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Effects of weather conditions on concrete work task productivity – a questionnaire survey

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Abstract

Purpose – This paper aims to study the effects of different weather conditions on typical concrete work tasks' productivity. Weather is one important factor that has a negative impact on construction productivity. Knowledge about how weather affects construction works is therefore important for the construction industry, e.g. during planning and execution of construction projects.

Design/methodology/approach – A questionnaire survey method is used involving means to perform pairwise comparisons of different weather factors according to the analytical hierarchical process (AHP). The survey also contains means to enable assessment of the loss in productivity for typical work tasks exposed to different weather types. The survey targets practitioners involved in Swedish concrete construction projects, and the results are compared with previous research findings.

Findings – The survey covers responses from 232 practitioners with long experience of concrete construction. The pairwise comparisons reveal that practitioners rank precipitation as the most important followed by wind and temperature. The loss in productivity varies significantly (from 0 to 100%) depending on the type of work and the type of weather factor considered. The results partly confirm findings reported in previous research but also reveal a more complex relationship between weather and productivity indicating several underlying influencing factors such as type of work, type of weather (e.g. rain or snow) and the intensity of each weather factor.

Originality/value – This paper presents new data about how 232 practitioners assess the effects of weather on construction productivity involving novel means to perform objective rankings such as the AHP methodology.

Keywords Construction, Productivity, Concrete, Pairwise comparison, Weather, Questionnaire survey

Paper type Research paper

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Introduction

Weather is one important factor that influences construction productivity. Therefore, several research projects have studied how weather influence construction works (Koehn and Brown, 1985; Thomas and Yiakoumis, 1987; Moselhi and Khan, 2010). Based on the focus of previous research, one can conclude that the most significant weather factors are temperature, wind and precipitation (snow and rain). For example, hot or cold temperatures affect human activity and slow down working pace. Snowfall increases the need for extra work tasks such as covering and uncovering work areas. High winds may obstruct certain tasks such as crane lifting operations resulting in reduced productivity.

In general, there are two different streams of research when studying the effects of weather on productivity. In one stream, the focus is on comparing (or ranking) a wide range of factors (including weather) based on their relative importance to productivity (Rojas and Aramvareekul, 2003; Dai *et al.*, 2009; Moselhi and Khan, 2012). This is important as it provides valuable insights for the research community to address in further research, but also for industry stakeholders to direct and prioritize industry initiatives. However, the focus in these studies has been on an aggregated level where the importance of weather was compared with other factors such as quality in design, labour skills, management skills, etc. Moreover, ranking of factors is made without specifying contextual conditions such as intensity of wind or snowfall. As a result, these studies do not provide any deeper understanding of what weather types are more important compared to another weather type.

In the other stream, the focus is on quantifying the effect of weather on productivity. These findings have a more practical value as they provide means to account for weather when planning construction works. In general, previous research studies have focused on quantifying effects of weather on productivity for typical construction works such as masonry (Koehn and Brown, 1985; Thomas and Yiakoumis, 1987), steel works (Thomas *et al.*, 1999; Thomas and Ellis, 2009), formwork (Ballesteros-Perez *et al.*, 2015; Moselhi and Khan, 2010) and road construction (Alvanchi and JavadiAghdam, 2019). However, these findings describe weather-productivity relationships at an aggregated level. Therefore, these findings lack necessary level of detail to distinguish the effects of certain weather factors on specific work tasks. For obvious reason, different types of work have different sensitivity to specific weather conditions. For example, lifting of light formwork panels are more sensitive to wind compared to lifting of heavy rebar bundles. The intensity of a weather factor also influences how much productivity is affected. Obviously, a heavy snowfall affects work tasks more than a light snowfall. Therefore, to account for weather when planning construction works, it is necessary to understand how different weather factors (including intensity of a factor) influence specific work tasks. The need to differentiate the effects of weather in terms of specific weather conditions and types of works was highlighted already by Smith and Hancher (1989) and later also by McDonald (2000) and Nguyen *et al.* (2010).

The aim of this paper is to make an in-depth study of how weather influence typical construction work tasks. More specifically, the study aims to explore the relative importance of weather factors on concrete productivity. Another aim is to quantify the effects of different weather conditions on productivity for different concrete-related work tasks. The study is limited to typical work tasks involved in the erection of concrete frameworks, and the weather factors that are in focus are temperature, wind and precipitation (rain and snow).

A structured questionnaire survey is chosen as the overall research method targeting site personnel (e.g. site managers) in construction companies. The study also uses the analytical hierarchy process (AHP) as a part of the questionnaire survey to enable objective ranking of weather factors. Based on the research aim and to guide the design and planning of the survey, the following research questions were formulated:

RQ1. What is the relative importance between temperature, wind and precipitation when it comes to the influence on concrete framework productivity?

RQ2. What is the impact of temperature, wind speed and precipitation on typical concrete work tasks' productivity?

RQ3. Referring to *RQ2*, are there differences between different work types and climatic conditions?

The scientific contribution of this study is that it provides new knowledge based on how practitioners estimate the effect of specific weather conditions on typical construction work tasks' productivity. This study also provides insights into methodological aspects of using questionnaire surveys to assess the influence of weather.

This paper is organized as follows. First, a theoretical section summarizes previous research focusing on the relation between weather and construction productivity. The next section describes the research approach focusing on the design of the questionnaire survey and data collection procedure. It also contains a description of how AHP was assessed in the survey to enable ranking of weather factors. The next section presents the results of the survey followed by a discussion section. Finally, conclusions and recommendations for future research are given.

Weather impact on construction productivity

It is well known that weather has a negative effect on construction productivity. Therefore, several researchers have studied the relation between weather factors (e.g. temperature, wind, precipitation) and productivity. A summary of previous research attempts is presented in Larsson and Rudberg (2019).

The effect of *temperature* on construction productivity has been quantified in several studies (Koehn and Brown, 1985; Thomas and Yiakoumis, 1987; Hassi, 2002; Thomas and Ellis, 2009; Moselhi and Khan, 2010). Based on these studies, it can be concluded that temperatures between 10 and 20°C have no significant effect on productivity, whereas productivity decreases substantially both at high (above 25°C) and low (below 0°C) temperatures. For instance, high temperatures increase risk of dehydration and heat stress. It also means that workers have to take breaks more often to rest and drink water. At cold temperatures, workers may experience general body cooling or tissue damages on exposed body parts. Temperature not only affects humans but also construction materials. For instance, cold temperature affects the chemical reactions needed for the concrete to develop necessary strength. As a result, the hardening process slows down (or even stops) and by that delaying the formwork removal time. To shield concrete against low temperatures, additional activities are needed which in turn reduce construction productivity.

Precipitation typically slows down the speed of construction. Rain or snow affects the ability to perform work tasks compared to when no precipitation occurs. It also increases the need for covering (and uncovering) of material and work areas. Heavy precipitation also reduces working pace for tasks where sight visibility is important. Previous studies have concluded that even light rain or light snowfall have a significant effect on productivity. For instance, Noreng (2005) and Moselhi and Khan (2010) indicate losses in the range between 40 and 65%.

Wind affects work tasks that are dependent on crane assistance for lifting operations. The influence of wind on lifting operations depends on several factors, e.g. wind speed and direction, the height at where lifting take place and type of objects to be lifted. Productivity may also be reduced owing to the need of extra safety measures subjected to humans and/or machinery. The effect of wind on productivity has been reported to be a loss around 20% at wind speed equal to 12 m/s (Moselhi and Khan, 2010). Other studies (Noreng, 2005) reported a 20–25% productivity loss at wind speeds above 10 m/s, whereas Birgisson (2009) points at a 20% loss at wind speeds between 8 and 14 m/s. Ballesteros-Perez *et al.* (2015) conclude that handling of formwork is already affected at 5 m/s. This supports the idea that different types of lifting operations have different sensitivity to wind. In addition, other studies have focused on maximum wind limits when lifting operations are cancelled for safety reasons (Jung *et al.*, 2016). In general, out of service levels of cranes are typically given by manufacturers, but national industry practices also exist.

Research approach

This study focuses on the effects of weather on work tasks' productivity which are typically involved in concrete construction methods. Concrete construction methods are widely used in many applications in most countries around the world. One important application is the construction of the structural frame in multistory buildings which is the scope of this study. As concrete construction works are carried out in unprotected environments, the performance of individual work tasks become strongly depended on current weather conditions.

The most straightforward method to study factors influencing productivity is to measure on-site activities' outputs and inputs and to document influencing factors. However, this method is relatively time-consuming and associated with practical difficulties as it assumes control of many factors that may influence productivity. As a result, it can be difficult to analyze to which extent a certain weather factor is responsible for a measured loss in productivity. Another approach is therefore to collect data directly from site personnel that possess practical knowledge about how different operational factors (e.g. weather) influence work productivity. This research approach was also employed by Alvanchi and JavadiAghdam (2019) where practitioners ranked the overall impact of weather on construction productivity. The authors argued that using a questionnaire survey to extract the collective knowledge from many experienced individuals are less complicated and a more effective procedure than performing extensive measurements.

Knowledge about how weather affects concrete works' productivity is indeed important for site personnel (e.g. site managers) responsible for planning and execution of construction projects. Such knowledge is often based on practical experiences gained over time and transferred from older to younger generations of professionals. Unfortunately, the knowledge is usually tacit and not documented for the purpose of public access. Therefore, this paper aims to study how practitioners, such as site managers, estimate the effects of weather on concrete work tasks' productivity. For this purpose, a structured questionnaire survey was used. Even though the response rate is generally low for this type of methods, it can still provide substantial amount of data since it can be distributed to a large population at a low relative cost (Karlsson, 2008). A digital questionnaire was considered as the best option to access a larger number of individuals in the target group, to fully capture the diversity in how practitioners value the effects of weather. To ensure consistency in assessments, it was decided to integrate methods enabling structured assessments as a part of the questionnaire, e.g. AHP. The questionnaire also contained standardized questions and response options to enable structured assessments of productivity losses owing to specified weather conditions.

The survey was directed to respondents in Sweden, where weather conditions (e.g. temperatures and precipitation) may vary significantly owing to seasonal effects and the far stretched geography in north-south direction. The use of a national survey is motivated by the changing weather conditions in Sweden, which is an important factor to consider during planning and execution of concrete construction projects. Using a national survey of course limits the generalizability of the results, but many countries in the northern hemisphere face similar conditions and previous studies are used to discuss analytical generalization.

Description of target population and planning of survey

The target group of the survey was personnel in construction companies responsible for, or actively involved, in the management of construction projects, e.g. construction managers, site managers, site engineers, etc. This group of individuals is believed to have necessary knowledge to make qualified estimations of how productivity is affected by weather.

Next, the target group was analysed in terms of size and how to access individuals using data from a market survey company [1] specialised in collecting information about the Swedish construction market. By searching the market survey company's database, 4,265 individuals currently involved in construction of multi-story residential buildings were identified. Compared to the total size of the target group, which was estimated at a maximum of 5,000 individuals, the search result indicated a high coverage, and it was decided to make a complete survey rather than making a sampled survey.

Design of data collection method

A structured questionnaire with a high level of standardised questions and response options were chosen as it enables analysis of quantitative data (Patel and Davidson, 2003). The design of the questionnaire involved selection, structure and phrasing of questions. This work was closely linked to the overall objective and was done in an iterative process. In total, the questionnaire consisted of 13 questions divided in three sections. The first section contained three general questions about the respondent's job position, experience and geographical residence.

The second section contained two questions specifically designed to let the respondent make pairwise comparisons of temperature, wind and precipitation (rain or snow) according to the AHP methodology (Saaty, 1990). Each respondent made pairwise comparisons of factors using a five-point scale of intensity as suggested by Fülöp *et al.* (2010) and Pecchia *et al.* (2013) to assess the importance of one factor relative to another (Figure 1). Comparisons were made for a summer and a winter case separately resulting in two unique correlation matrices for each respondent. To estimate how a respondent manages to provide consistent comparisons, a consistency ratio (CR) is calculated for each matrix. According to Saaty (1990), a CR-value ≤ 0.1 is considered to be acceptable. Comparisons with a CR-value above this threshold were not included in the final rankings. The priority (ranking) of each weather factor was given by calculating the priority vector of each matrix. The priority vector is determined by calculating the geometric mean of rows of the correlation matrix. More details are given in, e.g. Yoon and Hwang (2011). An example of a correlation matrix ($\boldsymbol{A_i}$) and the corresponding priority vector ($\boldsymbol{w_i}$) for respondent $\boldsymbol{i}$ is given in Figure 2. The calculated priority vectors for each respondent's comparisons were then aggregated into a single priority vector valid for all respondents as suggested by Zhou (1996).

The third section consisted of eight questions where the respondents were asked to estimate the loss in productivity for typical work tasks owing to specific weather conditions. To assess the impact on productivity a respondent could choose one of the following options: no reduction (0%), low (10%), moderate (25%), high (50%) and work stoppage (100%) (Figure 3). The use of an uneven scale was a consciously choice to study if there was

Question 4.
Compare the relative importance of high temperature, rain, and wind on productivity during summer conditions by selecting appropriate alternative below.
Where:
High temperature = 25 °C
Rain = 10 mm during 8 hours workday
Wind = 10 to 14 m/s

	A is much more important than **B**	**A** is more important than **B**	Equal importance	**B** is more important than **A**	**A** is much more important than **B**	Do not know
High Temperature (A) compared to Rain (B)	☐	☐	☐	☒	☐	☐
High Temperature (A) compared to Wind (B)	☐	☒	☐	☐	☐	☐
Rain (A) compared to Wind (B)	☐	☒	☐	☐	☐	☐

Figure 1.
Example of questionnaire layout in where respondents were asked to make pairwise comparisons of weather factors valid for Swedish summer conditions

Comparison Matrix $\boldsymbol{A_i}$

	High temperature	Rain	Wind
High temperature	1	1/3	3
Rain	3	1	3
Wind	1/3	1/3	1

Consistency Ratio ≤ 0,1

Priority vector $\boldsymbol{w_i}$

High temperature	0,28
Rain	0,59
Wind	0,13

Figure 2.
Example of a comparison matrix ($\boldsymbol{A_i}$) and the corresponding priority vector

Question 8.
Estimate the percentage reduction in labor productivity due to light rain (0.5 mm/hour) compared to weather conditions with no rain.
No effect = 0% reduction
Total effect = 100% reduction (work stoppage)

	No (0%)	Low (10%)	Moderate (25%)	High (50%)	Work stoppage (100%)	Do not know
Formwork and rebar work tasks (walls)	☒	☐	☐	☐	☐	☐
Pouring concrete walls	☐	☒	☐	☐	☐	☐
Formwork and rebar work tasks (slabs)	☐	☒	☐	☐	☐	☐
Pouring concrete slabs	☐	☐	☒	☐	☐	☐
Erection of precast elements	☒	☐	☐	☐	☐	☐

Figure 3.
Layout of Question 8 in where respondents are asked to estimate the potential reduction in productivity because of light rain

a difference between no reduction and low, but also to align the response options with findings reported in previous studies.

To limit the number of questions, it was necessary to carefully select weather types that were considered to be representative for typical Swedish weather conditions. Selection of appropriate intensity for each factor was therefore discussed with a meteorologist (Asp, 2018). As a result, the following weather types were included: wind speed (range between 10 and 20 m/s), low and high temperature (−10 and +25°C), light and heavy rain (4 and 32 mm per day) and light and heavy snowfall (8 and 32 cm per day). To facilitate assessments, each numerical value was supplemented with common meteorological descriptions to be more easily recognised. Each question and response option were carefully formulated and revised until they were considered to be relevant, clear and easy to interpret. For all questions, the option "do not know" was available to avoid respondents to provide a forced answer when they really do not know or are uncertain. To facilitate post-processing of pairwise comparisons, an Excel-based algorithm was developed to automate the calculation of priority vectors.

Finally, the questionnaire was tested on a group of six site managers in a pilot study prior to distribution of the final questionnaire. The pilot study was used to confirm that the questionnaire was easy to follow and understand. Two follow-up interviews were made to avoid any misconceptions. The time to complete the questionnaire was also examined. It was then concluded that the questionnaire was ready to be launched.

Data collection, analysis and documentation

Distribution of the questionnaire was performed in November 2018. Each respondent received an email containing an introduction text, explaining the purpose of the questionnaire and why they had been contacted, as well as a link to the actual survey. It was also pointed out that their responses were being handled anonymously to make respondents feel comfortable with providing answers. The expected time to complete the survey (about 10 min) was also indicated.

In total, 232 individuals completed the questionnaire where 124 answered during the first week and 108 completed the survey, after a remainder, during the second week.

Results

The results of the survey are presented in the following order: the first sub-section presents facts about the respondents, the second sub-section presents the results of the pairwise comparisons and the third sub-section presents the collective judgements on the influence of weather.

General facts about survey results

The survey resulted in that 232 respondents completed the questionnaire. This corresponds to a response rate about 5.5% which is very low for questionnaire surveys in general. However, this is in the upper limit to what is typical for self-administrated digital surveys according to the market survey company's experiences. The constantly growing number of web-based surveys reduces the willingness of individuals to participate in surveys in general.

Table 1. Distribution of job functions among respondents

Professional position	Distribution (%)
Site manager	41
Construction manager	29
Site engineer	13
Project manager	12
Construction foremen	4
Other (purchasing, planners, etc.)	11

The distribution of respondents' present job function is presented in Table 1. Most respondents were site managers (41%) followed by construction managers (29%). In Sweden, construction managers typically are responsible for overall project issues for a specific region involving multiple construction sites. Construction managers are involved in planning, resource allocation, cost estimations and follow-ups at an overall project level. About 13% of the respondents were site engineers who assist the site managers in projects with operational planning, purchasing and ordering of materials, etc. Most of the stated job functions require practical knowledge of managing construction works in general including planning and follow-up of projects. These types of activities assume knowledge about work task productivity and what factors that might be of importance, e.g. weather.

In Table 2, the respondents' experience of concrete construction is presented. Almost 75% of respondents state that they have more than ten years of experience and almost 90% have more than five years of experience. Obviously, the group can be assumed to collectively possess a considerable amount of experience of concrete construction.

Results of pairwise comparisons

In total, the questionnaire resulted in 464 unique comparison matrices where 232 refers to summer conditions and 232 refers to winter conditions. In Table 3, aggregated priority vectors for summer and winter conditions and with a CR $\leq$ 0.1 are presented. The numerical values represent the weight of each factor. The number of respondents (n) which constitutes the basis for the priority vector is shown for each column.

For the summer case, rain was ranked as most important (0.38), followed by wind (0.32) and high temperature (0.30). Another way to express this relation is to determine the relative importance of factors by dividing each factor's value with the lowest ranked factor's value. In this way, rain is ranked 1.27 times more important than high temperature (0.38/0.30). The relative importance for each factor is given in brackets in Table 3. The difference in ranking

Experience of concrete construction	Distribution (%)
More than 10 years	74
5–10 years	15
1–4 years	9
Less than 1 year	1
Do not know	1

Table 2. Respondents experience of concrete construction

Weather factor	Aggregated priority vectors (CR $\leq$ 0.1) Summer condition n = 178	Winter condition n = 175
High/low temperature[1]	0.30 (1.00)	0.29 (1.00)
Rain/snow[2]	0.38 (1.27)	0.40 (1.38)
Wind[3]	0.32 (1.07)	0.31 (1.07)

Notes: [1]Summer: Temperature = +25 °C; Winter: Temperature $\leq$ 0 °C. [2]Summer: Rain = 10 mm during 8 h; Winter: Snow = 8 cm during 8 h. [3]Wind speed between 10 and 14 m/s

Table 3. Aggregated priority vectors valid for summer and winter conditions based on pairwise comparisons with CR $\leq$ 0.1

between wind and high temperature is relatively small. For the winter case, snowfall is ranked as most important (0.40), followed by wind (0.31) and low temperature (0.29). The relative importance indicates that snow is 1.38 more important than low temperature.

Influence of wind conditions on lifting operations

Figure 4 shows the distribution in maximum wind speeds when lifting operations are cancelled based on estimations provided by 232 respondents. As seen in the diagram, there is a relatively large span in maximum wind speed where most estimations are between 13 and 19 m/s regardless of the type of lifting operation. About 80–85% of all respondents estimate that lifting operations are cancelled at wind speed higher than 19 m/s. A closer look indicates that lifting wall formwork, table forms and frame finishing materials are more sensitive to wind compared to lifting precast elements and pouring concrete. For instance, about 45-50% of respondents answer that lifting of wall forms, table forms and frame finishing materials are cancelled at wind speed higher than 15 m/s. At the same wind speed, only 35% of respondents answer that lifting operations of precast elements and pouring concrete are cancelled. It seems reasonable given the differences in lifting objects' sensitivity to wind conditions, e.g. large light-weight formwork versus heavy objects such as precast units or a skip filled with concrete.

Influence of precipitation on work task productivity

Figure 5 (diagram a) shows the estimated loss in productivity for different work tasks owing to light rain with a specified intensity of 0.5 mm per hour during a 8-h workday. In general, light rain seems to have limited effects on productivity. A majority of respondents estimate either a 0% or a 10% reduction. However, pouring concrete slabs seem to be a little bit more affected where 20% of respondents estimate a 25% reduction.

Diagram b in Figure 5 shows estimated loss in productivity owing to heavy rain with a specified intensity of 4 mm per hour during an 8-h workday. As expected, heavy rain is estimated to result in higher reductions compared with light rain regardless of work type. Most respondents estimate losses in the range between 10% and 25%. However, 15% of respondents estimates up to 50% losses for formwork and rebar activities of concrete slabs. Moreover, pouring of concrete slabs is even more affected where 25% of respondents estimate a 100% loss (equal to work stoppage). The results indicate that work tasks

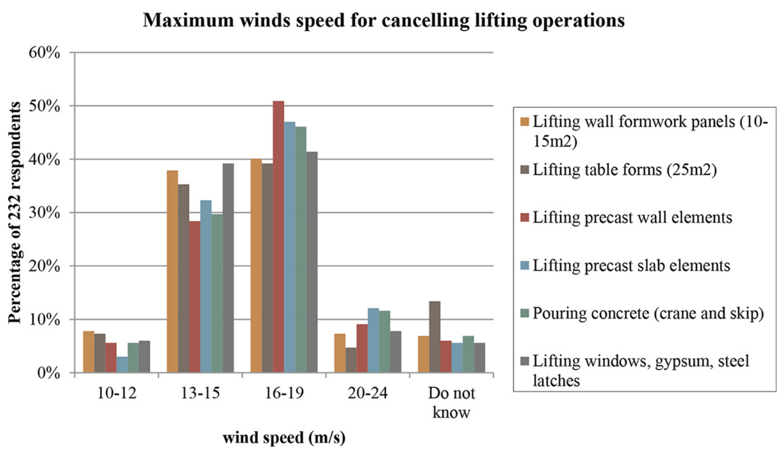

Figure 4.
Maximum wind speeds for cancelling lifting operations based on 232 respondents

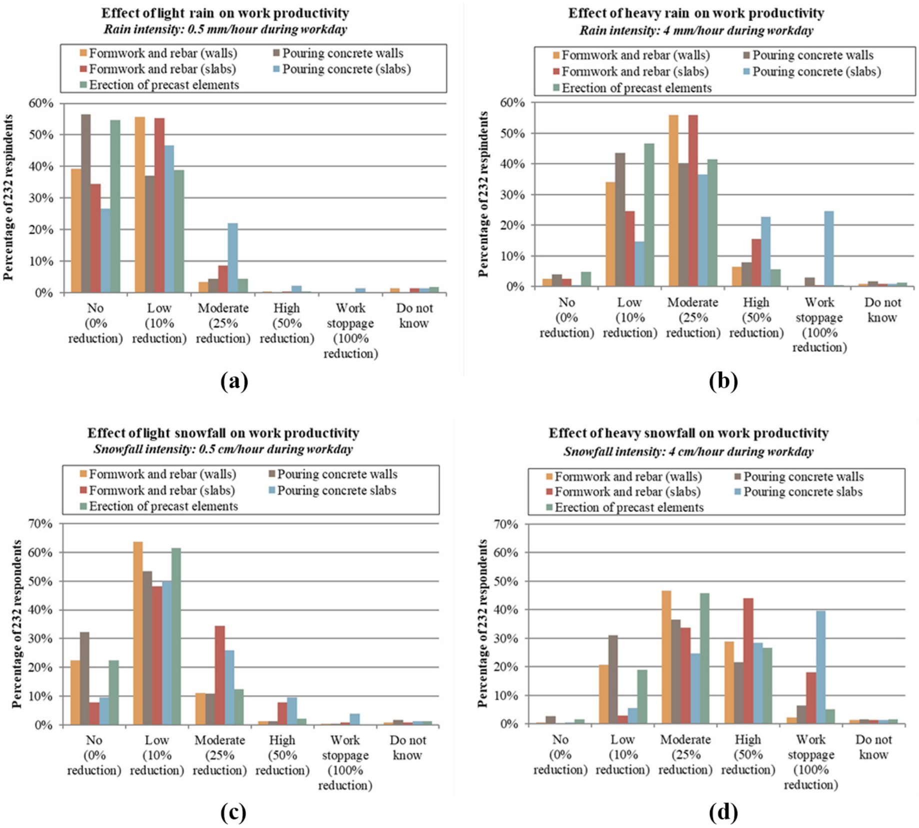

Figure 5. Estimated loss in work task productivity because of light rain (diagram a), and heavy rain (b), light snowfall (c) and heavy snowfall (d)

performed on horizontal areas (e.g. formwork and rebar, and pouring of slabs) are more sensitive to heavy rain compared with work tasks performed on vertical surfaces (concrete walls).

In Figure 5 (diagram c), estimated loss in work task productivity owing to light snowfall is presented. Most respondents estimate a low reduction (10%) in productivity. However, more respondents estimate a moderate loss in productivity compared to light rain. The effects of different work tasks are also more evident here compared to light rain. As seen in the figure, respondents tend to estimate higher loss in productivity for work types performed on slabs (e.g. formwork and rebar slabs, pouring concrete slabs) compared to work tasks performed on walls.

Considering heavy snowfall (diagram d), the estimated loss is in the range 10–50% for work tasks performed on concrete walls and for erection of precast elements. The estimated loss in productivity for formwork and rebar activities performed on horizontal surfaces (slabs) is in the range 25–100%. Apparently, heavy snowfall accentuates that different types of work are affected differently by weather. It should also be noted that the respondents have a significantly different opinion regarding the effect of heavy snow on pouring concrete slabs. However, a majority (40%) of respondents consider that this work task has to be cancelled at this weather condition.

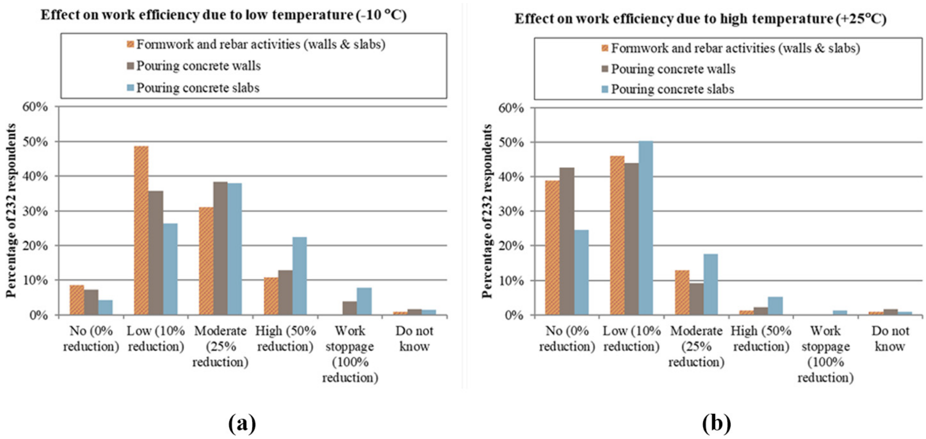

Figure 6. Estimated loss in work tasks' productivity because of low temperature (a) and high temperature (b)

Influence of temperature on work task productivity

The estimated loss in work task productivity owing to low temperature is presented in Figure 6 (diagram a). Almost 80% of respondents estimate a low or a moderate loss in productivity for formwork and rebar activities. The loss in productivity for pouring concrete walls is estimated to be higher. About 90% of respondents estimate a loss between low and high. As expected, highest reduction is estimated for pouring concrete slabs. Again, the results clearly show the difference in how work types are affected.

The estimated loss in productivity because of high temperature is presented in diagram b (Figure 6). In general, the losses are estimated to be zero or low for all work tasks. Again, the effect on pouring concrete slabs is somewhat higher compared with the other work tasks, but the difference is not as large as was the case with low temperature.

Discussion

Here, the results presented of the survey are discussed in relation to the three research questions. Thereafter, implications of the results are discussed, also addressing limitations and critical reflections on the study.

Ranking of weather factors (RQ1)

Addressing *RQ1*, the results of the pairwise comparisons show that precipitation is ranked as most important followed by wind and finally temperature. For summer conditions, rain is ranked about 1.3 times more important than high temperature and about 1.2 times more important compared to wind. For winter conditions, snowfall is ranked about 1.4 times more important compared to low temperature and 1.3 times more important than wind. These results are in contrast with what was found in Moselhi and Khan (2012) where temperature was ranked as the most important weather factor followed by wind speed and thereafter precipitation. The different outcome could be explained by that this study covers a broader perspective of construction operations (formwork, rebar, concrete) compared to the study performed by Mosehli and Kahn where only formwork operations were considered. Indeed, different work tasks are affected by weather factors differently which also may be reflected in rankings of their relative importance.

Moreover, the fact that temperature was set to zero degrees (or less) when making pairwise comparisons could explain why this factor was not ranked higher compared to wind and snowfall. Temperature around zero is typically a threshold for "concrete winter" but is far from an extreme temperature condition in the Nordic countries. Choosing a colder temperature value (e.g. minus 10 degrees) may have resulted in a different ranking.

Estimations of productivity loss owing to weather (RQ2 and RQ3)

On a general level, the results reveal that weather may play a significant role when estimating work task productivity. However, the estimated effects vary considerably depending on weather type, especially for more severe weather conditions. For instance, heavy precipitation (rain or snow) reduce productivity in the range of 25–100% compared to when no effects of precipitation are considered. It is also clear that different types of works are affected differently depending on type of weather factor. For instance, work tasks performed on horizontal areas are more sensitive to precipitation than work tasks performed on vertical areas. Obviously, it is much easier to shield a vertical work area against snow compared to a horizontal area. Snowfall on a slab form containing fixed reinforcement bars and different types of technical installations and cast in-goods are not easy to clean to make ready for pouring concrete. Therefore, the effects of weather cannot be generalized but should be treated separately depending on type of work task and weather factor.

Figure 7 shows a comparison between results from this study and reported findings in previous studies. To facilitate the comparison, only the most common responses (mode) for each weather type and work task according to Figure 5 (diagrams a–d) are included. The estimated effects in this study show both similarities and differences compared to previous research. Moselhi and Khan (2010), Thomas and Ellis (2009); and Noreng (2005) found that precipitation with a light or moderate intensity resulted in a loss in productivity by 40–60%. These findings are clearly in contrast to the results presented in this paper indicating only a 0–10% reduction for a light rain or a light snowfall. The effects of heavy precipitation have been reported in previous studies to be in the range 50–100%. In this study, the estimated

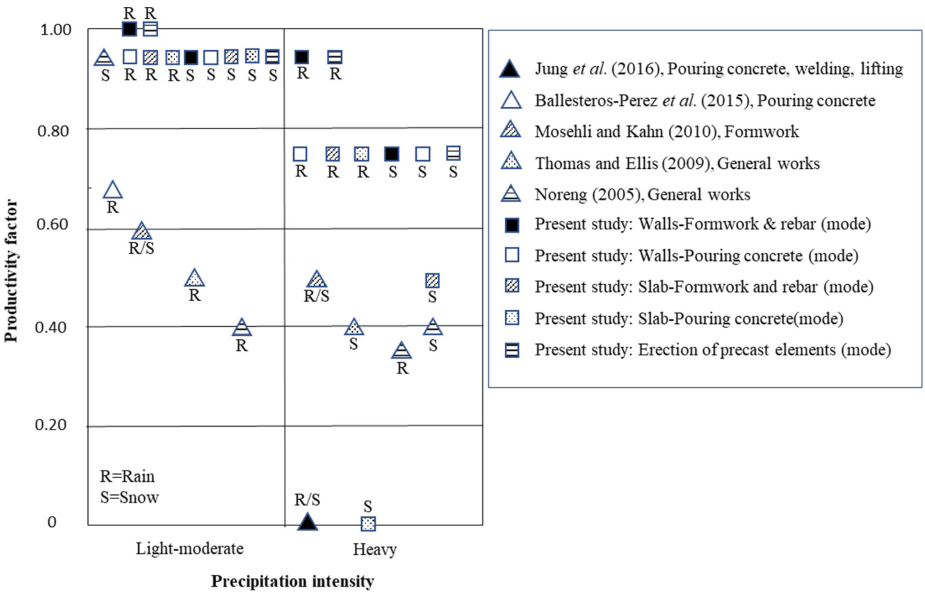

Figure 7. Effects of precipitation based on present and previous studies

effects of heavy rain are in the range of 10–25%, whereas the effects of heavy snow are estimated in the range 25–100% depending on work task. Obviously, the effects of heavy precipitation (especially snow) become more dependent on type of work. Indeed, a heavy snowfall on a concrete slab may lead to substantial extra work to clean before any work can proceed. This is also reflected in the results by large difference in productivity loss between a light and a heavy snowfall. This effect has also been reported by Noreng (2005). In overall, the findings in this paper suggest that the effects of precipitation should be treated separately depending on type of precipitation, intensity and work task.

The estimated effects of high and low temperatures are partly in line with reported effects in previous research (Koehn and Brown, 1985; Hassi, 2002; Moselhi and Khan, 2010). In this study, a majority of respondents estimate a 10–50% loss in productivity depending on type of work at temperature equal to −10°C. Previous research studies indicate a loss in the range of 10–35%. At high temperature (+25°C), the estimated losses presented here are in the range 0–25% depending on type of work. Estimated losses reported in previous research are in the range 0–15% at the same temperature. The differences between this study and previous studies can be explained by the fact that different work tasks have been considered. This study has clearly shown that different work tasks are affected differently by a certain weather type. In addition, some of the observed differences may also be explained by the fact that the studies have sampled data from countries with different climatic conditions. Obviously, humans adapt to the climatic conditions where they live. People living in the Nordic countries are obviously more adapted to cold weather compared to people living in, e.g. the south European countries. Also construction methods and practices are developed to be adopted to face the challenges of weather representative for a specific geographical region.

The estimated maximum wind speed for cancelling lifting operations is in the range of 13–19 m/s. Clearly, respondents have a relatively different view on when lifting operations should be avoided. The results indicate a lack of common knowledge regarding more precise threshold values for when lifting operations should be avoided. This is interesting because safety is stated as high priority among construction firms in Sweden, and lifting operations in windy conditions are indeed a safety issue. The results also reveal somewhat different threshold values for different type of lifting operations. As expected, lifting of lightweight objects (e.g. wall form panels) is estimated to be cancelled at lower wind speed compared to heavy objects such as precast elements.

Scientific and practical implications

Knowing the relations between weather factors and construction work task productivity is of both scientific and practical value. This paper is of scientific value as it provides a structured methodology to collect data from individuals that possess practical knowledge. This research provides new insights into the use of pairwise comparisons in order to quantify experts' opinions about the relative importance of weather factors. The results are also of academic interest as they add new insights to existing knowledge about how weather affects productivity more in detail. For instance, the findings reported in this paper indicate that the relation between weather conditions and construction productivity depends on several underlying variables, e.g. type of weather factor, intensity of each weather factor (e.g. light or heavy snow) and type of work task. These findings address the research need of how different weather types affect loss in productivity highlighted by Ibbs and Sun (2017). Accordingly, the real effects of weather cannot easily be generalized into a single value describing the effect but should instead be expressed as a function depending on the aforementioned variables. This type of knowledge is essential to develop models that can be used to estimate how weather affects construction productivity.

The practical contribution of this paper lies foremost in the estimations of productivity reductions for common work tasks. The estimated reductions can be used to adjust productivity rates for a certain work task and weather type. Contractors are for many reasons dependent on making good estimations of task productivity as it has a direct influence on project duration and cost. Enhanced knowledge about how weather influence productivity rates are therefore important as it enables for better estimations of project schedules. Neglecting or making poor estimations of the influence of weather increase the risk of experiencing weather-related delays. On the other hand, poorly adjustments of how weather affects productivity can also mean that the effects are overestimated. The need for enhanced knowledge is also motivated by the fact that weather conditions vary owing to seasonal effects. For instance, Larsson and Rudberg (2019) reported that without any measures taken to shield work tasks against weather, construction duration was extended by 14–46% owing to seasonal effects. Future changes in global climate may also increase the general awareness of weather. Existing industry practices used to deal with "typical" weather conditions may also have to be reconsidered as a result of a changing climate.

Limitations

The estimated loss in work task productivity as well as rating of weather factors is foremost valid for construction of multistory concrete frameworks. In addition, the reported effects of weather are based on practitioners' collective experience influenced by Swedish weather conditions and working procedures. The estimations of productivity reductions as well as rating of weather factors are also based on a few numbers of discrete values describing each weather type, e.g. cold temperature (−10°C) or hot temperature (+25°C). The selected values are typical for Swedish climate but could be considered as unrealistic in regions with a substantial different climate. Another limitation is that estimations of productivity reductions have not considered any interdependencies between weather factors. Nevertheless, ranking of weather factors and estimated productivity losses are of general interest as they refer to concrete work tasks which are common in many types of construction projects worldwide. In addition, the questionnaire survey as such including pairwise comparisons is universal and could be used with minor adjustments to collect data for the same or other work tasks in geographical areas with different climatic conditions.

The results presented in this paper are subjected to uncertainties related to the quality in answers provided by respondents. Clearly, respondents can provide incorrect answers in many ways, deliberately, by ignorance or by misconceptions. However, the measures taken in the design of the survey are believed to ensure high quality in estimations and rankings. For instance, careful planning and selection of target group facilitated high quality in the survey as such. The respondents are believed to possess necessary qualifications to provide reliable answers. To avoid forced answers, respondents had the option to mark "do not know." However, most respondents seem to have an idea about the effects of weather (including ranking of factors) as very few respondents checked the "don't know" option. To reduce errors related to misconceptions, each question and response options was carefully examined in an iterative process involving discussions with a meteorologist and by reviewing previous research literature. The final questionnaire was also tested on a group of site managers in a pilot study to ensure that the questions and response options were relevant and clearly phrased to avoid any misconceptions. Overall, all measures taken were considered to reduce the risk of errors and enhance the overall quality of the survey.

Summary and future research

Weather is an important factor influencing construction productivity as most projects take place outside in unprotected environments. Therefore, knowledge about how weather influence construction works is essential during planning and execution of projects. This paper provides new insights about how 232 experienced practitioners in Sweden estimate reductions in productivity for common concrete work tasks based on different weather types. It also provides insights into how practitioners rank the relative importance of temperature, wind and precipitation. The results partly confirm findings reported in previous research but also reveal a more complex relationship between weather and productivity indicating several underlying influencing factors. The results are believed to be of general interest for both researchers and practitioners. Researchers can use the results as a basis to develop more advanced models to predict the effect on productivity owing to various weather conditions. Practitioners can use the results when planning concrete works making the overall construction schedule more resilient to weather. The structured questionnaire survey itself is also a valuable contribution to the scientific domain as it can be used by other researcher to collect similar data, thereby further increasing the knowledge and amount of data on the effect of weather conditions, which is still too scarce.

Finally, future research should aim at performing additional studies to collect more data describing the effects of weather on construction productivity accounting for underlying factors such as weather type, intensity, type of work and site conditions. Increasing the amount of data of underlying variables enable to develop more advanced models to more accurately account for weather on productivity. The proposed questionnaire survey can be a cost-effective alternative to collect such data. It would also be of great interest to replicate this study in other regions to enlarge the data set and to make comparative studies between regions and countries.

Note

1. Sverige Bygger AB: www.sverigebygger.se

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