49 An Integrated Simulation-Based Methodology for Considering Weather Effects on Formwork Removal Times

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Abstract

This paper presents an integrated simulation-based methodology for considering the effects of weather on formwork removal times. An expert tool for estimating formwork removal times and weather data with high resolution are integrated into a discrete-event simulation model containing a process model of in situ concrete wall operations. In addition, operational measures (denoted as curing strategies) and their ability to shield concrete curing against various weather conditions are also studied. From the simulation results, it can be concluded that weather conditions and curing strategies may have a significant influence of construction duration. The proposed simulation-based approach facilitates systematic analysis of formwork removal times and curing strategies under various climatic conditions when planning concrete works.

Keywords

Productivity • Weather • Concrete curing • Formwork removal • Discrete-event simulation

49.1 Introduction

Efficient concrete construction require not only well planned and synchronized work tasks but also a predictable concrete curing process since it determines when formwork can be removed. Delayed formwork removal time causes disruptions for the whole construction cycle and lowers productivity. In addition, too early removal of formwork when concrete strength is not sufficient can lead to other serious effects, e.g. damages with potential future durability issues, or even structural collapse.

Weather conditions affect concrete strength development and by that, also the time when formwork can be removed. Accordingly, accurate predictions require good estimations of actual weather conditions considering natural variations both on short (daily or weekly) and long term (seasonal effects). This is important, not least when pouring concrete in regions with long periods of cold weather, as is typically the case in the Nordic Countries. Previous studies have focused on the effect of weather on productivity on project or work task level [1–4]. Moreover, studies that have limited the scope to the influence of weather on formwork productivity, e.g. [5, 6], have not explicitly considered the implications on formwork removal.

In the Nordic countries, special-purpose simulation tools are commonly used for prediction of concrete strength development. These simulation tools enable to predict formwork removal time for specific concrete types and external conditions. However, accounting for variable weather conditions in these tools is a relatively time-consuming work. Therefore, variations in weather conditions are normally neglected in order to make predictions manageable. Since weather conditions typically vary both on short and long term basis, such simplifications add uncertainty to the estimations. In addition, simulations of formwork removal times are not always properly integrated with tools for planning or analysis of the overall construction process. Lack of integration increases the risk of formwork removal that is poorly adjusted to the planned

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construction cycle and vice versa. Consequently, there is a need for an integrated solution which improves planning of concrete works by more accurately account for the effects of weather on formwork removal.

The aim of this research is to develop and demonstrate an integrated simulated-based methodology for considering effects on formwork removal time due to variations in weather conditions. Another aim is to study the efficiency in different operational measures employed in order to shield curing against varying climatic conditions which are typical for Sweden.

The proposed methodology combines discrete-event simulation (DES) and specific simulation tools for predictions of formwork removal times. DES is chosen since it offers powerful capabilities to model and study complex systems [7]. Various factors such as weather can be explicitly described and their relative effect on the model can be simulated in a highly controlled environment. Results from the expert-based simulation tool are integrated to the model to account for formwork removal. The model is then demonstrated by studying the effect of weather and curing strategies on the duration of concrete wall operations.

49.2 Research Approach

The research was divided into five steps; (1) Literature review of how weather influences concrete strength development; (2) Conducting two separate field studies to study and collect information about concrete wall operations, e.g. work sequence, productivity rates, and resource usage. Information about what measures that are typically used in order to shield curing against ambient climate was documented as well. These findings were used to formulate a set of different curing strategies. The field studies involved on-site visits and interviews with construction site managers; (3) Weather statistics were collected and analyzed for three geographical locations in Sweden representing different climatic zones; (4) An expert simulation tool was used to estimate formwork removal times as a function of different climatic conditions and curing strategies as were identified in step 2; (5) Based on knowledge gained from previous steps, a discrete-event simulation model was developed describing the workflow of concrete wall construction. A specific algorithm was developed to dynamically account for formwork removal times due to varying weather conditions. Finally, the model was applied to concrete wall operations to study the effect of weather on construction duration by accounting for different weather conditions and curing strategies.

49.3 Concrete Curing and Formwork Removal

49.3.1 Concrete Wall Construction

Construction of concrete walls is a common sub-process of reinforced concrete structures. It is characterized by several manual work tasks carried out in sequence repeated on a daily basis. Since formwork constitutes for a considerable amount of the cost of in situ concrete structures, formwork panels are reused. As a result, the time at which formwork panels can be removed becomes critical in order to keep up with the planned production cycle.

Removal of vertical formwork is determined by minimum value of concrete strength. In Sweden, general recommendation for minimum strength is 6 MPa. Removing formwork when concrete has not yet reached sufficient strength may have serious effects on safety. It may also cause issues related to damages to the structure with future durability issues. In this perspective, it is desirable to have a certain time margin (denoted as a time buffer) between the time when concrete has reached sufficient strength and the time at where formwork is actually removed. A small time buffer is positive for productivity reasons but increases risks related to safety and quality issues. On the other hand, a large time buffer indicates that measures employed to shield the curing process are too extensive. Ultimately, large time buffers may result in higher construction costs and unnecessary environmental impact. Accordingly, employment of measures to enable for “optimal” formwork removal must balance the needs of safety, quality and productivity.

49.3.2 Concrete Curing

The development of concrete strength is usually described as the hardening or curing process. This material-related process is crucial since it determines several critical aspects of a concrete structure both at early and later stages. The concrete strength is determined by the development of chemical reactions between cement and water (denoted as hydration).

The hydration process is influenced by several factors, e.g. cement type, chemical activation, and curing temperature [8]. It is well known that higher concrete curing temperatures result in higher short term strength compared to lower curing temperatures. As a result, the ambient climate becomes important since it strongly influence the curing temperature. Cold temperature and high winds reduce the concrete temperature which in turn slows down or even stops the hydration process.

Early strength development can be estimated using the maturity method [9]. The method is based on scientific findings that the concrete strength is directly related to the hydration temperature history of cement.

49.3.3 Measures to Shield Concrete Curing Against Cold Weather

In general, four types of measures (a to d) are typically employed to consider the effects of ambient climate. These types of measures can be used separately, but in most cases a combination of measures is used; (a) Concrete mix design: The type of cement (e.g. Portland cement CEM I or blended cement CEM II), water-to-cement ratio (w/c), and chemical additives influence the curing process; (b) Covering and isolation of concrete surfaces: Covering or isolation of concrete prevents that the curing process slows down or even stops due to rapidly heat losses to ambient climate; (c) Increased initial concrete temperature: Increasing the temperature of the concrete mix leaving the concrete batch plant is positive since it results in higher temperature at the construction site; (d) Use of heating system: Both external and internal heating system can be used. External systems temporarily increase the temperature at the concrete surface. Internal heating systems are embedded into the concrete structure, e.g. heating cables.

The use of both increased concrete temperature (c) and heating systems (d) requires isolation or coverage of concrete surface in order to be effective.

49.3.4 Simulation of Formwork Removal Times

Special-purpose simulation tools can be used for estimating strength development for different concrete structures, such as walls or slabs. In the Scandinavian countries, there exist different software tools, e.g. Hett11[1] or PPB[2]. The software tools simulate the dynamic change in concrete temperature as a result of hydration of cement and heat losses to the surrounding climate. It is possible to estimate the effects of different measures to shield the curing process against surrounding climate, e.g. isolation and heating of concrete. The software tools estimate concrete strength using temperature profiles and the maturity method.

In this research, the software tool PPB (version 1.2.2) was used. More details about the software's underlying temperature and maturity models can be found in [8]. Examples of simulation of strength development for a concrete wall exposed to varying climatic conditions are presented in Fig. 49.1. As shown, weather conditions influence the time when formwork can be removed, i.e. when concrete has reached a minimum of 6 MPa.

49.4 Discrete-Event Simulation Model

The model was developed using ExtendSim[3] (version 9) as the software platform. The structure of the DES-model is outlined in Fig. 49.2.

The model simulates the duration of concrete wall operations. Timing of work tasks, availability of resources, and status of weather are continuously updated during the simulation. Different type of information (project, weather, and formwork removal) are stored in databases and loaded into the model when needed as the simulation proceeds. During the run of the simulation, the model constantly updates current weather conditions and an algorithm dynamically accounts for the duration of curing based on current weather conditions and curing strategy (see Sect. 49.5.1).

The logical behavior of the algorithm is outlined in Fig. 49.3. When the concrete walls have been poured, current time is set to t0. Then, a forecast of weather is made for the next 12 h and the mean temperature and wind speed is calculated. Calculated mean weather parameters are then used to determine the duration of curing based on a predefined curing strategy.

[1]Hett11: www.cementa.se.
[2]PPB: Produktionsplanering betong, www.sbuf.se/ppb.
[3]www.extendsim.com.

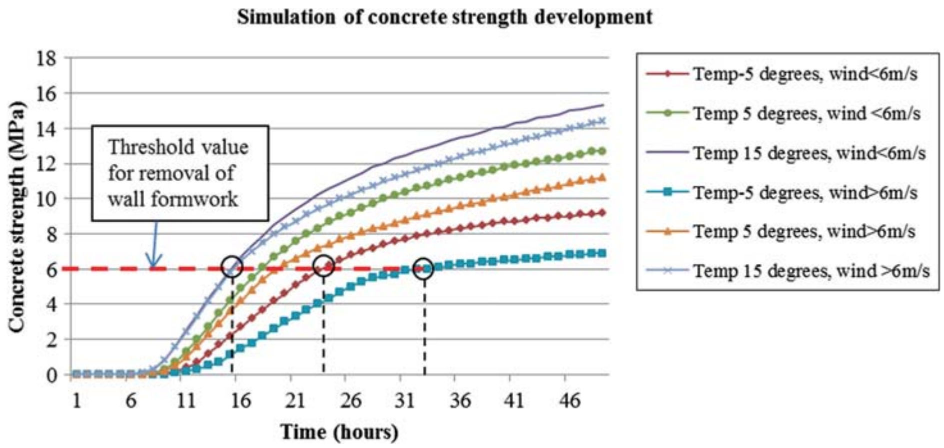

Fig. 49.1 Estimation of concrete strength and formwork removal times for climatic conditions

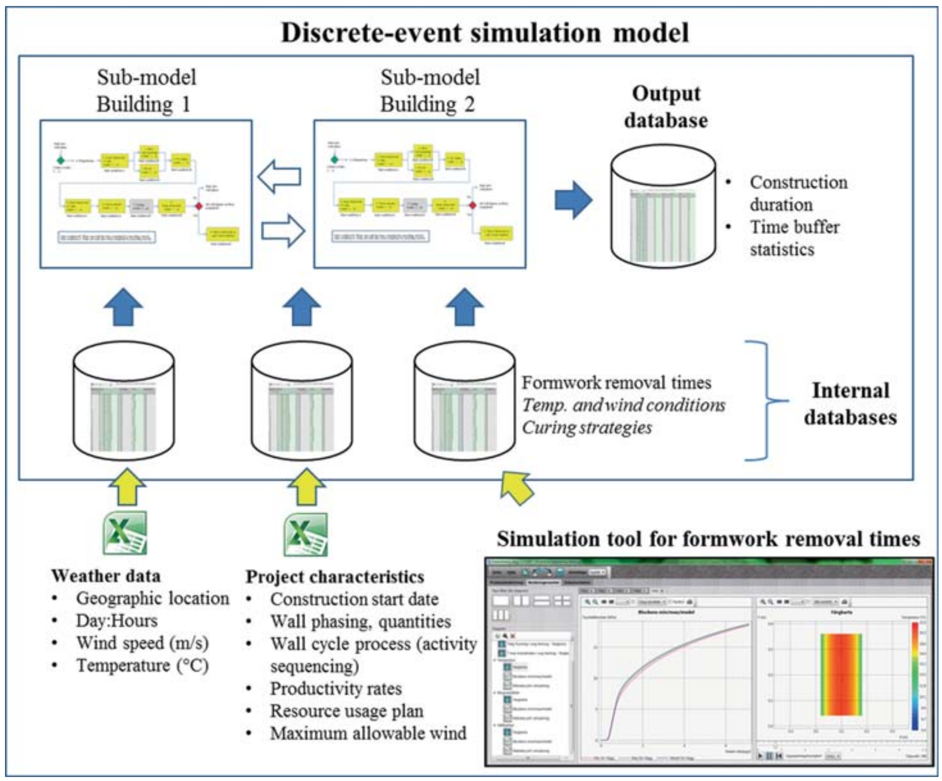

Fig. 49.2 Overview of discrete-event simulation model

The algorithm collects statistics for calculating buffer time as discussed in Sect. 49.3.1. The buffer time is defined as the difference in time between when formwork, at the earliest, can be removed and when formwork is actually removed.

49.5 Simulation Experiments

49.5.1 Construction Project, Curing Strategies and Weather Statistics

A project consisting of two six floor buildings were used as a reference for conducting experiments. Each floor was divided into four wall phases where each phase consisted of four wall segments. The buildings were erected simultaneously and the formwork system was moved between the two work locations during construction. The planned production cycle was set to

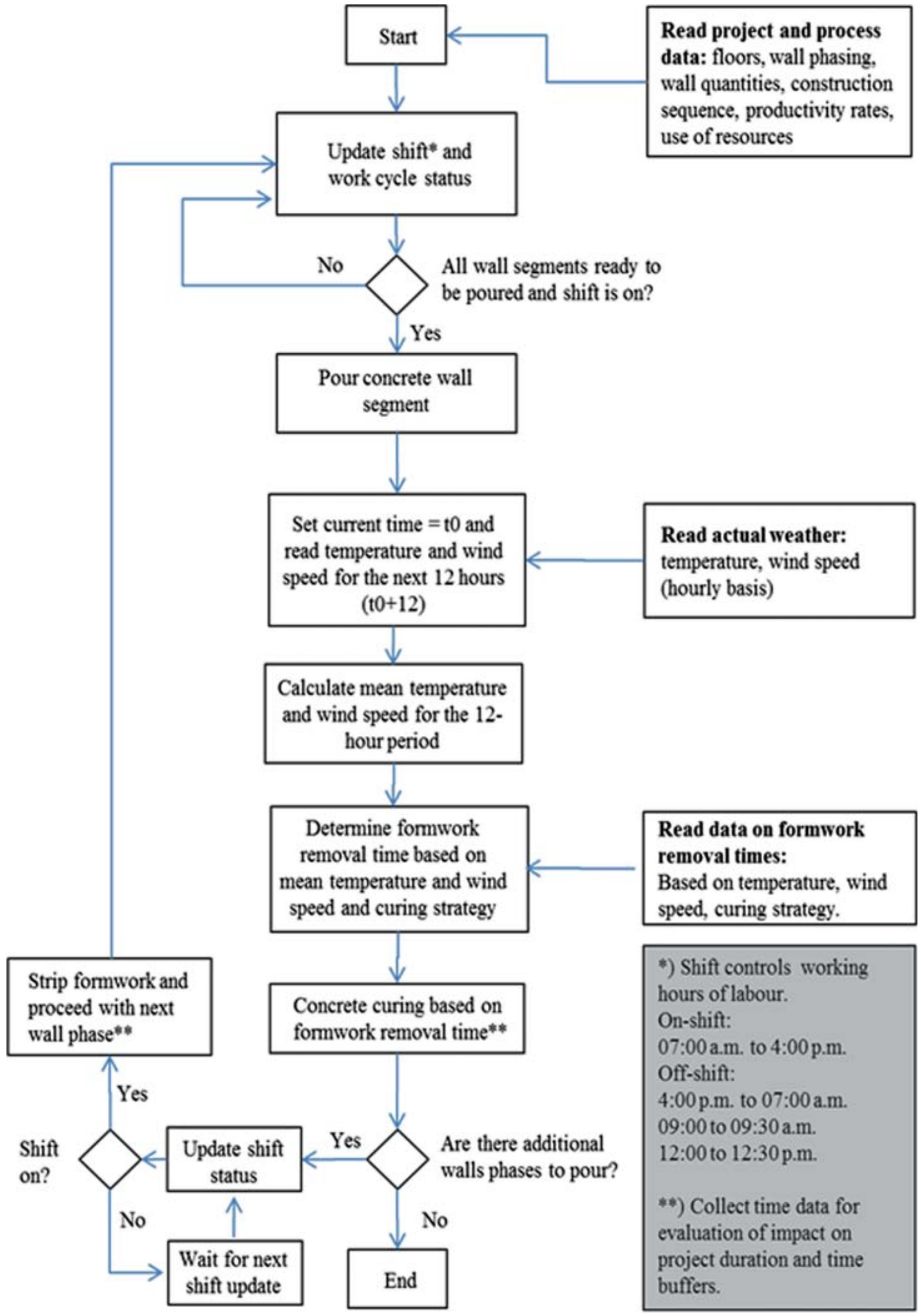

Fig. 49.3 Outline of the algorithm for estimating formwork removal time based on current weather and selected curing strategy

finish one wall phase per day resulting in a total duration of 48 days. Productivity rates and resource usage typical for concrete walls were obtained from site visits and discussions with site managers. To study the effect of different measures to shield the curing process against ambient climatic conditions, a set of different measures were identified involving concrete mix design, increased initial concrete temperature, isolation of formwork, and the use of embedded heating systems. These measures were either employed separately or in combination resulting in 12 different curing strategies (A–L), see Table 49.1.

The simulation tool PPB was used for estimating formwork removal times for the curing strategies A–L under varying weather conditions. The estimated formwork removal times were imported to the DES-model and used in the simulation experiments. Weather statistics for three geographical locations in Sweden (Malmö, Stockholm and Umeå) were collected. These locations were chosen since they represent three different climatic zones in Sweden. For Malmö and Stockholm, hourly

Table 49.1 Specification of measures employed for curing strategies A–L

Strategy	Concrete class	Cement (CEM II/A-V 52,5 N Portland-fly ash cement is used in all cases) content (kg/m^3)	Concrete temperature (°C)	Formwork isolation (30 mm)	Internal heating (3 × 40 W/m)
A	C25/30	300	15	No	No
B	C20/25	275	15	No	No
C	C28/35	330	15	No	No
D	C25/30	300	15	Yes	No
E	C25/30	300	20	Yes	No
F	C25/30	300	20	Yes	Yes
G	C20/25	275	15	Yes	No
H	C20/25	275	20	Yes	No
I	C20/25	275	20	Yes	Yes
J	C28/35	330	15	Yes	No
K	C28/35	330	20	Yes	No
L	C28/35	330	20	Yes	Yes

data for temperature, precipitation, and wind speed covering the period of 1997–2016 (20 years) were retrieved from official weather statistic databases (SMHI[4]). For Umeå, it was only possible to compile data for a 10 year period (2007–2016). The data sets were analyzed in order to identify a year which could be considered as a normal year. A normal year was defined as the year that had least annual mean deviation in precipitation, temperature and wind compared with mean values for the total period of 10 year (Umeå) or 20 years (Stockholm and Malmö).

49.5.2 Design of Experiments

The experiments focused on three variables, namely; (1) Geographical location (Malmö, Stockholm and Umeå); (2) Start of construction to consider the effect of different seasons: Winter (start date 1st January), Spring (start date 1st April), Autumn (start date 1st October); (3) Strategies for concrete curing according to Table 49.1.

49.5.3 Results

The effect on construction duration due to weather and curing strategies are given in Fig. 49.4. The results for Malmö, Stockholm, and Umeå are presented in the chart diagrams a, c, and e. In these diagrams, the y-axis shows the relative effect on construction duration. A value equals to one corresponds to an ideal scenario unaffected by variations in formwork removal, i.e. zero loss in productivity. A value higher than one indicates loss in productivity. In should be noted that values lower than one is not possible since it represents the best possible (ideal) situation.

Strategies A, B and C result in major productivity losses for all three locations (see chart diagrams a, c, and e in figure). Missing bars in the chart diagrams mean that the curing process is too slow to enable formwork removal. This occurs for example for strategy A and B in Umeå during winter and autumn. It is shown by diagrams that strategy A is not suitable for use in Umeå or Stockholm during any season. For Malmö, the strategy can be employed during spring and autumn but will then result in losses in the range of 10–15%. Lowering the concrete quality without any additional measures as was the case in strategy B is not recommended for any location or season. Increasing concrete quality (strategy C) is feasible for Malmö and Stockholm during spring and autumn. However, it is not adequate during winter since it will result in significant loss in productivity.

To study the extra time margin (time buffer), a time buffer index is introduced. This index is shown in diagram b, d, and f for Malmö, Stockholm, and Umeå respectively. The index represents the time between when formwork removal is possible

[4]SMHI, Swedish Meteorological and Hydrological Institute, www.smhi.se.

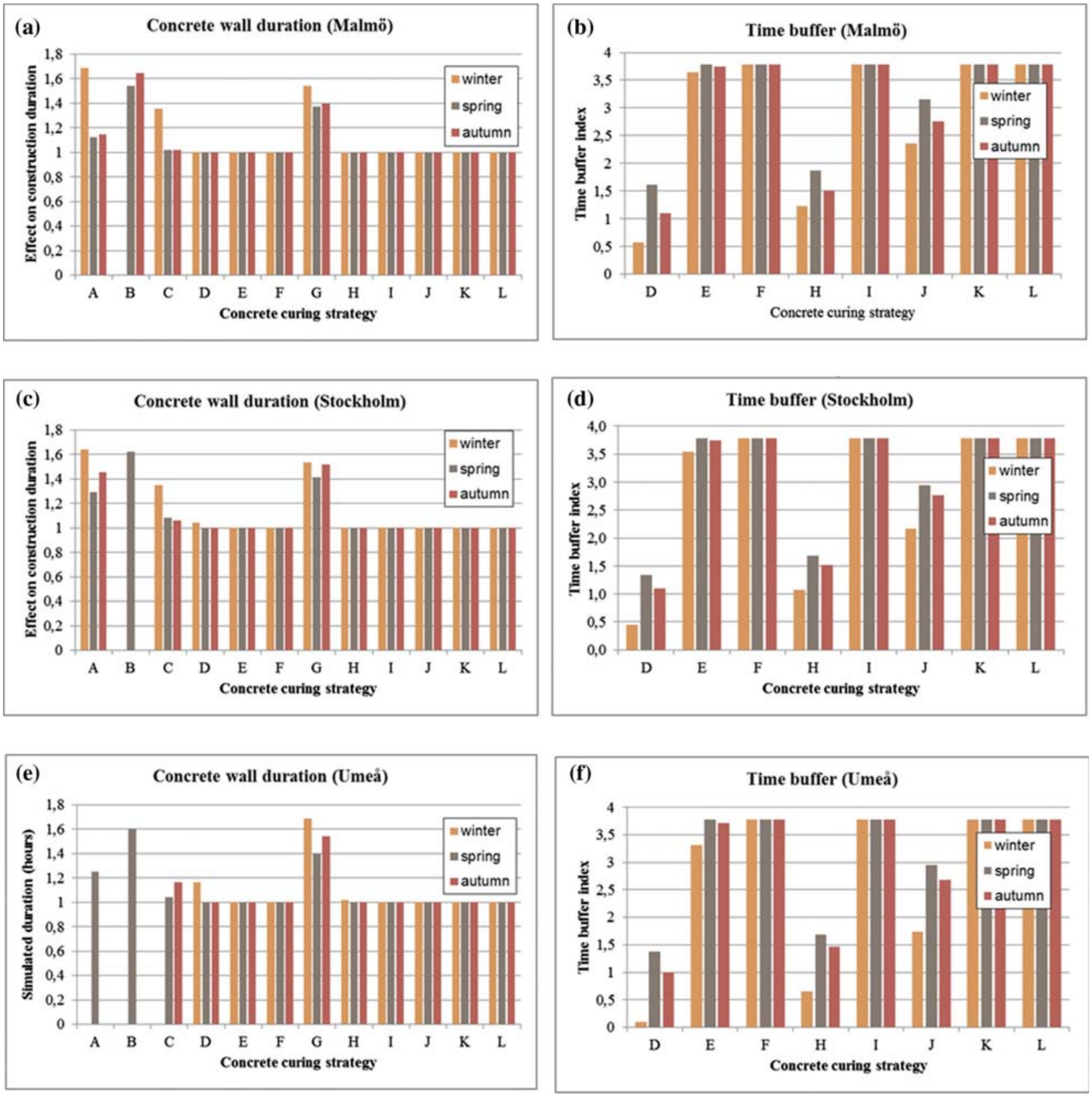

Fig. 49.4 Simulated effect on construction duration for various seasons and geographical locations (diagrams **a**, **c** and **e**). Diagrams **b**, **d** and **f** show corresponding time buffer index

(i.e. when concrete has reached at least 6 MPa in strength) and the time when removal of formwork actually begins. An index near zero means that the time buffer is non-existent. The higher the value of the index, the larger is the buffer. Strategies A, B, C, and G are not presented in the chart diagrams since these do not have any time buffers. Strategies F, I, K and L have the highest buffer index. The index values are also the same for all three places and seasons. This means that any further reduction in formwork removal is not possible without making other changes, e.g. using more rapid cement types. Strategy D has the lowest index followed by strategy H and then J. Note that the index is close to zero for strategy D during winter in Umeå indicating that there is no margin left.

49.6 Discussion

It was found that weather conditions may have significant influence on construction duration as a result of inappropriate employed operational measures to shield concrete curing. Consequently, decisions on what measures to employ are critical in order to avoid loss in productivity as well as increased safety risks and quality problems during construction. The findings also indicate that curing strategies involving more than one measure are very effective to enable for predictable formwork removal times. However, it was also shown that employing strategies combining four types of measures are unnecessarily extensive for all cases studied. The time buffer index can be useful in order to assess how well a measure is customized to effectively support a desired production cycle. It also reveals how large the margin is in cases of unexpected changes in weather. As such, the buffer index provides a measure of the robustness of the chosen measures. On the other hand, high buffer index indicates an overuse of project resources which may increase costs and environmental impact.

Previous studies reported, e.g. in [5, 6] have emphasized on the effects of weather on productivity in manual works tasks involved in construction of concrete structures. However, this paper indicates that also the influence of weather on concrete curing should be considered. In this respect, this paper provides new insights on how to integrate general discrete-simulation with expert simulation tools and weather data, in order to account for formwork removal.

The findings of this study are based on formwork removal times estimated for generic concrete wall types. However, to expand the applicability of the model also horizontal formwork used for concrete slabs should be included. It is believed that the proposed algorithm could be used to consider removal of horizontal formwork as well. It would also be interesting to include more weather types, e.g. unusual or extreme weather to study the effects of changing climatic conditions.

The findings of this study should be validated, e.g. by collecting data from ongoing projects. Measurements of concrete strength and weather variables would be of value in order to confirm assumptions made for estimating formwork removal times.

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