific project. This baseline is considered to reflect the best performance possible within a specific project, defining an ideal situation with no significant disruptions. Baseline productivity is considered to be affected only by actual work complexity. To determine baseline productivity for a specific project, it is reasonable to consider work complexity as a constant. By adding disruptive factors (one by one) to the baseline, it is possible to describe the effect of a single factor, e.g., weather conditions, on productivity. The theoretical procedure to determine baseline productivity for a specific project is described in Thomas and Zavrski (1999). In principle, baseline productivity is determined for a specific project (or work tasks within a project) using the following steps:

1. Define the size of a subset by selecting a percentage of the total number of daily productivity measurements. According to Thomas and Zavrski (1999), a reasonable percentage value is 10%.
2. Round this number to the next highest odd number. This number n should not be less than 5. The variable n defines the size of (number of days in) the baseline subset.
3. The content of the baseline subset is selected as the n days with the highest measured (or observed) productivity.
4. The baseline productivity is the median of the measured productivity in the baseline subset.

More recently, another study has proposed an alternative definition and procedure to establish baseline productivity (Jarkas and Horner 2015). However, in this study, baseline productivity is defined as a range in which productivity varies under normal conditions. Consequently, this does not reflect an ideal situation since the productivity is assumed to be influenced under normal circumstances by multiple types of factors. It is believed that the baseline theory according to Thomas and Zavrski (1999) is better suited to use as a basis for describing the effect of a specific factor, as described previously.

Table 1. Overview of references used in this paper to identify significant weather variables

Reference	Country	Weather variables in focus	Type of study
Koehn and Brown (1985)	United States	Temperature, humidity	Review and analysis of historical productivity data sets related to different temperature and humidity intervals.
Thomas and Yiakoumis (1987)	United States	Temperature, humidity	Measurements of productivity and weather variables in three projects
Holmér (1994)	Sweden	Temperature, wind speed (wind chill)	Measurements, experiments
Thomas et al. (1999)	United States	Temperature, precipitation	Measurements of productivity data and weather variables
Hassi (2002)	Sweden	Temperature	Measurements and experiences (labor works, not construction specific)
Watson (2004)	UK	Wind speed	Based on industry experiences and expertise
Mäkinen et. al. (2005)	Finland	Temperature	Tests of manual performance (dexterity) through controlled experiments
Noreng (2005)	Norway	Temperature, wind, precipitation	Assessments based on interviews and by documentation of productivity and weather variables in a number of construction projects
Thomas and Ellis (2009)	United States	Temperature, precipitation	Analysis of historical productivity data related to weather variables
Birgisson (2009)	Sweden	Temperature, wind, precipitation	Assessments based on interviews with industry practitioners
Moselhi and Khan (2010)	Canada	Temperature, wind, precipitation	Measurements of productivity and weather variables
Shahin et al. (2011)	Canada	Temperature, wind, precipitation, frost depth	Assessments based on interviews with industry experts
Ballesteros-Perez et al. (2015)	Chile	Temperature, wind, precipitation	Assessments based on previous research and industry experts' judgments
Jung et al. (2016)	South Korea	Temperature, wind, precipitation (stoppage criteria)	Interviews with site managers

Weather Effects on Construction Productivity

By reviewing the literature focusing on studies analyzing weather-related effects on construction productivity, it was possible to identify the most significant weather factors. Table 1 provides an overview of the identified references used in this study, showing that temperature, precipitation, and wind are the most important factors to include in the study. Each of these weather factors are described in more detail subsequently.

Influence of Temperature and Humidity

Not only humans, but also material and equipment are affected by temperature (Shahin et al. 2011; Jung et al. 2016). For instance, the curing process of concrete slows down when temperature decreases. The influence of temperature on construction labor productivity is relatively well documented. Productivity is affected both at low and high temperatures. Unpleasant temperatures affect humans, not only physiologically but also psychologically. Physiologically, high temperature may lead to heat stress or dehydration among individuals. At cold temperatures, workers may experience general body cooling or tissue damages (Holmér 1994) and reduced finger and hand dexterity (Mäkinen et al. 2005). The cooling effect of wind speed and low temperature in combination also increases the risk of health effects, and air humidity affects productivity both at high and low temperatures.

The effect of temperature and humidity on construction workers' productivity was explored in Koehn and Brown (1985). It was found that temperatures between 10°C and 25°C (50°F and 77°F) did not have any significant effect on productivity at normal humidity levels (about 60%). However, at colder or hotter temperatures, the effect is considerable. In a following study, Thomas and Yiakoumis (1987) claimed that temperatures between 10°C and 15°C (50°F and 59°F) were optimal in terms of work efficiency. Another study by Hassi (2002) stated that a temperature around 10°C (50°F) has no impact on labor productivity, but has significant effects on productivity when temperature rises above 20°C (68°F) or drops below −5°C (23°F). A more recent study by Moselhi and Khan (2010) suggests that an optimum temperature interval in terms of productivity is between 14°C and 18°C. Thomas and Ellis (2009) estimated that cold temperatures below −7°C (19°F) resulted in a 50% productivity loss while hot temperatures above 29°C (84°F) resulted in a 40% loss. In Fig. 3, the relationship between temperature and productivity based on three of the mentioned studies are presented.

In Fig. 3, a productivity factor (y-axis) equal to one means no loss in productivity due to temperature. Accordingly, a factor equal to zero means a 100% loss in productivity (work stoppage). As seen in Fig. 3, the estimated productivity loss based on Koehn and Brown and Moselhi and Khan are relatively equal, whereas Hassi

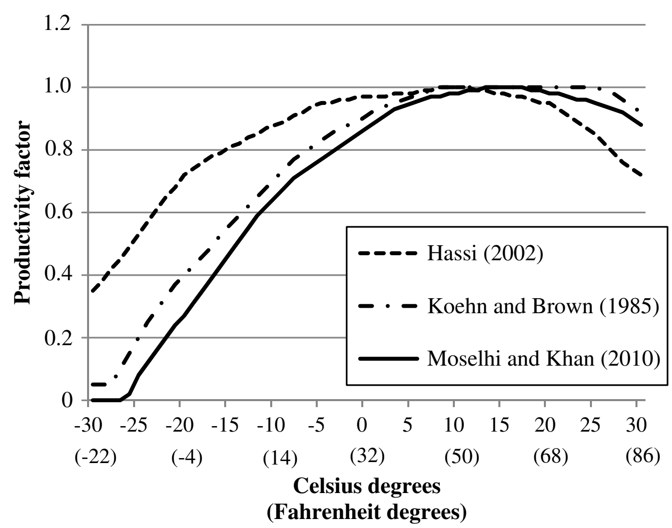

Fig. 3. Relation between temperature and productivity loss based on Moselhi and Khan (2010), Koehn and Brown (1985), and Hassi (2002).

indicates lower effects at cold temperatures and higher effects at warm temperatures.

Influence of Precipitation

Rain and snow also hamper labor productivity, since workers have to spend time on actions to cover materials and work areas. Precipitation also has a negative effect of work performance, in general, and precipitation in combination with cold temperatures can also cause slip-and-fall accidents (Jung et al. 2016). Moreover, a snowfall on an unprotected work area requires additional time for shoveling and cleaning. If the intensity of a rain or snowfall becomes too high, the work may have to stop, and Jung et al. (2016) state that precipitation is the weather factor that causes most work stoppages.

Several studies have reported that labor productivity is affected by precipitation even at light or moderate intensity. For instance, Moselhi and Khan (2010) report that light rain or snow results in a 40% loss in productivity. Noreng (2005) reports that rainfall with an intensity of 4 mm (per 12 h) causes a 65% productivity loss. The effect of snowfall is reported to vary between 10% and 60% depending on intensity. Thomas and Ellis (2009) conclude that the loss of productivity due to rain or snow is between 50% and 60%. Other studies have defined threshold values for when productivity is affected by precipitation. For instance, Ballesteros-Perez et al. (2015) state that a daily rainfall of more than 10 mm can cause a loss in productivity when pouring concrete. Another study by Jung et al. (2016) states that precipitation with intensity of 5 mm/h results in work stoppage during concrete placement. Birgisson (2009) argues that construction works on a horizontal surface are more sensitive to precipitation compared with a vertical surface.

Fig. 4 presents a summary of how construction efficiency is affected by precipitation intensity. The numbers in the diagram are based on documented studies. The red dotted line is a simplified approximation of the influence on efficiency as a function of precipitation intensity. The approximation is based on mean values for each of the intervals of precipitation intensity, as indicated by the vertical lines in Fig. 4.

Influence of Wind Speed

The influence of wind on lifting operations depends on a combination of factors, such as wind speed, height of lifting operation, ambient terrain, and type of objects to be lifted. For instance, lifting operations of large light-weight formwork panels are more affected

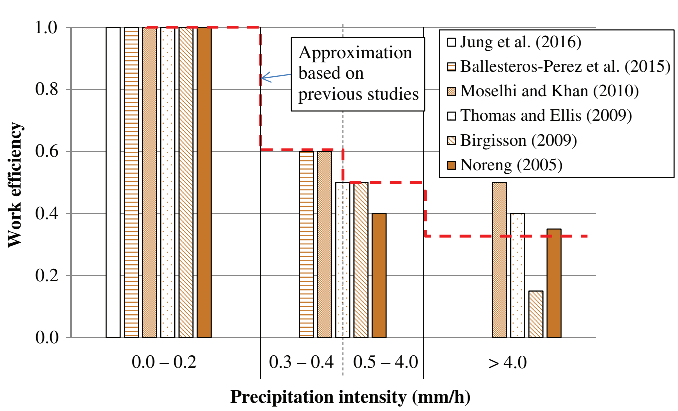

Fig. 4. (Color) Influence of precipitation on construction efficiency based on previous studies.

by wind compared with lifting heavy rebar bundles. Wind also affects workers at higher altitudes. Strong gusts of wind increase the risk of accidents and may require additional safety measures.

The most comprehensive study of the influence of wind speed was reported in Moselhi and Khan (2010). Here, wind was studied as one of several factors influencing formwork operations. It was concluded that wind speeds of about 12 m/s reduce formwork productivity by 17%. Other studies (e.g., Noreng 2005), indicate a 20%–25% productivity loss at wind speeds above 10 m/s. A study by Birgisson (2009) concluded that wind speeds between 8 and 14 m/s reduced formwork productivity by 20%. Ballesteros-Perez et al. (2015) point out that handling of formwork started to be affected at wind speeds above 5 m/s.

For safety reasons, there also exist recommendations for maximum wind speeds at which crane usage is not allowed. In general, maximum wind speed for crane usage is dependent on several factors: crane type, height, wind direction, surrounding terrain, and type of load to be lifted (surface, weight). According to international crane manufacturers, in-service wind speeds are, in general, up to 20 m/s for modern tower cranes (Watson 2004). For mobile cranes, in-service wind speeds up to 14 m/s are typically recommended. However, these recommendations may vary somewhat between countries and manufacturers. Some manufacturers provide additional information of maximum wind speeds considering the weight and size of the load to be lifted (Liebherr 2012). As a complement to manufacturer recommendations, there may also exist local industry praxis and agreements on maximum wind speed for specific lifting operations. In Sweden, for instance, lifting large formwork panels are normally avoided at wind speeds above 15 m/s (Å. Andersson, personal communication, 2017; M. Jönsson, personal communication, 2016). In Jung et al. (2016), maximum wind speeds of 10 m/s are used as a threshold value for cancelling lifting of curtain walls and pouring concrete using crane and skip. In a study by Shahin et al. (2011), the crane stoppage condition was set to wind speeds above 14 m/s.

Fig. 5 gives an overview of the documented relationship between wind speed and loss in productivity together with thresholds for both recommended and maximum allowed wind speeds for lifting operations.

Summary of Weather Effects

A summary of weather effects on construction activities based on reviewed reports is presented in Table 2. It can be noted that relatively small changes in some weather factors may have significant impact on work efficiency. For instance, a small increase in precipitation intensity may reduce work efficiency by 40%, or increasing wind speed above 14 m/s may cause a work stoppage for some lifting operations. It is therefore necessary to describe these relations in as much detail as possible, e.g., by describing effects of weather factors on individual work tasks using climatic data sets with hourly resolution. In this paper, the relationships presented in Figs. 3–5 are used as a basis to describe how weather parameters influence losses in efficiency for different work tasks. A description of how these relationships are incorporated into the simulation model is described in the section "Procedure for Considering Weather Conditions." Specific values on the weather–productivity functions that are used when performing the simulation experiments are outlined in Table 6.

Field Study Projects

Two projects (A and B) were used to gain knowledge about the construction process of in situ concrete walls. An overview of

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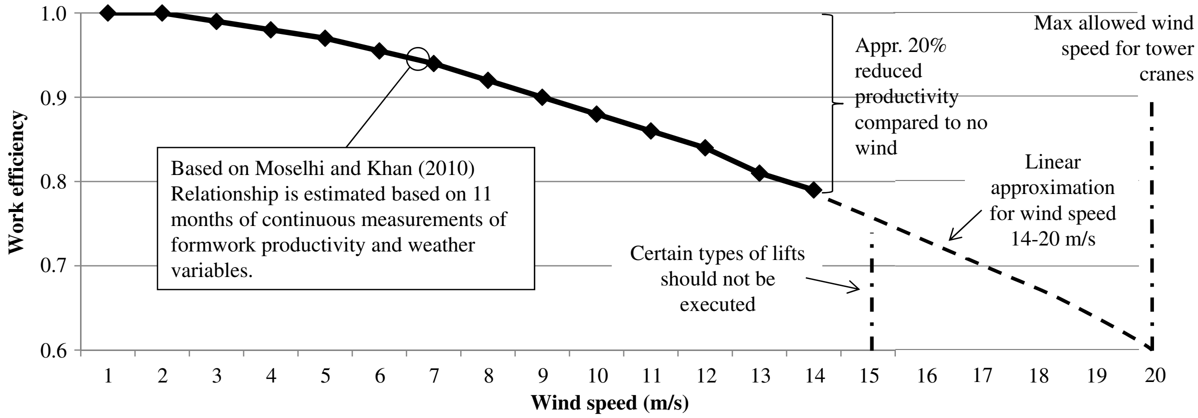

Fig. 5. Influence of wind speed on construction works based on Moselhi and Khan (2010) and threshold for recommended and maximum allowable wind speeds.

Table 2. Summary of documented effects of weather on construction productivity

Weather parameter	Type of work affected	Influence on activity	Remark
Temperature	Most type of works involving individuals	Reduced productivity at cold and hot temperatures. Examples of relationships are given in Fig. 3.	Curing of concrete is affected by temperature which determines the time when formwork can be removed. Also, equipment and machines may be affected by extreme temperatures.
Rain	Most type of works involving individuals	Labor productivity is already reduced even at light rain. Light rain (above 0.2 mm/h): 40% loss. Rain above 0.5 mm/h: 50%–65% loss.	Pouring concrete slab is sensitive to heavy rainfall. Pouring may have to be cancelled or measures to protect the surface have to be carried out. Materials have to be protected from rain.
Snow	Most type of works involving individuals	Labor productivity is also reduced during snowfall. The effect varies between 10% and 60% loss due to intensity.	Works on concrete slabs are more sensitive to snowfall than walls. Actions to protect a working area must be carried out if snowfall is expected. Materials have to be protected from snow.
Wind	Work at heights, lifting operations (e.g., formwork).	Lifting operations cancelled at wind speeds >20 m/s	Thresholds for cancelling formwork and concrete operations may vary. For instance, in Sweden, formwork operations and pouring concrete are normally avoided at wind speeds above 15 m/s
		About 20% productivity loss at wind speeds in the range of 10–12 m/s. Above these wind speeds, the loss in productivity increases rapidly, as discussed in Moselhi and Khan (2010).	Additional safety measures may be required at high winds.

Table 3. Description of field study projects and data collection activities

Field study	Project type	Building characteristics	Construction method	Field study activities
A	Multifamily building	Two buildings Six floors 74 apartments	In situ concrete Modular formwork	Process documentation (work sequence, resource usage) Interviews with site personnel and suppliers (work practice, activity durations) On-site observations
B	Multifamily building	One building Four floors 126 apartments	In situ concrete Modular formwork	Process documentation (work sequence, resource usage) Time studies (productivity data)

the project characteristics and description of data collection activities is outlined in Table 3.

Description of Construction Process and Formwork Management

The construction sequence of in situ concrete walls consists of a set of work tasks carried out both sequentially and simultaneously. The construction sequence is typically cyclical and repeats itself on a daily basis. A sequence starts with erecting the first side of formwork. When finished, box outs for openings are mounted onto the panels. Simultaneously, subcontractors place pipes and outlets. Rebars are then mounted and fixed. When all rebars are in place, the second side of formwork is erected and then concrete is poured. The formwork is then stripped when the concrete walls have reached sufficient strength. Formwork panels are then moved to

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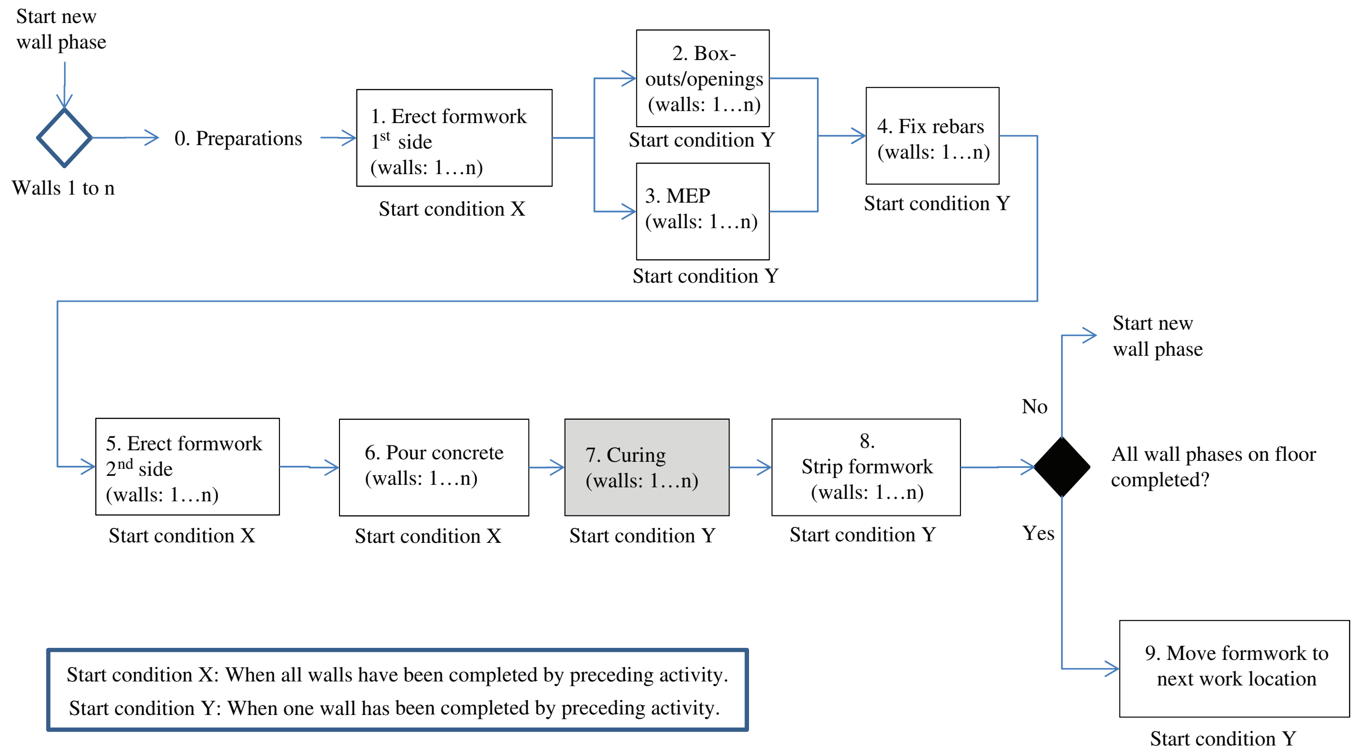

Fig. 6. (Color) Construction sequence of concrete walls found in field projects.

the next position where the sequence starts over again. The construction sequence documented in the field studies is schematically illustrated in Fig. 6.

Moreover, the start of a work task is dependent on the output from a preceding activity. This dependency is indicated by Start Conditions X and Y in Fig. 6. For instance, pour concrete (Work Task 6) is allowed to start when Work Task 5 has finished formwork erection for all walls subjected to a particular wall phase. Start Condition Y enables an overlapping processing. For instance, fix rebars (Work Task 4) is allowed to start when one wall has been completed by Work Tasks 2 and 3, respectively. It should be noted that on a general level, the starting conditions may vary from project to project.

The most important work tasks involve handling of the formwork system, which include preparations, erection, stripping, and movement to the next work location. The walls on a floor plan are divided into groups (wall phases). The division of wall phases and the formwork handling scheme in Field Project A are illustrated in Fig. 7, in which each floor plan consists of four wall phases with a varying number of walls.

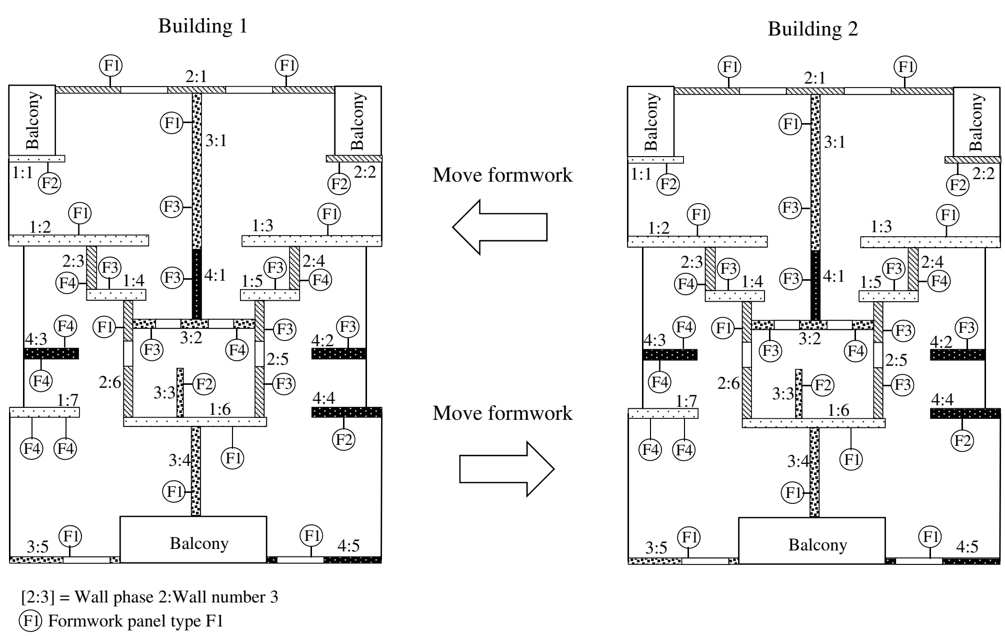

Fig. 7. Floor plan layout and construction sequence of walls including formwork usage scheme of the two buildings in Field Project A.

The first number in brackets represents wall phase number (overall sequence) and the second number represents the construction sequence of walls within each phase. The denotations F1–F4 represent different types (sizes) of formwork panels. Since the formwork panels are shared between the two buildings, they are moved between these, as indicated by the two opposing arrows. When the walls in the last wall phase are completed in Building 1, the formwork panels are stripped and lifted to Building 2. Here, the work sequence starts over until all walls are finished and the formwork is moved back once again. The procedure is repeated until all floors in the two buildings are finished.

Estimation of Baseline Productivity

Labor productivity for each work task (as described in Fig. 6) was collected by time study observations in Field Study B. The measurements were carried out during a period of five weeks. A standardized time study collection form was used in which resource usage, work quantities, and man hours for each activity was documented. The collected data was used to determine labor productivity and also for estimation of baseline productivity, according to Thomas and Zavrski (1999). As an example, a copy of data collection of labor productivity for pouring concrete walls is given in Fig. 8. In Fig. 8, the baseline subset and the determined baseline productivity are displayed. Baseline productivity data for remaining work tasks, according to Fig. 6, were estimated in the same way and are given in Table 4.

Simulation Model Development

Model Description

The simulation model was implemented in ExtendSim AT (version 9.2), which is a general-purpose discrete-event simulation software (Imagine That, Inc. 2019). More details about the simulation

Productivity data collection protocol

Activity: Concrete pouring (walls)

Concrete pour number	Quantity (m3)	Man-hours	Productivity (mh/m3)	Remark	Productivity sorted (mh/m3)
2	4.4	1.2	0.27		1.08
3	5.7	1.2	0.21		0.78
4	12.3	5.1	0.41		0.75
5	10.4	5.0	0.48		0.58
6	6.0	1.2	0.20		0.50
7	9.6	3.4	0.35		0.49
8	7.8	2.7	0.34		0.48
9	5.0	1.8	0.36		0.46
10	2.9	2.2	0.75		0.44
11	7.6	3.2	0.42		0.42
12	9.6	2.7	0.28		0.41
13	4.0	3.1	0.78		0.40
14	7.9	2.8	0.35		0.39
15	7.0	2.6	0.37		0.38
16	9.7	4.8	0.49		0.37
17	3.0	3.3	1.08		0.37
18	8.1	2.9	0.36		0.36
19	5.8	2.9	0.50		0.36
20	6.0	1.8	0.30		0.36
21	3.7	1.3	0.35		0.35
22	4.6	1.8	0.39		0.35
23	9.7	3.3	0.34		0.35
24	3.2	1.2	0.38		0.34
25				no observations made	0.34
26				no observations made	0.32
27	6.7	2.0	0.30		0.30
28				no observations made	0.30
29	8.3	3.0	0.36		0.30
30	3.6	2.1	0.58		0.28
31				no observations made	0.28
32				no observations made	0.27
33				no observations made	0.27
34	3.3	1.5	0.46		0.25
35				no observations made	**0.22**
36				no observations made	0.21
37	7.3	2.7	0.37		0.20
38	7.3	3.2	0.44		
39	9.3	2.5	0.27		
40	7.2	1.8	0.25		
41				no observations made	
42	9.4	3.0	0.32		
43				no observations made	
44	5.5	1.2	0.22		
45	2.0	0.8	0.40		
46	9.3	2.8	0.30		
47	5.4	1.5	0.28		

Sorted data from low to high productivity

Baseline subset = 5 observations with highest daily productivity

Baseline productivity = median value of baseline subset.

Fig. 8. (Color) Example of data productivity sampling protocol and productivity observations used to determine baseline productivity for pouring concrete walls.

Table 4. Summary of baseline productivity data for concrete wall activities

Activity (according to Fig. 6)	Unit	Baseline (man-hours/unit) size of baseline subset = 5
1. Erect formwork 1st side	m^2	0.1
2. Box outs	pcs	0.3
3. Place MEP	m^2	0.02
4. Fix rebars	kg	0.01
5. Erect formwork 2nd side	m^2	0.06
6. Pour concrete	m^3	0.22
7. Curing	h	15[a]
8. Strip formwork	m^2	0.02
9. Move/relocate formwork	m^2	0.02

Note: MEP = mechanical electrical and plumbing.
[a]Refers to the time necessary for concrete to reach 6 MPa in compression strength, which is a recommended threshold in Sweden for removing wall formwork.

software and how it works can be found in, for example, Krahl (2003) and Schriber et al. (2013). A schematic illustration of the simulation model and its components are illustrated in Fig. 9. An essential part of the model is the logical description of the workflow. The model is hierarchical using ExtendSims's predefined construct block elements to describe project's characteristics, including workflow and the use of resources, and for import and export of data. In the example in Fig. 9, the construction setup for Field Study A is shown.

User-defined data is imported at the beginning of the simulation from Excel spreadsheets and stored in internal databases. Data are retrieved depending on model update status during the run of the simulation. Simulation results are continuously logged and stored in output databases. Timing data of the simulated process can be retrieved both at an overall level (project duration) and at a work task level (daily output). The model also reports when the crane stops due to high winds and the activities that are affected. Simulation starts at a user-defined date and simulates the construction process until all walls have been completed.

Procedure for Considering Weather Conditions

Another essential part of the simulation model is the algorithm for considering the impact of weather conditions on construction productivity based on the findings from the literature review. The loss in productivity as a result of changing temperature is given by the variable p_{temp}, which is determined by the graphs in Fig. 3. In the same way, p_{prec} determines the productivity loss due to precipitation according to the approximated graph in Fig. 4. The loss in productivity due to increasing wind speed is given by the variable p_{wind}, which is determined by the graph in Fig. 5 including thresholds for maximum allowable wind speeds for crane usage. These variables are used to dynamically calculate the productivity loss for a new set of climatic data during the run of a simulation. The influence on actual productivity is determined by multiplying the baseline productivity with a weather factor (wf). The weather factor describes the combined effect of wind speed, temperature, and precipitation intensity [Eq. (1)]

$$wf = p_{\mathrm{wind}}(w) \times p_{\mathrm{temp}}(t) \times p_{\mathrm{prec}}(p) \tag{1}$$

where $p_{\mathrm{wind}}(w)$ defines the effect on productivity as a function of wind speed $0 \leq p_{\mathrm{wind}}(w) \leq 1$; $p_{\mathrm{temp}}(t)$ defines the effect on productivity as a function of temperature $0 \leq p_{\mathrm{temp}}(t) \leq 1$; $p_{\mathrm{prec}}(p)$ defines the effect on productivity as a function of precipitation intensity $0 \leq p_{\mathrm{prec}}(p) \leq 1$; w = wind speed (m/s); t = temperature (°C); and p = precipitation intensity (mm/h).

The weather factor (wf) varies between 1 and 0, in which 1 indicates no loss in productivity due to weather effects and 0 means a 100% loss in productivity (equal to work stoppage). In Fig. 10, the overall procedure for considering the impact of weather conditions on construction duration is presented. The main steps are as the following:

1. At every hour, actual weather conditions (wind speed, temperature, precipitation) are imported from the climatic database. The weather data is updated on an hourly basis. Depending

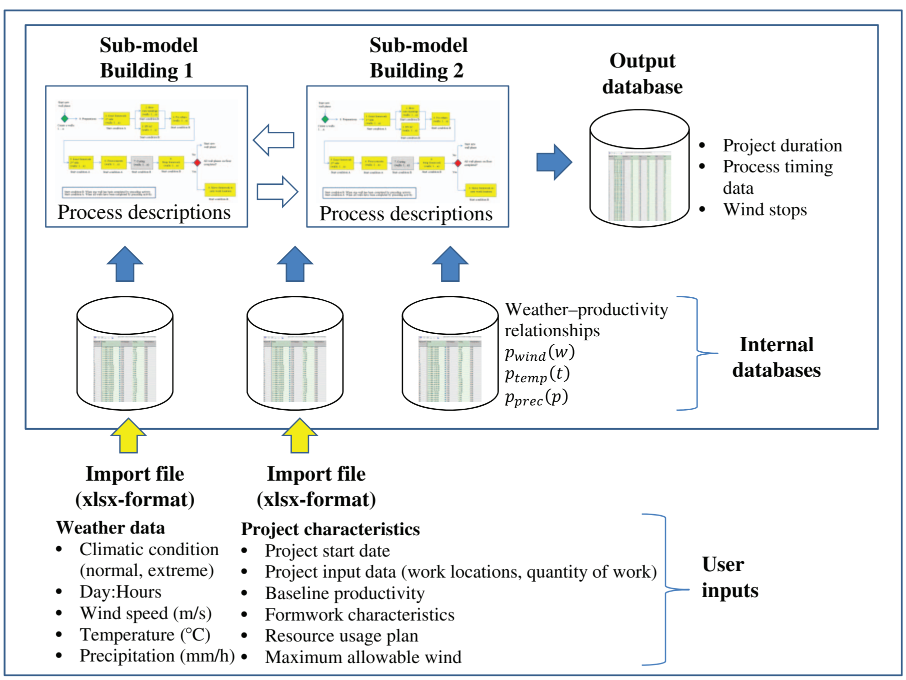

Fig. 9. (Color) Simulation model and its components including data management.

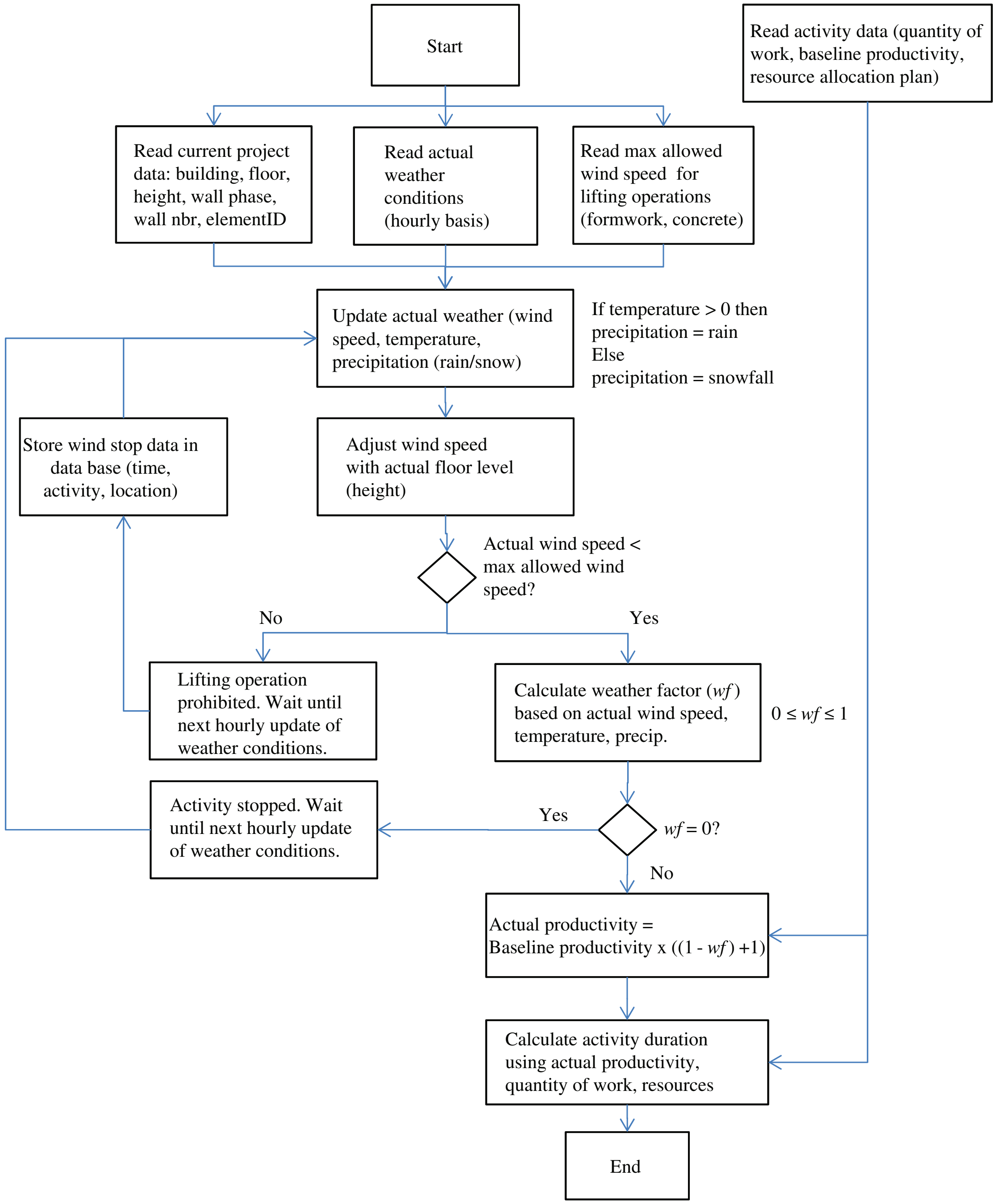

Fig. 10. (Color) Description of how weather is accounted for in the simulation model.

on actual temperature, the type of precipitation (rain or snow) is determined.

2. Wind speed is adjusted to current altitude at which construction work is taking place. This is done according to power law wind profile [see Eq. (2)]

$$w_z = w_g * \left(\frac{z}{z_{\mathrm{ref}}}\right)^{\alpha} \quad (0 < z_{\mathrm{ref}} < z) \qquad (2)$$

where w_z = wind speed at height z; w_g = measured wind speed at measured altitude z_{ref}; and α = coefficient that is dependent on the surface type and atmospheric stability. According to Şen et al. (2012), α is about 0.4 for urban areas.

3. Actual wind speed is then compared with maximum allowed wind speed for lifting operations. Threshold values are user defined and imported into the model at the beginning of the simulation. Different types of lifting operations can have different threshold values. Also, different thresholds can be defined for different formwork types, e.g., large panels may have a lower threshold value than panels with small surface area exposed to wind.
4. If the wind speed is higher than maximum allowed wind speed, the model stops until the next update of weather conditions.
5. If wind speed is lower than allowable wind speed, the effect on labor productivity is determined by the weather factor (wf). If wf is equal to zero, the work is stopped until the next update of weather conditions.

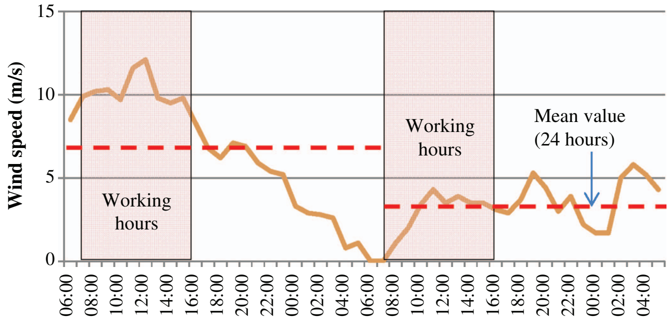

Fig. 11. (Color) Hourly wind speed variation versus average wind speed.

Weather Data Analysis

Weather data was retrieved and analyzed in collaboration with the SMHI. For a specific geographic location (Stockholm), data sets for five different climatic conditions were compiled on the basis of a 20-year period (1997–2016) of weather data.

1. *Normal*: The year that had least deviation in annual precipitation, annual average temperature, and average wind speed compared with average values for the total period of 20 years. Based on the analysis, year 1997 was selected.
2. *HighTemp*: Year 2014 was selected because it had the highest annual mean temperature.
3. *LowTemp*: Year 2010 was selected because it had the lowest annual mean temperature.
4. *Windy*: Year 2011 was selected because it had the highest average wind speed.
5. *HighPrec*: Year 2012 was selected because it had the highest annual precipitation.

For each year selected, wind speed, temperature, and precipitation for every hour during a full year was compiled. Each data set was controlled for completeness. In cases of missing data points, they were completed manually by interpolating between nearby values. Since the weather data sets contain hourly data for each parameter, the simulation model accounts for weather effects at a detailed level. As a result, the variation of a weather parameter during a day is considered. This is illustrated in Fig. 11, in which wind speed variation during a 48-h period is given. As seen, the actual wind speed varies and the actual hourly value may deviate from the average. In the same way, the model accounts for variable temperature and precipitation intensity (rain or snow), that occur during working hours. In this way, the effect of weather can be estimated more precisely.

Input Data and Simulation Model Validation

Validation concerns both analysis and quality check of input data as well as various methods for ensuring the reliability of the model itself. Validation of model inputs was done as an integrated part of the data analysis discussed in previous sections, e.g., weather–productivity relationships (section "Weather Effects on Construction Productivity"), baseline productivity (section "Estimation of Baseline Productivity"), and weather data (section "Weather Data Analysis").

According to Sargent (2013), validation of the simulation model concerns both underlying logic descriptions and comparison between simulated results and real-world output. The logic description was closely examined and compared with the documented workflow as was observed in field studies. The process logic was then validated by stepwise simulation through a construction sequence. Critical steps were examined in detail with the help of ExtendSim's animation functionalities. As a final test, simulated project duration was compared with real process knowledge gained from Field Project A, consisting of 138 separate concrete walls divided in 48 wall phases. In order to facilitate analysis of the simulated output values, the model was run in an ideal mode with no impact of weather conditions and the results were analyzed and discussed with site managers from Project A. It was concluded that the model was capable of reproducing the expected construction sequence both at a detailed level (daily output) and in terms of total project duration.

Simulation Experiments

To study the effects of weather, Project A was used as a reference with the construction process, as described in Fig. 6 and project layout in Fig. 7.

Design of Experiments

Five different weather conditions, as described in section "Weather Data Analysis," were used in the simulation model and individual and combined effects of temperature, wind speed, and precipitation were simulated. For each scenario, also seasonal effects were considered by adjusting the construction start date: Winter (Win) to January 1, spring (Spr) to April 1, summer (Sum) to July 1 and autumn (Aut) to October 1. The simulated scenarios, in total 80 different scenarios, are given in Table 5. The effect of wind conditions was also further studied by changing the height of the building from 6 to 10 floors, as well as reducing allowable wind speed (from 15 to 11 m/s) related to lifting formwork.

Table 6 summarizes the relationships and thresholds used in the simulation model in order to describe the effect of weather variables on concrete wall activities. Note that for temperature, the relationship defined by Moselhi and Khan (2010) is used for three reasons: (1) the relationship is based on continuous measurements over a long period of time; (2) it is also valid for formwork activities; (3) data was collected in climatic conditions similar to the Nordic countries. To describe the effect of precipitation given in

Table 5. Overview of variables included in the simulation experiments

Weather condition	Year	Effect of temperature	Effect of wind	Effect of precipitation	Combined effects (temperature + wind + precipitation)
Normal	1997	Win/Spr/Sum/Aut	Win/Spr/Sum/Aut	Win/Spr/Sum/Aut	Win/Spr/Sum/Aut
HighTemp	2014	Win/Spr/Sum/Aut	Win/Spr/Sum/Aut	Win/Spr/Sum/Aut	Win/Spr/Sum/Aut
LowTemp	2010	Win/Spr/Sum/Aut	Win/Spr/Sum/Aut	Win/Spr/Sum/Aut	Win/Spr/Sum/Aut
Windy	2011	Win/Spr/Sum/Aut	Win/Spr/Sum/Aut	Win/Spr/Sum/Aut	Win/Spr/Sum/Aut
HighPrec	2012	Win/Spr/Sum/Aut	Win/Spr/Sum/Aut	Win/Spr/Sum/Aut	Win/Spr/Sum/Aut

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Table 6. Summary of weather–productivity relationships and thresholds for work stoppages incorporated into the simulation model

Activity	Temperature (p_{temp})	Rainfall/snowfall (p_{prec})	Wind speed (p_{wind})
1. Erect formwork (1st side)	According to Fig. 3 (Moselhi and Khan)	According to Fig. 4	W > 15 m/s[a]: Lifting is cancelled W < 15 m/s: According to Fig. 5
2. Box outs/openings	According to Fig. 3 (Moselhi and Khan)	According to Fig. 4	W > 20 m/s: Lifting is cancelled
3. Place MEP	According to Fig. 3 (Moselhi and Khan)	According to Fig. 4	W > 20 m/s: Lifting is cancelled
4. Erect formwork (2nd side)	According to Fig. 3 (Moselhi and Khan)	According to Fig. 4	W > 15 m/s[a]: Lifting is cancelled W < 15 m/s: According to Fig. 5
5. Fix rebars	According to Fig. 3 (Moselhi and Khan)	According to Fig. 4	W > 20 m/s: Lifting is cancelled
6. Pour concrete	According to Fig. 3 (Moselhi and Khan)	According to Fig. 4	W > 15 m/s: Lifting is cancelled
7. Curing concrete	N/A	N/A	N/A
8. Strip formwork	According to Fig. 3 (Moselhi and Khan)	According to Fig. 4	W > 15 m/s[a]: Lifting is cancelled W < 15 m/s: According to Fig. 5
9. Move formwork to next location	According to Fig. 3 (Moselhi and Khan)	According to Fig. 4	W > 15 m/s[a]: Lifting is cancelled W < 15 m/s: According to Fig. 5

Note: MEP = mechanical electrical and plumbing.
[a]Indicates threshold for maximum allowable wind speed for lifting operation.

Table 7. Sample of model input data used for simulation experiments

Row no.	Building ID	Floor level	Height (m)[a]	Wall phase	Wall no.	Wall area (m^2)	Concrete volume (m^3)	Rebars (kg)	Box outs (pcs)	MEP (Y/N)	Formwork[b] usage strategy TRH-540	TRH-360	TRH-270	TRH-180
1	1	1	12	1	1	5.2	0.9	52	0	Yes	0	1	0	0
2	1	1	12	1	2	13.3	2.9	133	0	Yes	1	0	0	0
3	1	1	12	1	3	13.3	2.9	133	0	Yes	1	0	0	0
4	1	1	12	1	4	5.5	1.2	55	0	Yes	0	0	1	0
5	1	1	12	1	5	5.5	1.2	55	0	Yes	0	0	1	0
6	1	1	12	1	6	13.8	3	138	0	Yes	1	0	0	0
7	1	1	12	1	7	6.8	1.5	68	0	Yes	0	0	0	2
…	…	…	…	…	…	…	…	…	…	…	…	…	…	…
134	1	6	32	4	1	6.0	1.3	60	0	Yes	0	0	1	0
135	1	6	32	4	2	5.2	1.1	52	0	Yes	0	0	1	0
136	1	6	32	4	3	5.2	1.1	52	0	Yes	0	0	0	2
137	1	6	32	4	4	6.8	1.5	68	0	Yes	0	1	0	0
138	1	6	32	4	5	10.1	1.8	101	1	Yes	1	0	0	0

Note: MEP = mechanical electrical and plumbing.
[a]Relates to maximum height of lifting position. Calculated as follows: $[(\text{Floor level} - 1) \times 4\ \text{m}] + 12\ \text{m}$. For visual reasons, highest lifting position should be 12 m above highest point of building.
[b]Concerns different formwork types, e.g., TRH-540.

Fig. 4, the approximated function defined by the dotted line is used.

Finally, specific project characteristics needed as model input are summarized in Tables 7 and 8. Also, baseline productivity data according to Table 4 was used as model input.

Table 8. Resource allocation plan for concrete wall construction activities

Activity	Resource allocation plan: Carpenters	Concreters	Subcontractors	Crane
1. Erect formwork (1st side)	3	2	0	1
2. Box outs	3	0	0	0
3. Place MEP	0	0	1	0
4. Fix rebars	1	2	0	0
5. Erect formwork (2nd side)	3	2	0	1
6. Pour concrete	0	2	0	1
7. Curing	N/A	N/A	N/A	N/A
8. Strip formwork	3	2	0	1
9. Move formwork	3	0	0	1

Note: MEP = mechanical electrical and plumbing.

Results

The effect of weather conditions are presented in Fig. 12, with all values related to an ideal, baseline situation with no effects from weather. As seen in Fig. 12, temperature is the single most important weather parameter, followed by wind speed, and then precipitation. The effect of temperature under normal weather conditions results in a 35% (1.35) increase in project duration when the construction takes place during the winter season (win). For the other seasons, the effect of temperature varies between 10% and 17%. Worst case was found during the winter season for the year with the lowest annual mean temperature (+60%), which is not surprising given that the weather data is collected in a country with cold winters. Similarly, the effect of temperature is reduced for the year with highest temperature compared with a normal year.

Under normal weather conditions, the effect of wind is at the most during winter and spring season (10% and 14%, respectively). Somewhat surprising, the year with highest annual wind speed in average did not result in the largest effect on project duration. This further highlights the importance of using detailed weather data, rather than daily or weekly averages. It is the weather conditions during the actual working hours that matter. Precipitation was found to have the least effect on construction duration. Worst case

Weather condition	Effect of temp				Effect of wind				Effect of precipitation				Combined effect of temp, wind, precipitation			
	Win	Spr	Sum	Aut	Win	Spr	Sum	Aut	Win	Spr	Sum	Aut	Win	Spr	Sum	Aut
Baseline	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Normal	1.35	1.10	1.12	1.17	1.10	1.14	1.02	1.08	1.00	1.04	1.02	1.02	1.46	1.25	1.14	1.29
HighTemp	1.33	1.08	1.10	1.08	1.06	1.06	1.08	1.06	1.04	1.06	1.04	1.08	1.39	1.19	1.17	1.14
LowTemp	1.60	1.06	1.06	1.14	1.00	1.08	1.08	1.08	1.02	1.04	1.06	1.12	1.60	1.14	1.17	1.37
Windy	1.50	1.00	1.06	1.08	1.08	1.10	1.06	1.02	1.06	1.02	1.10	1.04	1.54	1.17	1.14	1.21
HighPrec.	1.41	1.04	1.00	1.14	1.04	1.06	1.08	1.02	1.06	1.10	1.06	10.4	1.52	1.25	1.12	1.21

Fig. 12. (Color) Simulated weather effects on project duration relative to the baseline scenario (no impact from weather effects).

occurs during autumn (12%) for the year with lowest temperature. It should be pointed out that the year with highest annual precipitation only resulted in the largest effect during one of the seasons considered. Similar effects were also present for temperature and wind speed. Once again, this further promotes the use of hourly weather data during working hours, rather than averages for the different weather factors.

The combined effect of the three weather parameters indicates a 14%–46% increase in project duration under normal weather conditions, depending on season. Highest impact occurs, as expected, during the winter season. The effect during spring and autumn was found to be more or less equal (25% and 29%, respectively), whereas the combined effect of weather during summer indicates a 14% increase in project duration. When comparing the identified extreme years (high/low temperature, windy, high precipitation) with a normal year for the combined weather effects, there are differences, but rather limited variations. For the year with high temperature, the project duration increases marginally (2.6%) during summer period compared with normal weather conditions (1.17/1.14), whereas it decreases for all other seasonal periods (by 5%–12%). Once again, bear in mind that the weather data represents a cold country and high temperatures is normally positive during these seasons. For the year with low temperature, construction duration increases during winter (10%), summer (3%), and autumn (6%) compared with normal weather. For the windy year, project duration increases during winter and autumn (by 5% and 6%, respectively) compared with normal weather. However, project duration decreases during spring and it is unaffected during summer season. The year with highest annual precipitation also shows variations depending on season, but in general there are only moderate differences compared with the seasons of a normal year. In summary, one can conclude that there are large variations between seasons when looking upon the combined weather effects, but that the variations of extreme years compared with a normal year are smaller.

Turning to the effect of wind, relative building height, and thresholds for allowable wind speeds, the results are summarized in Fig. 13. Here, only normal weather conditions have been simulated. For a six-story building, changing the threshold from 15 to 11 m/s for lifting formwork increases project duration during winter and spring season by 14% and 25%, respectively. The total number of wind stop days increases to 2.9 days during winter and 3.5 days during spring. For a 10-story building, the project duration increases by 32% during winter if maximum allowed wind speed for lifting formwork is set to 11 m/s. This is an increase by 14% compared with a threshold value equal to 15 m/s. Wind stop days increase from 3.6 to 17.6 days. Increased project duration could also be expected during spring and summer periods even though the effects are more limited.

Analysis and Discussion

The simulated results show to what level different weather conditions affect productivity. For instance, the simulation results indicate approximately a 30% longer duration if construction takes place during winter compared to summer. These findings are in accordance with experiences based on follow-ups of construction projects in the Nordic countries (Larsson and Söderlind 2006).

Simulation scenarios (normal weather)	Winter		Spring		Summer		Autumn	
	Impact on duration	Wind stop (days)	Impact on duration	Wind stop (days)	Impact on duration	Wind stop (days)	Impact on duration	Wind stop (days)
Baseline: 6 floors (20m/s)	±0%	0	±0%	0	±0%	0	±0%	0
6 floors, Formwork 15m/s, concrete 15m/s	+10%	0	+14%	0	+2%	0	+8%	0
6 floors, Formwork 11m/s, concrete 15m/s	+14%	2.9	+25%	3.5	+2%	0	+8%	0
Baseline: 10 floors (20m/s)	±0%	0	±0%	0	±0%	0	±0%	0
10 floors, Formwork 15m/s, concrete 15m/s	+16%	3.6	+11%	0	+10%	1.8	+5%	0
10 floors, Formwork 11m/s, concrete 15m/s	+32%	17.6	+19%	3.6	+12%	4.9	+5%	0

Fig. 13. (Color) Simulated effects of building height and allowable wind speeds for formwork relative to a baseline scenario (no weather effects) for normal weather conditions.

Another study reported a 35% loss in efficiency due to winter conditions (Thomas et al. 1999).

Impact of Weather Conditions

It was found that temperature is the single most important weather factor followed by wind speed and precipitation. This is well correlated with other studies (e.g., Moselhi and Khan 2012). Since temperature seems to be of such importance, it is important to carefully evaluate which temperature–productivity relationship to use. Referring to Fig. 3, the three relationships value the effect on productivity due to cold and hot temperatures somewhat differently. This could be a result of geographical differences. It is not unlikely that construction workers in, for example, Nordic countries, as studied by Hassi (2002), are more adapted to cold temperatures than hot temperatures.

The wind speed was found to be the second most important weather parameter, suggesting that it should be further investigated. As expected, the effect of wind becomes more important to consider when the height of construction increases. Also, maximum threshold values for lifting operations strongly influence the number of wind stop days and, in the end, the project duration. Consequently, identifying thresholds for different types of lifting operations (and loads) are important when considering the effects of wind speed. In addition, other crane types (mobile cranes) may have lower limits for maximum allowable wind speed (Liebherr 2012). Accordingly, wind speed becomes even more important to consider when using mobile cranes for lifting light-weight loads with large surfaces.

The intensity of precipitation (both rain and snow) that occurred during actual working hours did not have any significant effect on productivity. One can argue that precipitation that falls during night (or even days) prior to the actual working day should be considered as well. Other studies have employed such lingering effects (Shahin et al. 2011; Jung et al. 2016), but in this particular case with wall construction, the effect of past precipitation is believed to be much more limited. Of course, a snowfall event will definitely influence the productivity since workers have to spend time on shoveling and cleaning unprotected work areas, but that is more related to horizontal work areas such as floor slabs.

Considering the effects of varying weather conditions, it was found that more extreme weather can have both negative and positive effects on project duration depending on actual season for construction (winter, summer etc.). These findings suggest that attention should be devoted to exploring the effects of weather on construction considering more extreme conditions as well as seasonal variations.

Accounting for Weather Conditions in Project Planning

The results presented in this paper provide an understanding of how construction projects may be influenced by weather during different contextual settings. This knowledge can be useful in different ways when planning construction projects. At a project level, the results can be valuable for making better estimations of project durations by accounting for weather more accurately. Implications on project duration can be analyzed by simulating different weather conditions, building characteristics, and construction start dates. The results can be used to verify that the construction plan is realistic considering the weather conditions that are expected during the time for construction. Productivity rates may also be adapted to various weather conditions or seasonal variations. It will also facilitate selection of necessary measures to shield production against weather in order to preserve a desired rate of construction. This also includes evaluation of suitable methods and equipment in order to mitigate risks related to adverse weather; for instance, evaluating the risks of lifting operations and crane setup related to expected wind conditions. Improved accuracy in estimations of weather effects on project duration also enables for optimization. For instance, the need for buffers to manage weather-related risks could be reduced, or even eliminated. On a short-term perspective, the simulation model could be supplied with daily weather forecast data. In this way, simulated results can be used in order to validate the production plan for the next following work days, or even longer depending on the quality of the forecast.

Research Limitations

The results presented in this paper are first of all valid for concrete wall construction under the effect of Swedish climate conditions, in particular the Stockholm region. However, using climatic data representative for other geographical areas, the effect of weather can be studied in a similar way. It should also be emphasized that the results are strongly dependent on the underlying relationships between weather parameters and labor productivity. If possible, each relationship should always be evaluated against own figures or personal experiences. Increasing the empirical base by collecting more data in order to verify existing relationships or making new ones is a priority for future research.

The model presented in this paper is limited to describe the effect of concrete wall operations. In order to estimate the duration of a concrete framework, other work tasks must be considered as well, e.g., curing of concrete, erecting horizontal formwork, and pouring concrete slabs. It is believed that such work tasks could be relatively easily incorporated into the existing model. However, other relationships and thresholds describing the effect of weather on concrete slab operations may then be required.

In spite of the mentioned uncertainties associated with the model itself and the input data used, it is believed that the combined measures of model and input data validation increase the confidence of the findings presented in this paper; for example, validation of input data through collection of real process data from field studies, review of underlying weather–productivity relationships, and the use of high quality weather data from trusted sources.

Conclusions

Weather is one important factor that has a negative effect on construction efficiency. Usually it is also related to uncertainties when estimating its impact on work efficiency. Means to improve accuracy in such estimations during planning are therefore important. In this paper, the influence of weather on a common construction method is studied. In short, temperature, wind speed, and precipitation are those variables that are reported to be the most significant. Both cold and hot temperatures have a negative effect on productivity. Also, machinery and material can be affected, especially by cold temperatures. High wind speeds and high precipitation also result in lower work efficiency. By importing climatic data with hourly resolution to a simulation model, the effect of weather could be simulated at a detailed level, which demonstrated how weather can be studied using a simulation-based approach enabling systematic analysis in a highly controlled way. Different scenarios were simulated including variations in weather conditions representative for Swedish climate (Stockholm), seasons for construction, and height of construction. It was found that construction is mostly affected by weather during winter season, which is to be expected for Nordic climate. The least effect on construction was during summer season. Extreme weather conditions were found to have both negative and positive impact, depending on season. Consequently, increased awareness and knowledge about weather conditions and seasonal variations will become even more important in the future to account for climate change effects. The findings presented in this paper also address the need for planning construction related to different climatic zones and seasonal variations, not only in Sweden but also on a global scale.

This paper contributes with knowledge of how weather affects construction and how it can be accounted for using simulation tools and climatic data with high resolution. The methodology is general and the influence of weather in other geographical regions other than the one studied here can be analyzed by adding other climatic data sets. Future research should focus on increasing the empirical base for developing relationships between weather variables and labor productivity. Developing relationships (or thresholds) which are specific for a certain work task (or group of work tasks) would make future estimations of weather even more precise. Future work should also focus on enhancing the capabilities of the simulation-based approach in order to account for weather in a more comprehensive way. For instance, including weather effects on other types of construction work tasks, equipment, and materials, such as concrete curing, and so forth.

Data Availability Statement

Data generated or analyzed during the study are available from the corresponding author by request. Information about the *Journal*'s data-sharing policy can be found here: http://ascelibrary.org/doi/10.1061/(ASCE)CO.1943-7862.0001263.

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