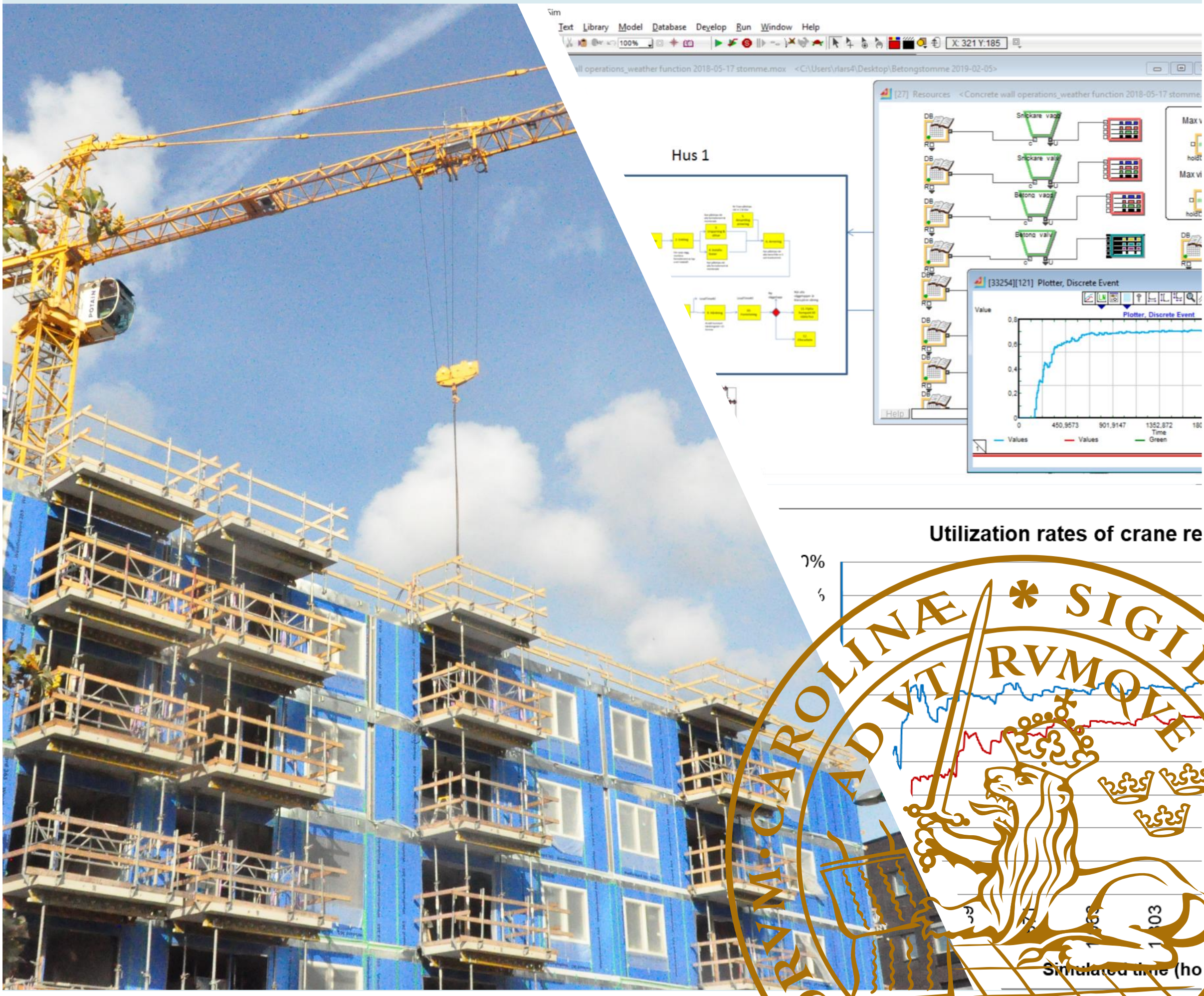
Modelling and simulation of factors influencing on-site construction of concrete frameworks

Studying the effects of resource allocation, weather conditions, and climate-improved concrete

ROBERT LARSSON | FACULTY OF ENGINEERING | LUND UNIVERSITY



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Robert Larsson

LUND
UNIVERSITY

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Abstract

Concrete is the most common material used to build the structural framework in multistory buildings. However, the construction works carried out on the building site are affected by many different factors that may reduce productivity. Delayed material deliveries, poor planning and coordination of work tasks and production resources, as well as unfavorable weather are examples that reduce productivity. Reduced productivity results in extended construction duration and increased costs for the concrete framework, which ultimately can affect the entire construction project. It is therefore important to increase knowledge about how different factors affect productivity to avoid construction delays and increased costs. Studying how different factors affect productivity is complex as a production system may consist of a large number of factors that can affect the outcome. One method that makes it possible to describe and study complex production systems is discrete event simulation (DES).

The aim of this research is to increase knowledge about how DES can be used to systematically analyze the impact of factors that affect productivity during construction of a concrete framework structure. Three factors that are considered to be particularly important for concrete production methods are included in this research study, namely: 1) utilization of labor and crane resources, 2) impact of varying weather conditions, 3) use of climate-improved concrete.

Considering utilization of labor and crane resources (factor 1), this study shows that DES is a suitable method for studying in detail how the utilization of these resources affects construction time and cost of the framework. The study highlights the importance of describing the production process in detail to enable identification of workflow bottlenecks caused by resource allocation conflicts. To support identification and analysis of bottlenecks and corrective measures, it is suggested that the traditional performance measures time and cost are supplemented with two additional indicators, namely waiting time and utilization rate.

Regarding the impact of weather (factor 2), this study contributes with new knowledge about how this can be described and studied by using DES. The basis for this is a definition of a weather function that describes the relationship between weather and labor productivity. In addition, another function is described that considers the effect of actual weather conditions on the development of concrete strength, which is also important for the productivity of the concrete production cycles. In this way, the impact of weather when using climate-improved concrete can also be studied (factor 3). By implementing these functions in a discrete-event simulation model together with weather statistics, the impact of different weather conditions was simulated. A separate calculation tool was also developed to supplement simulated construction duration of the framework with cost and climate impact.

The results from the simulations show that the weather has a significant impact on construction duration of the concrete framework. For example, the construction duration increases in the range 8-42% compared with a reference scenario that is unaffected by weather. The extended duration depends on the season for construction and where the project is located, but also on the extent to which climate-improved concrete is used. The results also show that climate-improved concrete has a significant potential to reduce CO_2-emissions of a concrete framework during the construction phase. But to realize the potential of climate-improved concrete also in periods with colder weather, selection of appropriate curing methods becomes imperative. At a more detailed level, a questionnaire survey was also conducted in which contractors estimated the impact of weather on productivity for typical concrete work. These results confirm the importance of the impact of the weather also at a work task level.

This study describes how DES can be used to systematically study and analyze how the productivity of construction-related production systems is affected by various factors. The study also provides new insights into how resource utilization, weather, and climate-improved concrete affect the construction of concrete frames. In overall, this can lead to a better basis for planning and selection of production methods to enable increased productivity.

Key words: Discrete-event simulation, concrete frameworks, productivity, resource usage, weather, carbon emissions.

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Preface

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Lomma, October 2021

Robert Larsson

Abstract

Concrete is the most common material used to build the structural framework in multistory buildings. However, the construction works carried out on the building site are affected by many different factors that may reduce productivity. Delayed material deliveries, poor planning and coordination of work tasks and production resources, as well as unfavorable weather are examples that reduce productivity. Reduced productivity results in extended construction duration and increased costs for the concrete framework, which ultimately can affect the entire construction project. It is therefore important to increase knowledge about how different factors affect productivity to avoid construction delays and increased costs.

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The results from the simulations show that the weather has a significant impact on construction duration of the concrete framework. For example, the construction duration increases in the range 8-42% compared with a reference scenario that is unaffected by weather. The extended duration depends on the season for construction and where the project is located, but also on the extent to which climate-improved concrete is used. The results also show that climate-improved concrete has a significant potential to reduce CO_2-emissions of a concrete framework during the construction phase. But to realize the potential of climate-improved concrete also in periods with colder weather, selection of appropriate curing methods becomes imperative. At a more detailed level, a questionnaire survey was also conducted in which contractors estimated the impact of weather on productivity for typical concrete work. These results confirm the importance of the impact of the weather also at a work task level.

This study describes how DES can be used to systematically study and analyze how the productivity of construction-related production systems is affected by various factors. The study also provides new insights into how resource utilization, weather, and climate-improved concrete affect the construction of concrete frames. In overall, this can lead to a better basis for planning and selection of production methods to enable increased productivity.

Sammanfattning

Att bygga stommen i betong är den vanligaste produktionsmetoden för flerbostadshus i Sverige. Arbetet med att bygga stommen påverkas dock av många olika faktorer som kan försämra produktiviteten. Försenade materialleveranser, bristande planering och koordinering av produktionsresurser, samt ogynnsamt väder är några exempel på faktorer som kan minska produktiviteten. En lägre produktivitet medför längre byggtider och ökade kostnader för stommen vilket kan påverka hela byggprojektet. Det är därför viktigt att öka kunskapen om hur olika faktorer påverkar produktiviteten för att undvika förseningar och ökade kostnader.

Att studera hur olika faktorer påverkar produktiviteten är komplext då ett produktionssystem kan innehålla ett stort antal faktorer som kan påverka utfallet. En metod som gör det möjligt att beskriva och studera komplexa produktionssystem är diskret-händelsestyrd simulering (DHS).

Målsättningen med denna forskning är att öka kunskapen om hur DHS kan användas för att systematiskt analysera inverkan av faktorer som påverkar produktiviteten vid byggandet av betongstommar. Tre faktorer som anses vara speciellt viktiga för betong ingår i denna forskningsstudie, nämligen: 1) utnyttjande av arbetskraft och kran-resurser, 2) inverkan av olika väderförhållanden; 3) användning av klimatförbättrad betong.

Ser man till utnyttjande av arbetskraft och kran-resurser (faktor 1) så påvisar denna studie att DHS är en lämplig metod för att i detalj studera hur utnyttjandet av dessa resurser påverkar byggtid och kostnad för stommen. Studien lyfter fram vikten av att i detalj beskriva produktionsprocessen för att identifiera flaskhalsar orsakade av en obalans mellan behovet av och tillgången på resurser för ett givet produktionsupplägg. Som stöd för att identifiera och analysera flaskhalsar och korrigerande åtgärder föreslås även att de traditionella måtten tid och kostnad kompletteras med nya indikatorer i form av väntetid och utnyttjandegrad.

När det gäller inverkan av väder (faktor 2) så bidrar denna studie med ny kunskap om hur detta kan beskrivas och studeras med hjälp av DHS. Basen för detta utgörs av en definition av en väderfunktion som beskriver sambandet mellan väder och arbetsproduktivitet. Dessutom beskrivs ytterligare en funktion som tar hänsyn till vädrets inverkan på betongens hållfasthetstillväxt, som också är viktig för produktiviteten under stomskedet. På detta vis kan även vädrets inverkan vid användning av klimatförbättrad betong studeras (faktor 3). Genom att implementera dessa funktioner i en simuleringsmodell tillsammans med väderstatistik så simulerades inverkan av olika väderförhållanden. Ett separat beräkningsverktyg utvecklades också för att komplettera simulerade byggtider med kostnader och klimatpåverkan.

Resultaten från simuleringarna visar att vädret har en stor påverkan på byggandet av betongstommar. Exempelvis så ökar byggtiden med mellan 8-42 % jämfört med ett referensscenario som är opåverkat av vädereffekter. Utfallet beror på tidpunkten för genomförande och var projektet är beläget, men också på i vilken grad klimatförbättrad betong används. Resultaten visar också att klimatförbättrad betong har stor potential att minska stommens klimatpåverkan under byggskedet. Men för att möjliggöra användning av klimatförbättrad betong i perioder med kallare väder så blir valet av härdningsåtgärd mycket viktig. På en mer detaljerad nivå gjordes även en enkätstudie där entreprenörer värderade inverkan av väder på produktiviteten för typiska betongarbeten. Dessa resultat bekräftar betydelsen av vädrets påverkan även för enskilda arbetsmoment.

Denna studie beskriver hur DHS kan användas för att på ett systematiskt sätt studera och analysera hur produktiviteten hos byggrelaterade produktionssystem påverkas av olika faktorer. Studien bidrar även med nya insikter om hur resursutnyttjande, väder, och klimatförbättrad betong påverkar byggandet av betongstommar. Sammantaget kan detta leda till bättre underlag för planering och val av produktionsmetoder för att möjliggöra en ökad produktivitet.

1 Introduction

This chapter first describes a background to three factors that influence on-site concrete production methods and how discrete-event simulation can facilitate systematic analysis of these factors. Next, the aim and scope of the research is described followed by the outline of the thesis.

1.1 Background

This thesis focuses on discrete-event simulation as a methodology to perform systematic analysis of factors influencing on-site productivity of concrete frameworks.

Concrete is the most used construction material worldwide (Andersson, Stripple, Gustafsson & Ljungkrantz, 2019). The material has unique properties in terms of strength, durability, and geometrical flexibility, making it suitable in most construction applications, e.g. as a structural material in buildings, tunnels, bridges etc. In many applications concrete is the only realistic alternative (Schrivener, John & Gartner, 2018).

Considering construction of multifamily buildings, reinforced concrete is commonly used in the structural framework of those buildings. The structural framework is an important sub-system in multi-story residential buildings since it provides fundamental properties such as load bearing capacity, durability, fire resistance, and sound insulation. In Sweden for instance, almost 90% of all multifamily residential buildings are built with a structural frame made of reinforced concrete (Andersson & Larsson, 2014). Concrete frameworks can be built by pouring concrete on-site using temporary formwork systems, or by prefabricating concrete elements off-site which then are shipped to site for final assembly (Illingworth, 2000). However, a third method that is being used more commonly, is to combine these two methods into a hybrid solution where prefabricated elements are used in combination with concrete poured on-site (Glass, 2005). Despite the increasing use of prefabricated components, many activities are still needed to be performed on the construction site.

The on-site construction works of concrete frameworks are exposed to multiple factors that may influence construction productivity. For instance, buildability

(Jarkas, 2010), availability and performance of materials, labor, or equipment (Dunlop & Smith, 2003; Proverbs, Holt, & Olomolaiye, 1999; Smith & Hanna, 1993), inclement weather (Moselhi & Kahn, 2010). Some of these factors are applicable for other construction methods in general, but three factors can be distinguished as important for the productivity of on-site concrete production. These are related to: 1) complexity of the on-site production; 2) influence of weather; 3) the use of new concrete types with reduced carbon footprint.

1.1.1 Factor 1: Complexity of the production system

The first factor considers the complexity of the production system. The on-site production process is complex as it contains multiple interactions between activities and resources (Löfgren, 2002). The process complexity is also related to the fact that most of the construction works are carried out in an unprotected and dynamic environment. In the pursuit to optimize production time and resource cost, work is often executed simultaneously at different work locations by sharing the same resources, e.g. labor and crane (Larsson, 2010). This means that not only the execution of activities must be controlled, but also the coordination and allocation of the resource flows. If the allocation of resources is not properly managed it may result in workflow interruptions, low resource utilization, and productivity losses. The occurrence of non-value adding activities and their implications on project performance is a well-known problem highlighted in several studies, e.g. in (Josephson & Chao, 2014; Larsson, 2010; Winch & Carr, 2001). Inefficient use of resources may have a significant economic impact considering that resources (e.g. labor and machinery), comprise for a substantial share of total construction costs, especially in industrialized countries. For instance, in Sweden the cost of labor including sub-contractors constitutes for almost 30% of total construction cost whereas cost for equipment and machinery are about 20% (Byggföretagen, 2020).

In addition, the production is also dependent on concrete curing since this material-related process determines when formwork can be removed which is crucial to keep up with planned production cycles. Due to the many interactions between activities, labor, equipment, and material resources, planning and control of the workflow becomes a complex task.

1.1.2 Factor 2: Influence of weather conditions

The second factor is related to the fact that weather influence construction projects in general and concrete production methods in particular. The on-site production of concrete frameworks is mostly carried out in an unprotected environment exposed to varying weather conditions. 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. As a result, weather becomes an important factor to consider during the construction phase as it influences the ability to perform work effectively. Hot and cold temperatures, rain or snowfall reduce labor productivity. Also other resources, like machinery, are affected by weather. For example, strong winds may result in that cranes cannot be used for safety reasons.

Due to its importance for construction projects, the effects of weather on productivity have been a common research topic (e.g. Jung, Park, Lee & Kim, 2016; Koehn & Brown, 1985; Moselhi & Kahn, 2010; Thomas & Yiakoumis, 1987). However, despite the many research studies performed, there is a lack of data describing the effects at a detailed level considering that different work tasks are affected differently by weather.

Weather do not only affect manual or machine-assisted operations. The development of concrete strength is also strongly dependent on weather (Bagheri-Zadeh, Kim, Hounsell, Wood, Soleymani & King, 2007). Cold temperatures and windy conditions reduce the rate at which concrete gain strength. A slower curing process means that the formwork may not be possible to remove as planned since actual concrete strength has not met the minimum strength requirements for formwork removal. Delays in formwork removal may have serious effects on the construction duration and any corrective measures to make up for such delays are typically difficult and costly to employ.

It is worth mentioning that weather protection of concrete is related to shield the early strength development to meet desired production cycles. Considering quality and durability, concrete as a construction material is resilient to weather and for these reasons, weather protection is not necessary.

1.1.3 Factor 3: New concrete types with reduced carbon footprint

The third factor that may influence concrete productivity is related to concrete curing and the growing interest in using concrete types with reduced carbon footprint. Production of Portland cement clinker, which is the essential binder in concrete mixtures, constitutes for about 8% of global carbon emissions (Schrivener, 2020). Therefore, reducing the climatic impact of concrete usually means to partially substitute Portland cement clinker with supplementary cementitious materials (SCM:s). Examples of SCM:s are fly ash or blast-furnace slag. However, using SCM:s in concrete mixtures may delay formwork removal since these concrete types have typically a slower concrete strength development at lower temperatures (Lothenbach, Scrivener & Hooton, 2011). In addition, the release of internal heat from the chemical hydration process is also lower which means that these concrete types become more sensitive to cold temperatures and/or high winds. As a result, the use of new concrete types challenges existing industry practice when it comes to manage concrete construction in varying weather conditions.

Unfortunately, previous (and current) research focusing on the effects of weather on productivity is divided in two separate research fields. The influence of weather on labor productivity has been studied in the domain of construction management whereas the effects on concrete curing have been studied by material scientists. However, there is a lack of studies where the knowledge from each domain have been integrated to make a more comprehensive analysis of the effects on the production system.

1.1.4 Analysis of factors require a systematic approach

To analyze the inherent complexity of the production system associated with the many process-resource interactions and the variety of external factors (e.g. weather) that influence the overall productivity, a systematic approach is needed.

Discrete-event simulation (DES) has been proposed by researchers as suitable to systematically analyze the complexity characterized by construction systems (AbouRizk, Halpin, Mohamed, & Hermann, 2011; Lucko, Benjamin, & Madden, 2008). It offers powerful capabilities to logically and quantitatively model construction processes, its resources, surrounding environment, and any external factors that may impact it. Different production setups can be simulated in a very short time in a highly controlled environment having precise control of critical variables. External factors such as weather, can be systematically altered to understand how they influence the production system as a whole. Simulation can output multiple performance indicators, such as time, cost, resource utilization, and waiting time, which can be used to understand (analyze) the system. Additional performance indicators can also be integrated, e.g. carbon emissions. Accordingly, DES facilitates to model and systematically analyze production systems considering the effects of multiple decision indicators, such as time, cost, resource usage, and carbon-emissions.

Discrete-event simulation has successfully been used to model and analyze different factors influencing construction systems. However, there is still more research needed to address how it can be used to model and systematically analyze the complexity associated with construction systems. For instance, to model the task-resource interactions or the multiple effects of weather on concrete productivity.

1.2 Aim and scope

1.2.1 Research aim

The aim of this research is to develop knowledge about how discrete-event simulation can be used for systematic analysis of factors influencing on-site productivity of concrete frameworks. More specifically, the research focus on modelling and analysis of three factors that are considered important for on-site productivity of concrete frameworks. The factors considered are; 1) process complexity due to availability and allocation of labor and crane resources; 2) impact of varying weather conditions; 3) use of climate-improved concrete types.

The first factor, focusing on the usage of labor and crane resources, is related to the design of the production system. Knowledge about how resources can be used more effectively are essential to improve any type of construction system. However, erection of concrete frameworks is relatively labor-intensive and the costs of labor, equipment, and machinery comprise for a significant share of a concrete framework's total cost. Therefore, new insights in how to improve the use of resources during production are even more important for concrete-related construction systems.

The second factor is related to how weather conditions influence productivity of concrete work tasks. Weather conditions affect most on-site construction activities and construction of concrete frameworks are no exception to this. To increase knowledge about how different weather conditions affects both working methods, labor, machinery, and materials, are important to improve construction planning but also to facilitate decision-making during the production phase.

Connected to the second factor, another aim is also to specifically study how weather conditions influence concrete work tasks' productivity. This is motivated by the need to validate existing knowledge related to the influence of weather on typical concrete work tasks.

The third factor concerns the use of climatic-improved concrete and how it affects the construction of concrete frameworks exposed to varying weather conditions. The cement and concrete industries are globally working on several technological strategies to reduce carbon emissions of cementitious materials. For example, Carbon Capture and Storage (CCS), increased energy efficiency and electrification of cement process, designing for optimum use of concrete in structures, and increasing the use of SCM:s in concrete mixtures (Schrivener et al., 2018). One of the most promising strategies, especially on short term, is to increase the use of SCM:s to reduce carbon emissions of concrete structures. However, introducing climate-improved concrete may, if not properly managed, result in negative effects on productivity due to delays in formwork removal. Therefore, it is necessary to develop means to make analysis of production methods considering indicators of both productivity and environment in an integrated way. In addition, awareness of weather become even more important in situations where climatic concrete is used since these concrete types are in general more sensitive to colder and more windy conditions.

The choice of a simulation-based research methodology is motivated by the need to apply a system approach due to the complexity associated with many process-related interactions and a variety of factors influencing the system as a whole. Employing a system approach, the problem is viewed in the context of a system composed of interacting items (Hopp & Spearman, 2000). The emphasis is on taking a holistic view of the problem. Moreover, all variables that may influence the system can be studied isolated or in specific combinations in a highly controlled environment (Lucko et al., 2008).

1.2.2 Scope and research limitations

This research project is limited to study the on-site production process of concrete frameworks. More specifically, the work tasks and resources that are involved in the erection of the concrete framework are in focus. This means that not only main concrete work tasks (formwork, rebar, concreting) are considered, but also other work tasks such as placing pipes and ducts for technical installations and installing prefabricated stairs and balconies. However, work tasks that are related to foundation or frame finishing works are not included. A principal illustration of the dissertation's focus and boundaries are presented in figure 1.

When studying the effect of resource allocation, the use of labor and tower cranes are in focus. The costs of labor and tower crane(s) comprise for a significant share of the total cost of the concrete framework. Therefore, it is important to optimize the use of these resources. However, optimization of resources may introduce bottlenecks in the workflow reducing the overall production capacity. Design of the production system must therefore employ a systematic and holistic analysis of the overall system considering multiple indicators such as time, cost, resource utilization, and process waiting time.

When studying the effects of weather on work tasks' productivity, temperature, wind, rain, and snow are the weather factors considered in this research. Previous research studies indicate that these factors are most important for construction productivity. Humidity has not been considered even though it is also mentioned as an important factor in previous research, especially in regions with long periods of high humidity levels in combination with e.g. very hot temperatures. However, such climate conditions are not typical for the Nordic countries explaining why humidity has been excluded in this research. Effects of weather on work tasks' productivity are focusing on manual and crane-assisted operations. This is motivated by the fact that weather have a direct impact on labors' ability to perform work tasks optimally whereas tower cranes are a critical resource which are sensitive to windy conditions.

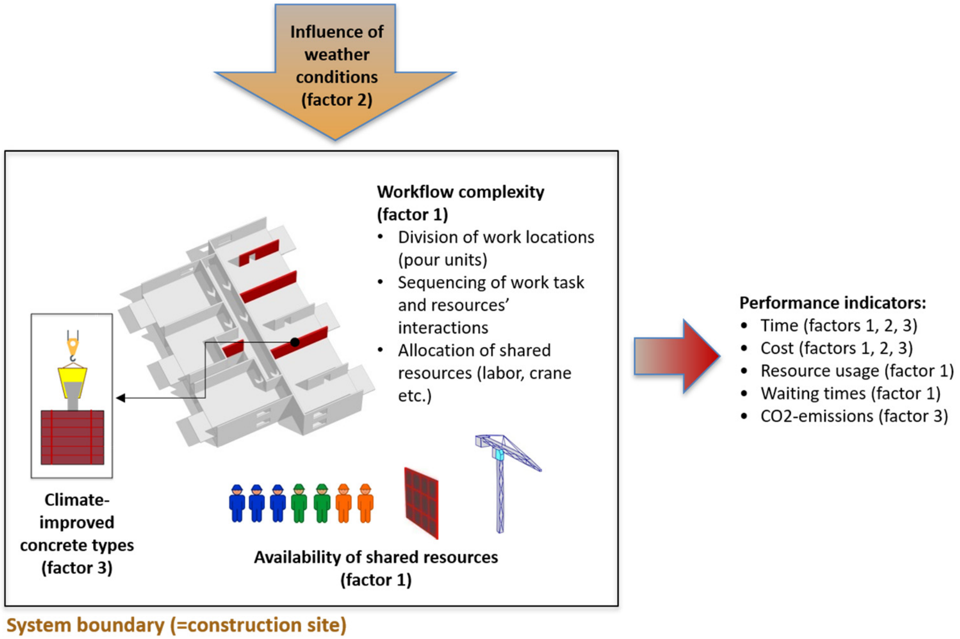


Figure 1.
Principal illustration of dissertation's focus and boundaries.

When studying the effects of weather on concrete properties, only effects related to development of concrete temperature and strength are considered. Development of strength is important from an operational point of view since it determines when formwork can be removed.

In this research, studying the effects of using climate-improved concrete under various weather conditions are limited to certain measures to reduce carbon footprint of the concrete mixture. The chosen measures involve reduction of Portland clinker in concrete mixtures by using a cement type (CEM II/A-V 52,5 N) containing fly ash in combination with reducing the total amount of cement in the concrete mixture. The measures chosen is motivated by that hydration properties of these concrete mixtures are already validated through laboratory tests and the effects on concrete strength development can therefore easily be studied using existing special-purpose simulation tools. Choosing other measures such as replacing cement in the concrete mixture with SCM:s require extensive laboratory testing to obtain parameters describing the hydration properties for each concrete mixture.

Another important material-related process is drying of humidity in concrete slabs. However, drying of concrete is a relatively slow material-process and the control of moisture levels extends into the next production phase (frame finishing and interior works) where knowledge about actual moisture level is of primary interest. Since this research focus on effects of weather on manual work tasks and formwork removal during erection of the concrete framework, drying of concrete is therefore not considered here.

This research combines scientific knowledge from both construction management research and material science. The research employs concepts of productivity derived from the field of construction management. Moreover, the influence of weather on construction productivity is mainly based on results published by researchers in the field of construction management. However, to contribute to the body of knowledge, the effects of weather on typical concrete work tasks are specifically studied as a part in this research.

Scientific concepts related to modelling and simulation of production systems are inspired by published materials within construction management research even though its theoretical and methodological foundations are grounded in operational management research. Knowledge and practical tools used for studying the influence of weather on concrete properties (e.g. temperature and strength development) are foremost based on results published by material scientists.

1.3 Thesis outline

This thesis is of a compilation character (thesis by publication) comprising five papers. The title of the thesis is “Modelling and simulation of factors influencing on-site construction of concrete frameworks – studying the effects of resource allocation, weather conditions, and climate-improved concrete”. The thesis is structured in the following way: The first part consists of an introductory section describing the background and the purpose of the research. Thereafter, a contextual description of concrete construction is given focusing on characteristics and challenges of on-site production methods. Next, an overview of relevant literature is provided focusing on factors that affect construction productivity. This is followed by a section introducing theoretical, methodological, and practical aspects of discrete-event simulation. The theoretical elements from previous chapters are thereafter synthesized forming the basis of the research questions. The next chapter presents the research process at an overall level outlining the four studies that have been conducted throughout the research project. Moreover, each study is also described on a more detailed level specifying the content of each research activity, but also addressing how research quality issues have been addressed. The next chapter presents the research findings addressing the four research questions. In a following chapter, contributions of the thesis are presented followed by ideas for future research.

The thesis is based on five papers as listed below also stating the author's contribution to the appended papers.

Paper 1

Larsson & Rudberg (2020). "A simulation-based approach for systematic analysis of workflow during the construction of in-situ concrete frames", Research report TVBK-3074, 32 p., Lund University, doi:10.13140/RG.2.2.35696.28160. Larsson was responsible for data collection, model development, performing simulation experiments, and main responsible for writing the paper.

Paper 2

Larsson & Rudberg (2019). "Impact of Weather Conditions on In Situ Concrete Wall Operations Using a Simulation-Based Approach". Paper published in *Journal of Construction Engineering and Management*, Vol 145, Issue 7. Larsson was responsible for data collection, model development, performing simulation experiments, and main responsible for writing the paper.

Paper 3a

Larsson (2019). "An Integrated Simulation-Based Methodology for Considering Weather Effects on Formwork Removal Times", Conference paper published in *Advances in Informatics and Computing in Civil and Construction Engineering – proceedings of the 35th CIB W78 2019 Conference: IT in Design, Construction, and Management*, Editors: Mutis, I., and Hartmann, T., Springer, pp. 415-422. Larsson was the sole author of this paper responsible for data collection, modelling, simulation experiments, and authorship.

Paper 3b

Larsson (2020). "An integrated simulation-based method for considering weather effects on concrete work tasks' productivity and concrete curing", Research report TVBK-3075, 52 p., Lund University, doi:10.13140/RG.2.2.24791.09121. Larsson was the sole author of this paper responsible for data collection, developing simulation model, performing simulation experiments, and report writing.

Paper 4

Larsson & Rudberg (2021). "Effects of weather conditions on concrete work task productivity – questionnaire survey". Paper published in *Construction Innovation*. Larsson was responsible for planning and designing the survey, data collection in collaboration with a market survey company, data analysis and main responsible for writing the paper.

2 The context of concrete framework construction

This chapter first describes concrete as a building material and an overview of existing production methods for concrete frameworks. This is followed by a section focusing on challenges related to on-site production methods. Thereafter, the maturity method and simulation tools used to determine concrete strength is presented. The chapter continues with sections describing the effects of weather on concrete construction. Finally, the drivers and recent development of industry initiatives to reduce carbon emissions are described addressing especially climate-improved concrete.

2.1 Concrete as a building material

Concrete is one of the most commonly used construction material today (Andersson et al., 2019). The material is essential for the development of societies in both urban and rural areas. In fact, most built structures in our societies, e.g. dams, bridges, tunnels, railways, roads, multi-story buildings, would not be possible to realize without the use of concrete (Scrivener et al., 2018).

Concrete consists in principle of cement, sand, aggregates, and water, which all are available in relatively large quantities in most places around the world. Therefore, concrete can be produced locally reducing costs and environmental impact associated with transportation. Concrete as a structural material has several functional advantages. When properly designed, concrete structures can last for very long time periods, often more than hundred years (Öberg, 2005). Concrete structures are resistant to moisture, wind, and extreme temperatures during its lifetime. The need for maintenance during its service life is much lower compared to other building materials. It is amendable to most geometrical shapes enabling a high degree of freedom in architectural design. Reinforced concrete (RC) has also advantages from a mechanical resistance perspective. RC structures typically follow a ductile behavior where failures are proceeded by substantial deformations and cracking. RC structures have in general also a capacity to withstand changes in load conditions due to refurbishments or accidents. Other functional advantages are related to fire resistance, thermal mass and sound insulation properties (Andersson, 2018). At the end of its life cycle, concrete structures can either be reused or recycled.

The main drawback of concrete as a building material is related to a higher carbon footprint compared to other materials. Carbon emissions of concrete is mainly attributed to the production of cement comprising for about 8% of the world's total CO_2 emissions (Scrivener, 2020). Also high weight in relation to its strength is another disadvantage attributed to concrete as a building material. Other drawbacks are more related to the production methods of concrete structures which are further discussed in sections 2.2 and 2.3.

2.2 Production methods for concrete frameworks

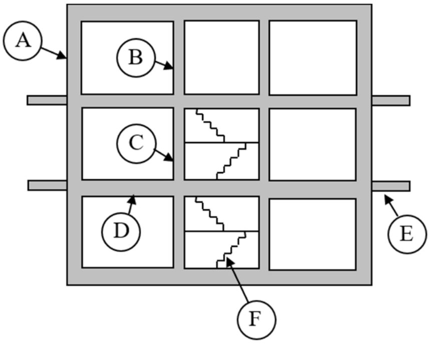
A production method is here defined as a collection of formwork, rebar, and concrete technologies that are used in combination during erection of the concrete framework. Each combination of technologies determines the sequence of tasks and the need for resources. Moreover, technologies also determine the need for on-site works by its level of prefabrication. The wide range of technologies available which also can be combined in different ways, means that the overall production method can have many different configurations. To simplify the overview, a production method is here distinguished by its degree of prefabrication which determine the need for on-site works.

2.2.1 Overview of common concrete production methods

To generalize, there exist three production methods to build concrete frameworks. The first method involves pouring concrete on-site using temporary formwork systems. This is an established method where formwork, rebar, and concrete activities are carried out on-site. It is popular among professionals for its simplicity in structural design, but also since it enables high flexibility in geometrical layout of buildings. Even though advancements in material and machinery technology have continuously improved safety and labor productivity, it is still labor-intensive and involves heavy and repetitive manual work tasks. The method also consists of several non-value added work tasks such as formwork removal and propping. It is also dependent on concrete curing to enable reuse of formwork and drying out of concrete to enable floor laying on concrete slabs. As a result, the rate of the on-site production becomes dependent on material-related properties.

The second method involves manufacturing of concrete elements in off-site factory facilities. Finished elements are transported to site where they are assembled to form the final structure. The rationale behind prefabrication is to reduce on-site work complexity and shorten construction time (Vriehoof & Koskela, 2000). Also, the quality of components can be improved since they are manufactured in a controlled environment. However, the method requires a more detailed design, is less flexible in terms of geometrical freedom, and more sensitive to late design changes (Illingworth, 2000).

The third method is a mix of in-situ and prefabrication methods. Here, prefabricated components are combined with in-situ techniques to exploit the benefits of each method (Glass & Baiche, 2001). This hybrid method is also known as hybrid concrete construction, "HCC", (Goodchild, 1995), or mixed construction (FIB, 2002). As pointed out by Glass (2005), the scope of HCC is potentially very broad because it may include all in-situ techniques and a variety of precast components, fabricated rebar solutions, and other options such as structural steel. The proportion between prefabricated and in-situ techniques may vary in order to find optimum solution for a particular set of circumstance of a given project. For instance, precast elements can be used as a permanent formwork (e.g. lattice girder elements) containing most of the required reinforcement. Concrete is then poured on top of these elements forming a monolithic slab structure. In similar way, prefabricated concrete twin walls function as a permanent formwork system where concrete is placed on-site between precast panels forming a homogenous wall structure. Even a concept where temporary formwork systems are used for concrete walls and slabs could be defined as a hybrid solution since it may contain prefabrication of other structural sub-systems, e.g. columns, beams, balconies, and stairs. High flexibility, ease of construction, robustness, fire safety, and sound insulation, are reasons for why the method has become popular as a solution for the structural framework, especially in Northern Europe and the Scandinavian countries (Glass, 2005). For example, 80-90% of all multi-dwelling building projects in Sweden were built with structural frames made of reinforced concrete (Andersson & Larsson, 2014). A majority of these frameworks consisted of a mix of prefabricated and in-situ methods. Figure 2 presents an overview of typical production techniques for concrete frameworks in multi-story residential buildings based on a survey presented in Larsson (2010). As seen, the load-bearing structure forming the concrete framework consists of both prefabricated components and concrete poured in-situ.



		Percentage of 38 projects*
A	Facade	73% Steel columns
		34% Concrete in-situ
		5% Precast double walls
B	Load-bearing internal walls	84% Concrete in-situ
		11% Precast double walls
		11% Precast solid elements
C	Staircase walls	74% Concrete in-situ
		13% Solid concrete elements
D	Floor slabs	76% Filigran-elements + concrete in-situ
		24% Concrete in-situ
E	Balconies	82% Precast elements
		13% Concrete in-situ
F	Stairs	97% Precast concrete
		3% Steel

* Several answer-options possible, i.e. the total sum can be more than 100%

Figure 2
Summary of construction methods used for concrete frameworks in Swedish multi-story residential buildings (Larsson, 2010).

2.2.2 Challenges of on-site concrete production

The on-site production process contains some challenges that origins from the fact that most activities are performed on-site, the design of the production system with many interactions and resource flows, the dependency between production cycles and concrete material properties (e.g. rate of concrete curing). These challenges apply for hybrid construction methods in general but depending on the level of prefabrication, some challenges may be more important than others. The challenges that are relevant for this thesis are the following:

- *Work is executed in sub-optimal conditions*: Erection of concrete frameworks are carried out at construction sites, usually unprotected to varying weather conditions. This applies regardless of whether in-situ or prefabricated methods are used. However, in-situ concrete methods contain more on-site works and the construction time is longer compared to prefabricated methods why it become more exposed to weather. In a recent study presented by Koch, Shayboun, Manès and Nordlund (2020), weather is considered to contribute to the largest disturbances during production of office and residential buildings according to site managers in Sweden.

- *On-site workflow involves multiple resource interactions*: The on-site production process is quite complex as it involves multiple inputs and flows in terms of labor, materials, and equipment (Löfgren, 2002). Different work tasks are executed by different labor disciplines, e.g. carpenters handle formwork and concreters place rebars and pour concrete. In addition, the workflow also involves placing of pipes and ducts for technical systems that are poured into the concrete structure. Since the work tasks are performed in a certain sequence, they become dependent on each other. Initiation and completion of tasks according to plan presume predictable inputs, e.g. connected works are finished, necessary crews, instructions, workspace, materials, and equipment, are simultaneously available when needed. On a theoretical level, Koskela (1999) addresses these constraining inputs as preconditions for a reliable execution of work tasks. Any missing input will have negative effect on the execution of tasks. Considering the workflow as a network of individual work tasks, the number of inputs that have to be controlled increases exponentially with the number of tasks. Consequently, a predictable workflow presumes controlling and managing all the inputs during the on-site production. Poor planning and control of inputs results in low productivity as tasks cannot be executed and resources become idle. Previous studies have reported non value-added time comprising for about 20% of total available time (Josephson & Chao, 2014; Larsson, 2010; Winch & Carr, 2001). One way to reduce on-site complexity is to increase the level of prefabrication since it reduces the number of input flows (Vriehoof & Koskela, 2000). However, prefabrication result in other type of complexity, e.g. being dependent on timely deliveries as well as the quality of delivered components.

- *Workflow is dependent on availability of shared resources*: Production of concrete frameworks are often divided into multiple physical work locations (also referred to as pour units) to find an optimum balance between desired production cycle and available resources (Illingworth, 2000). To reduce production time, multiple pour units are being processed simultaneously sharing common resources, e.g. tower crane, labor, and formwork systems. Moreover, workers are divided into different crews assigned to perform specific tasks, e.g. handling formwork, fixing rebars, placing concrete (Larsson, 2010). Each crew moves between pour units completing their specific tasks. As a result, a smooth and continuous progress of work tasks presume that all types of resources are available when needed. A missing resource may result in that a work task cannot be started as planned, or being processed with reduced capacity. Either way, unavailable resources, as a result of poor planning and coordination of resources, are an important reason to workflow disruptions and why delays occur. An illustrative example is when multiple work tasks request assistance of a tower crane simultaneously. The implications of shared resources on concrete production cycles have also been highlighted by Howell, Laufer and Ballard (1993).

- *Speed of production is dependent on the concrete curing process*: During construction, temporary formwork systems are commonly used. Therefore, the production cycle becomes dependent on the strength gain of concrete since it determines when formwork can be removed (Rudeli, Santilli, & Arrambide, 2015). Indeed, formwork removal times can be critical for the speed of production cycles and the overall duration of the concrete framework also directly influences the time-dependent costs of project resources. As a result, when planning the production cycle, knowledge about the rate of the curing process must be known. But the hydration process is also dependent on concrete temperature which in turn is dependent on ambient weather conditions (Bagheri-Zadeh et al., 2007). The curing process and how it is affected by weather is further discussed in section 2.3.
- *Concrete types with reduced carbon footprint*: There is a strong trend towards introducing new concrete types with a reduced carbon footprint. In these concrete mixtures, some of the Portland cement clinker is replaced with supplementary materials such as fly ash or furnace blast slag. Therefore, these concrete mixtures have somewhat different behavior compared to traditional concrete mixtures containing only Portland cement clinker as the binder material (Lothenbach et al., 2011). For instance, the early strength gain is slower and the hydration heat is lower making the concrete mixture more sensitive when pouring at lower temperatures. This is further discussed in section 2.4.

In overall, these challenges mentioned above must be addressed to improve planning and control of the on-site production of concrete frameworks. By planning the workflow more in detail accounting for the dynamic interactions between tasks and resources enables to better foresee hidden problems resulting in workflow interruptions. Reliable production plans must also account for the effects of weather on task, resources, but also on the concrete curing process since it is an integrated part of the production cycle. In this context, it is also important to understand how production cycles are influenced by new concrete types under varying weather conditions.

2.2.3 Maturity method to determine concrete strength

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. For instance, early strength growth of concrete is important to enable for an efficient and safe removal of formwork.

Concrete gains strength due to the exothermic chemical reactions between the water and cementitious materials in the mixture. Provided that sufficient moisture is present, the rate of the chemical reactions depends on several factors where concrete temperature is important, especially at early age (Fjellström, 2013). An increase in temperature increases the rate of reactions and by that also the rate of concrete strength development. Similarly, a decrease in concrete temperature slows down the rate of reactions and the strength growth. However, the influence of temperature is more complex since it has also been confirmed that high temperatures at early age may reduce the long-term strength (Carino & Lew, 2001).

Early strength development can be estimated using a maturity method (ACI Committee 228, 2019; Benaicha, Burtschell & Alaoui, 2016), which is based on scientific findings that the concrete strength can be estimated by considering the relationship between temperature and curing time.

There exist several maturity functions where two are commonly used, namely the Nurse-Saul function (Nurse, 1949; Saul, 1951), and the equivalent age method (Freiesleben Hansen & Pedersen, 1977). In figure 3, a schematic illustration of a typical temperature curve and corresponding strength development is given. Note that the exact temperature profile and strength curve depends on specific concrete mixture and external conditions.

The equivalent age method is common in the Scandinavian countries (Fjellström, 2013) and the mathematical expression is usually described according to equation 1.

$$t_e(T_r) = \int_0^t exp\left[\frac{E}{R}\left(\frac{1}{273+T_r} - \frac{1}{273+T_c}\right)\right] \times dt \qquad (1)$$

where t_e equivalent curing age (h); E = activation energy (J/mol); R = universal gas constant (8.3144 J/mol/K); T_r = reference temperature (°C); and T_c = average concrete temperature. The reference temperature is typically set to 20 °C. Since the activation energy E is not always constant, an empirical expression according to equation 2 was suggested by Jonasson (1985) as a more suitable approximation.

$$\theta = \frac{E}{R} = \theta_{ref}\left(\frac{30}{T_c+10}\right)^{\kappa_3} \qquad (2)$$

where θ (K) is denoted as the activation temperature; θ_{ref} and κ_3 are maturity parameters determined based on measured concrete strength.

When the equivalent curing age of a concrete is known it can be related to strength by knowing the strength-maturity relationship for a specific concrete mix. This relationship is determined by testing the compression strength at different ages of concrete specimens (cube or cylinder) cured at 20 °C. In Sweden, the strength-maturity relationship for a concrete mixture is commonly referred as the “tendency curve”. The function for describing the tendency curve can be found in Fjellström (2013).

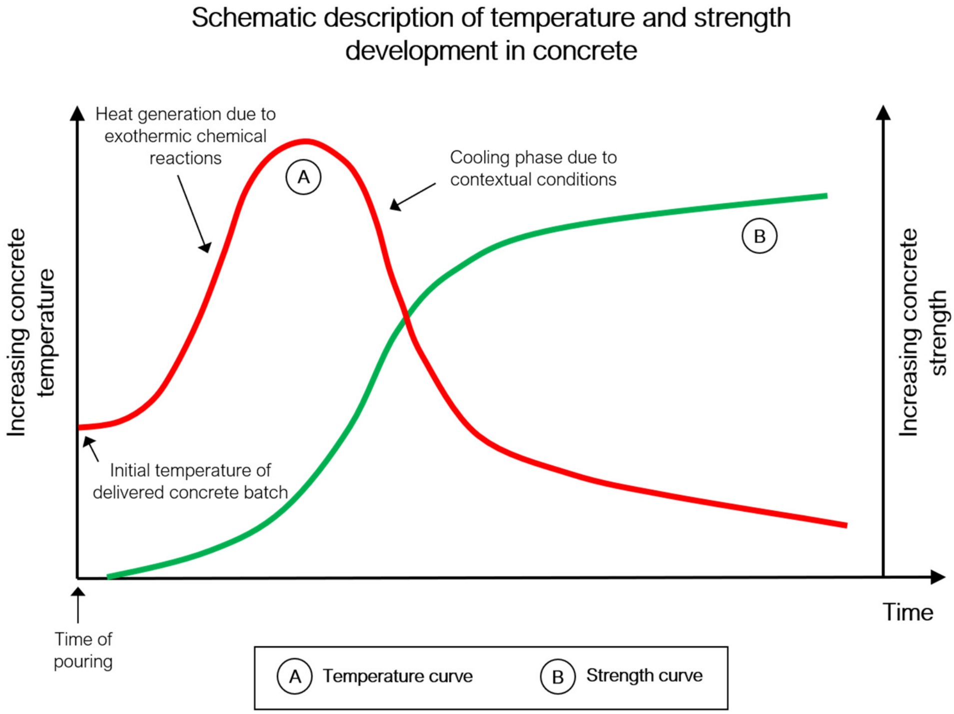


Figure 3
Schematic description of temperature and strength development in concrete.

2.2.4 Tools for simulation and measurement of concrete temperature and strength

Special-purpose simulation tools can be used for estimating concrete temperature and strength development for different structures, such as walls or slabs. In the Scandinavian countries, there exist different software tools, e.g. Hett II (Cementa, 2018a), PPB (Byggföretagen, 2019), AP TempSim, and AP Maturity (Aalborg Portland, 2018). The software tools simulate the dynamic change in concrete temperature as a result of hydration of cementitious materials and heat losses to the surrounding environment. In principal, a concrete structure (typically a cross section) is divided into a mesh of connected elements. During simulation, the heat development (due to exothermic chemical reactions) for each element is calculated.

In addition, the heat transfer between connected elements is also calculated resulting in a net gain (or loss) in temperature for each element. The calculation models also consider boundary effects in terms of heat transfer to adjacent concrete structures and to the surrounding air. Also, the effects of using different types of formwork, insulation, or the supply of energy (e.g. heating systems) can be modelled. The essential parameters used by simulation tools (e.g. PPB) to estimate temperature development are schematically illustrated in figure 4.

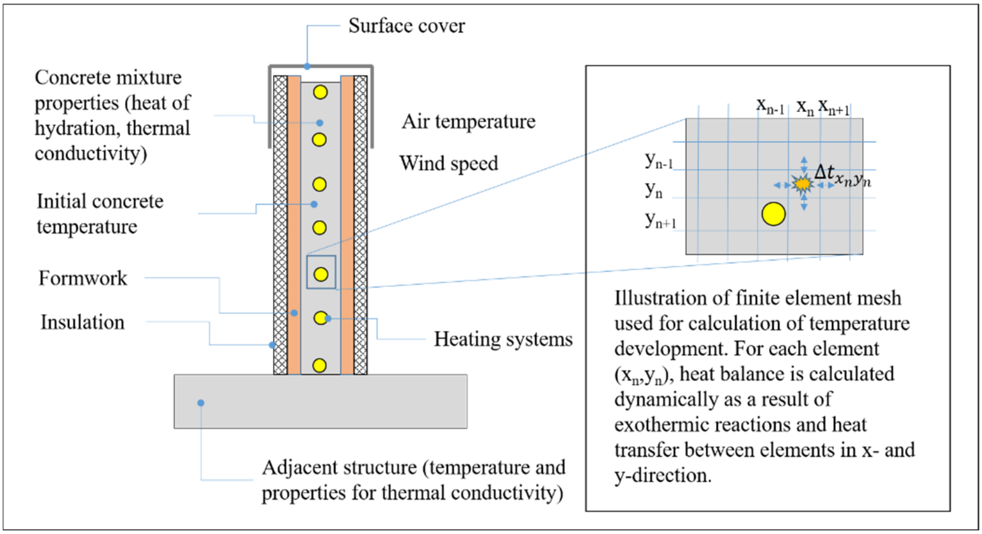


Figure 4
Schematic illustration of essential parameters often used by simulation tools to estimate temperature development in concrete during hardening process.

The software tools estimate concrete strength based on simulated temperatures and the equivalent age method. For any given time, equivalent maturity age is calculated according to equations 1 and 2 using simulated temperature as input. The actual concrete strength is then determined using the calculated equivalent time and a tendency curve for the actual concrete type.

It should be noted that these software tools are restricted to study the material-related effects of different options, e.g. concrete mixture, curing measures, weather conditions. Indeed, they are proven to be effective for studying the effects on formwork removal times due to different concrete mixtures, curing measures, or varying weather conditions. However, they do not address secondary effects of weather on productivity due to the extra work needed to protect concrete during the curing process.

Wireless sensor systems that are placed into concrete can be used for real-time monitoring of concrete temperature. Today, several systems are available enabling efficient measurements where data are stored in cloud-based services allowing for remote access of actual status at any time, e.g. Sensohive[1], Vema Distant[2], Celsicom[3]. These systems typically have integrated maturity functions to provide actual strength for a specified concrete mixture. Measurement of concrete temperature can also be used to verify simulation tools, e.g. by comparing measured and simulated temperature profiles having the same settings of concrete mixture and curing measures.

2.3 Effects of weather on concrete construction

As mentioned earlier, most concrete construction works are carried out at unprotected working areas (construction sites) and therefore exposed to varying weather conditions. Due to the size of the built structures and the fact that they change in layout as the construction evolves, it is not easy to employ measures to shield production against weather. As a result, workers, machinery, and material are influenced by current weather conditions, but in different ways. For instance, adverse weather slows down working pace among labor, weather-sensitive materials must be protected, and machinery cannot be operated as usual. All these examples show on different consequences due to adverse weather, but the ultimate effect is typically a loss in construction productivity. The influence of weather on concrete construction productivity can be divided into effects on manual work tasks including machinery-assisted work tasks and effects on concrete curing as it is critical to keep-up productivity in concrete work cycles. It should be mentioned that other material-related processes such as drying out of concrete are also affected by ambient climate. However, as mentioned in section 1.2.2, the effects of weather on drying out of concrete is not included in the scope of this research. Again, concrete as a material is highly durable and resilient to weather. Accordingly, from a quality and durability perspective, there is no need for weather protection measures during the framework erection process provided that the concrete is allowed to dry out sufficiently during the next production phase to enable application of moisture sensitive materials.

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[1] https://sensohive.com

[2] https://distant.vemaventuri.se/

[3] https://www.celsicom.se

2.3.1 Effects on manual and machine-assisted work tasks

It is well known that weather has a negative effect on construction productivity. Therefore, several researchers have studied the relation between weather factors and productivity, e.g. temperature, precipitation, and wind.

The effect of temperature on construction productivity has been quantified in several studies, e.g. Koehn and Brown (1985), Thomas and Yiakoumis (1987), Hassi (2002), Thomas and Ellis (2009), Moselhi and Kahn (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 must 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.

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 Kahn (2010) indicate losses in the range between 40-65 %.

Wind affects work tasks that are dependent on crane assistance for lifting operations. The effect of wind on formwork productivity has been reported to be a loss around 20 % at wind speed equal to 12 m/s (Moselhi & Kahn, 2010). Other studies (e.g. 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 8-14 m/s. Ballesteros-Perez et al. (2015) conclude that handling of formwork is already affected at 5 m/s. In addition, crane manufacturers provide maximum limit for when lifting operations should be cancelled. These limits vary depending on crane type and manufacturer, but as a rule of thumb, tower cranes should not be operated at wind speed above 20 m/s (Watson, 2004). However, different types of cranes or sensitive lifting operations may be cancelled at much lower wind speeds.

When studying the effects of weather on productivity, previous studies have considered construction works at an aggregated level, such as masonry (e.g. Koehn & Brown, 1985), steel work (e.g. Thomas & Ellis, 2009), formwork (e.g. Moselhi & Kahn, 2010). It is obvious that these work tasks are quite different, both in how the work is carried out and what resources that are being used. This in turn affects for instance, how sensitive a work task is to different weather conditions. A work task that depends on crane assistance, e.g. assembly of larger form panels, is more sensitive to strong winds while work tasks such as masonry is more sensitive to low temperature and precipitation. Therefore, analysis of how productivity is affected by weather must also take into account both the intensity of a certain weather factor and the type of work in question. 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 on also addressed by McDonald (2000), and Nguyen, Kneppers, García de Soto and Ibbs (2010).

2.3.2 Effects on concrete curing

Since the concrete temperature is essential for strength growth, the ambient climate condition become important as it may influence the concrete temperature. For instance, cold temperatures and high winds reduce the concrete temperature which in turn slows down or even stops the hydration process.

An important criteria is to ensure that the concrete strength is at least 5 MPa before internal concrete temperature falls below 0°C (freezing criteria). Early freezing when concrete strength is low may cause a permanent damage and significant loss in final strength (Bagheri-Zadeh et al., 2007).

Due to the influence of cold weather conditions on the curing process, it is usually necessary to employ different types of curing measures to protect concrete against weather. Different types of measures are commonly used either separately, or in combination (Cementa, 2014).

a) *Concrete mixture*: An important way to influence the strength growth is to change the constituent materials in the concrete mixture. For instance, lowering the w/c ratio has a positive impact on strength development. Also, the cement type and/or chemical admixtures influence the rate of strength development.

b) *Heated concrete*: Increasing the temperature of the concrete mixture delivered to construction site is another way of establishing a strength growth at early age. A higher initial concrete temperature prevents a rapid cooling at early age and by that facilitates a more rapid development of cement hydration process.

c) *Covering and isolation*: Covering of concrete surface and isolation of formwork prevents heat losses during the concrete curing process. Examples of practical measures is to place isolated carpets onto newly poured concrete slabs or by using isolated formwork panels.

d) *Use of heating system*: Other types of measures to facilitate the hardening process involve adding energy to the concrete structure. This could be achieved by using external heating systems (e.g. infrared heating) which temporarily increases the temperature at the concrete surface. Another way is to use internal heating systems which are embedded into the concrete structure, e.g. electrical heating cables.

It should be pointed out that the use of heated concrete and heating systems requires isolation or coverage of concrete surfaces in order to be effective. Moreover, measures such as c) and d) also require additional works on-site related to covering, isolation, and installation of heating systems.

To illustrate the effect of weather conditions and curing measures on concrete strength and formwork removal, an illustrative example is proved in figure 5, As seen, colder weather extend formwork removal time compared to original plan. However, adding extra curing measures (e.g. change in concrete mix design, isolation of concrete surface etc.), may compensate for bad weather, or even shorten the time when formwork can be removed.

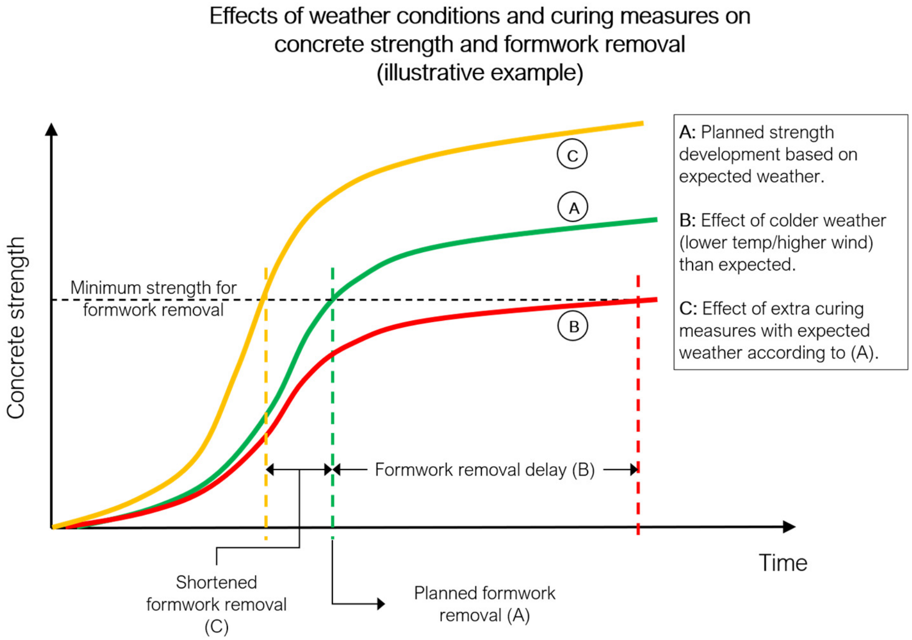


Figure 5
Effect of weather condition and curing measures on concrete strength and formwork removal (illustrative example).

2.3.3 Swedish climate conditions

Sweden is located in the northern part of Europe characterized by a relatively long period of cold weather. However, weather conditions may vary significant between different geographical regions, e.g. between the northern and southern parts of Sweden. To illustrate the geographical variation, the number of days per year where mean daily temperature is below 5 °C for four different locations are given in figure 6. The number of days is based on mean number of days over the period 2015-2019.

In Sweden, when the daily mean temperature drops below 5 °C is usually defined as start of the “concrete winter” period. Obviously, there is a relatively large difference in temperature conditions between Kiruna and Malmö. The number of days when temperature is below 5 degrees are more than twice as many for Kiruna compared to Malmö.

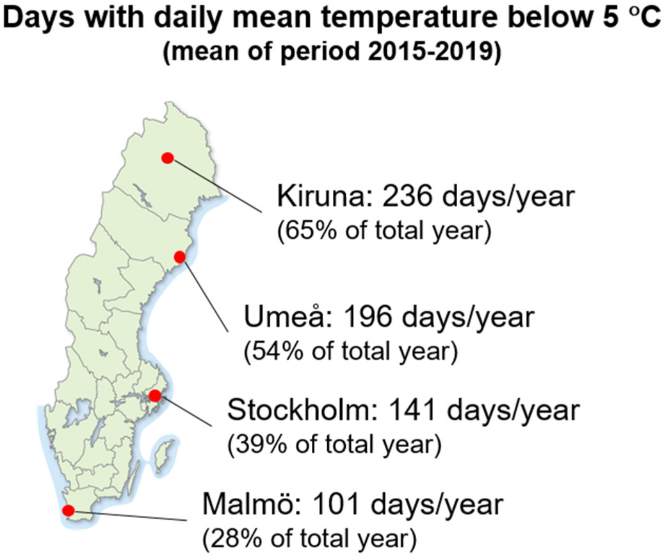
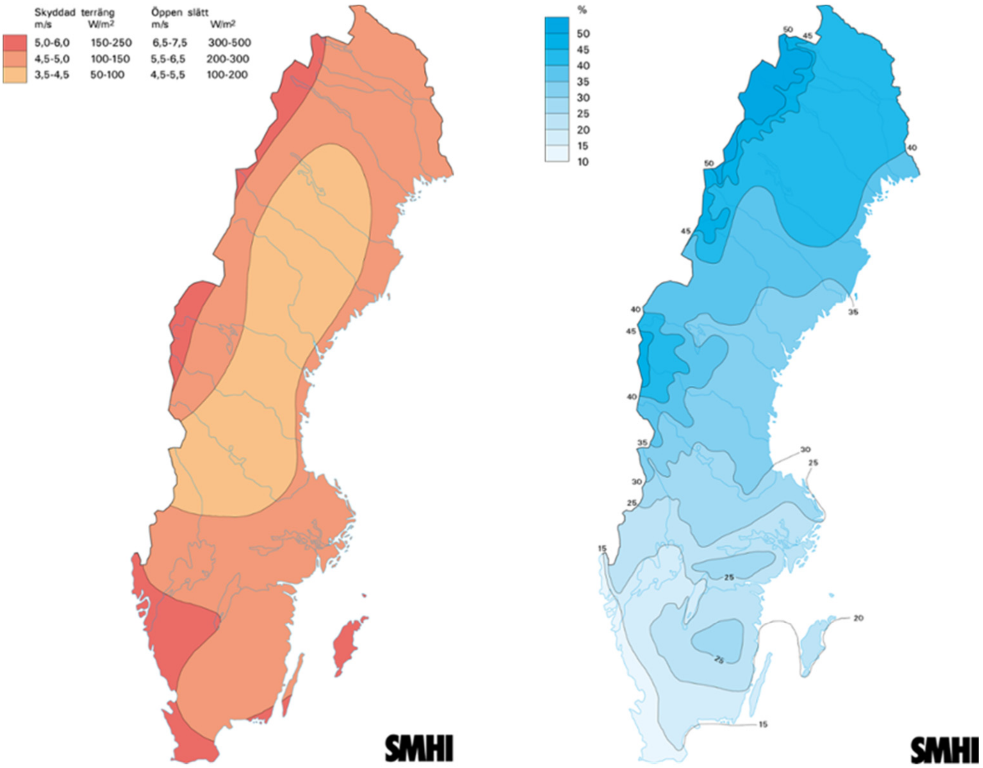


Figure 6
Number of days with daily mean temperature below 5 °C (SMHI, 2019).

Also other weather factors such as wind and precipitation vary depending on geographical location. For example, wind statistics (expressed as wind energy), are shown in figure 7 (a) whereas snow statistics are shown in figure 7 (b) expressed as the proportion of snow of annual precipitation. Wind and snow statistics are mean values over the standardized normal weather period 1960-1990 (SMHI, 2009). In figure, darker colors indicate more windy conditions or higher proportion of snow. As seen, the very southern and western parts together with the upper north-west mountain areas, are exposed to more windy conditions compared to other regions. As expected, the northern parts are exposed to more snow compared to the southern parts.



a) Normal wind energy conditions (W/m^2), mean values of years 1961-1990.

b) Proportion (%) of snow of annual precipitation, mean values of years 1961-1990.

Figure 7
a) Wind conditions, mean values for the standardized normal weather period 1961-1990, b) Proportion of snow of annual precipitation, mean values for the period 1961-1990 (SMHI, 2009).

Weather conditions also vary due to seasonal effects, e.g. differences between winter, spring, summer, and autumn. These are example of long-term variations, but weather conditions also change on daily or hourly basis. Temperature typically varies between day and night. However, wind and precipitation can change more rapidly. Planning of construction operations must therefore consider both long-term and short-term changes in weather. For instance, strategic planning must account for both seasonal and geographical effects while operational planning (week or days ahead) must consider daily or even hourly changes in weather, e.g. to plan concrete pouring, or sensitive lifting operations.

2.4 Climate-improved concrete

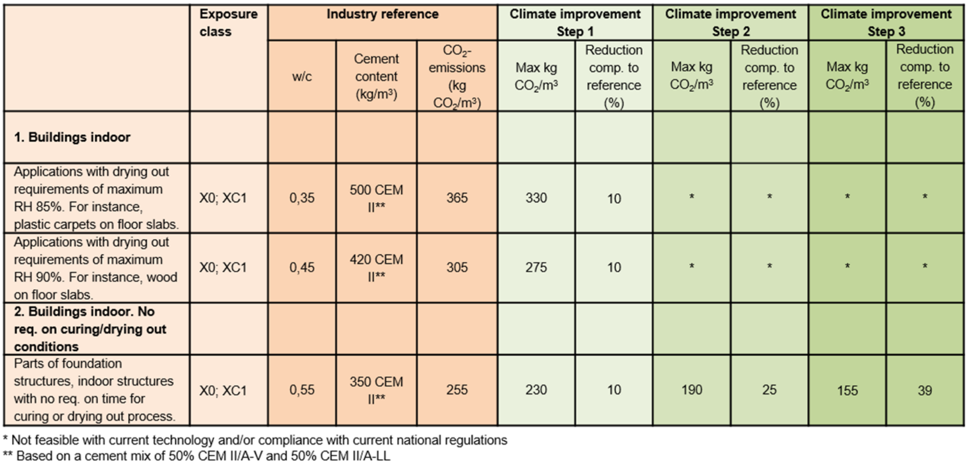
Production of cement, the key ingredient in concrete, accounts for about 8% of global carbon emissions (Schrivener, 2020). About 60% of emissions are attributed to the calcination process when limestone is heated to produce cement clinker (Andersson, 2018). Therefore, the cement and concrete industry are devoted to seek ways to reduce carbon footprint of cementitious products. Roadmaps for development of sustainable concrete construction have been put forward by governments and industry organizations, to guide political decisions, research communities, and industry initiatives at global, national, and regional levels, e.g. Betonginitiativet (2018), Cementa (2018b), Dansk Beton (2019), IEA (2009). These roadmaps include a wide range of technological solutions to reduce carbon emissions covering the whole value chain of cementitious products.

One solution is to avoid the use of higher concrete quality than required with respect to durability and structural requirements. Eliminating the use of "over-quality" reduces CO_2-emissions of concrete structures. Another solution is to replace part of the Portland clinker in the cement, or in the concrete mixture with supplementary materials (SCM), e.g. fly ash or granulated blast furnace slag. Fly ash and slag do not require calcination why partial replacement of cement result in significant reductions of carbon emissions (Linderoth, 2020). Reducing cement or clinker content in concrete structures are two mature techniques that can be implemented on a relatively short basis with high potential to reduce carbon emissions (Dansk beton, 2019). In Sweden, the concrete industry association have established a guidance to facilitate the introduction of concrete types with lower cement and clinker content (Svensk Betong, 2019). Reductions up to almost 40% are indicated by using climate-improved concrete types instead of traditional concrete types (see figure 8).

However, reducing the cement and clinker content affects concrete properties, e.g. early hydration (Linderoth, 2020). Concrete mixtures containing SCM typically have a lower heat production rate compared to concrete mixtures containing only ordinary Portland cement as the binder (Lothenbach et al. 2011). This is important, especially since early heat production governs early strength development which is critical for enabling safe removal of formwork. The lower heat production also make concrete with lower cement and Portland clinker content more sensitive to colder weather. For instance, early heat production is important to avoid freezing of the concrete structure before is has gained sufficient strength.

To enable a large-scale introduction of climate-improved concrete, also in regions with colder climate, require extended knowledge about necessary curing measures to shield concrete against varying weather conditions. It concerns practical knowledge about effective measures to keep up with desired formwork removal times, but also implications on productivity due to additional on-site measures.

Current knowledge about operational curing methods is characterized by experience-based use of concrete types containing Portland cement clinker as the main binder. Introduction of climate-improved concrete types that behave differently entails a need for new practical knowledge.



	Exposure class	Industry reference			Climate improvement Step 1		Climate improvement Step 2		Climate improvement Step 3	
		w/c	Cement content (kg/m^3)	CO_2-emissions (kg CO_2/m^3)	Max kg CO_2/m^3	Reduction comp. to reference (%)	Max kg CO_2/m^3	Reduction comp. to reference (%)	Max kg CO_2/m^3	Reduction comp. to reference (%)
1. Buildings indoor										
Applications with drying out requirements of maximum RH 85%. For instance, plastic carpets on floor slabs.	X0; XC1	0,35	500 CEM II**	365	330	10	*	*	*	*
Applications with drying out requirements of maximum RH 90%. For instance, wood on floor slabs.	X0; XC1	0,45	420 CEM II**	305	275	10	*	*	*	*
2. Buildings indoor. No req. on curing/drying out conditions										
Parts of foundation structures, indoor structures with no req. on time for curing or drying out process.	X0; XC1	0,55	350 CEM II**	255	230	10	190	25	155	39

* Not feasible with current technology and/or compliance with current national regulations

** Based on a cement mix of 50% CEM II/A-V and 50% CEM II/A-LL

Figure 8
Possible three-step reductions in CO_2-emissions by employing climtae-improved concrete types. Section of data set based on Svensk Betong (2019).

3 Construction productivity

In this chapter, an introduction to construction productivity is provided followed by a section describing the concept of baseline productivity. Thereafter, an overview of factors that influence construction labor productivity based on findings in previous research is presented. Finally, methods for measuring construction labor productivity are discussed.

3.1 Introduction

Construction industry suffers from low productivity compared to many other industries (McKinsey Global Institute, 2017). In Sweden, the problem has been addressed by both researchers and industry stakeholders (Josephson & Saukkoriipi, 2005; Koch et al., 2020). Since the global construction industry accounts for almost 10% of the world's gross domestic product (GDP) (Horta et al., 2013), it is understood that poor productivity results in a significant economic loss not only for companies, but also for the society in general. Low productivity also means that the construction industry cannot keep up with producing dwellings that people can afford to pay for or rent. Especially multifamily houses are important for the development of societies as they provide homes for a majority of the residents. In Sweden there is an acute shortage of multifamily houses in most municipalities, especially in urban areas (Boverket, 2020). Therefore, improvement in construction productivity is particularly important to increase production capacity of multifamily buildings and for reducing costs related to rental or buying of dwellings.

According to OECD, productivity is defined as 'a ratio between the output volume and the volume of inputs (OECD, 2001). In other words, it measures how efficiently production inputs, such as labor and capital, are being used to produce a given level of output. Productivity can be classified as a total factor productivity in which outputs and all inputs are considered, or as a partial factor productivity Talhouni (1990). In a partial factor productivity, only selected outputs and inputs are measured. Partial factor productivity is also commonly referred to as single factor productivity.

Labor productivity is an example of a partial factor productivity measure that is widely used in construction industry (Yi & Chan, 2014). Here, only the input of labor is considered and is usually defined as the ratio between actual work hours and the physical quantity of the completed work. Many researchers have adopted this definition when measuring labor productivity (e.g. Proverbs et al., 1999; Thomas & Yiakoumis, 1987). Jarkas and Horner (2015) argues that partial factor productivity is much easier to measure compared to total factor productivity. By focusing on a selected factor, the measurements become easier to control which normally is positive from a reliability and quality perspective. Measuring multiple inputs are obviously more difficult to accurately determine and measure.

A common method for measuring productivity performance in construction is to measure labor input in relation to a physical output. For instance, man-hours to pour one cubic meter of concrete or install one square meter of formwork. The results of such measures are commonly referred to as productivity data (or productivity rates). Productivity data are essential when planning and scheduling of construction projects, but also for estimation and cost control (Herbsman & Ellis, 1990).

3.2 Baseline productivity

Benchmarking construction productivity is of high importance for companies in order to compare their performance against competitors and to identify areas for improvements. To make such comparisons relevant and useful, researchers have studied and developed theoretical methods for measurements and comparisons at industry, project, and operational levels (Proverbs et al., 1999; Thomas & Završki, 1999).

To understand if a company or project is performing good or bad, it is necessary to establish some kind of reference, or baseline (Jarkas & Horner, 2015). Baseline productivity has been suggested as an adequate method to establish such a reference. However, there exist different views on how to define and measure baseline productivity. According to Thomas and Završki (1999) and Thomas and Sanvido (2000), a baseline can be considered as the best level an activity can be performed at. It assumes that activities are being performed under optimal conditions where no disturbances occur such as need for rework, material delays, unavailable labor and equipment, adverse weather etc. The theoretical procedure to determine baseline productivity for a specific project is described in Thomas and Završki (1999). In principle, baseline productivity is determined for a specific project (or work tasks within a project) by measuring daily productivity. Statistical methods are then employed to determine a baseline subset containing those days with highest daily productivity. The baseline productivity is then determined by the median of the daily productivity in the baseline subset.

Baseline productivity is considered to be affected only by actual work complexity (see figure 9). Thomas and Završki (1999) also provided a scale to define various degree of complexity relating to geometrical layout and possibilities to repeat work tasks. To determine baseline productivity for a specific project, it is reasonable to consider work complexity as a constant even though it may vary to some extent, e.g. between floors. 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.

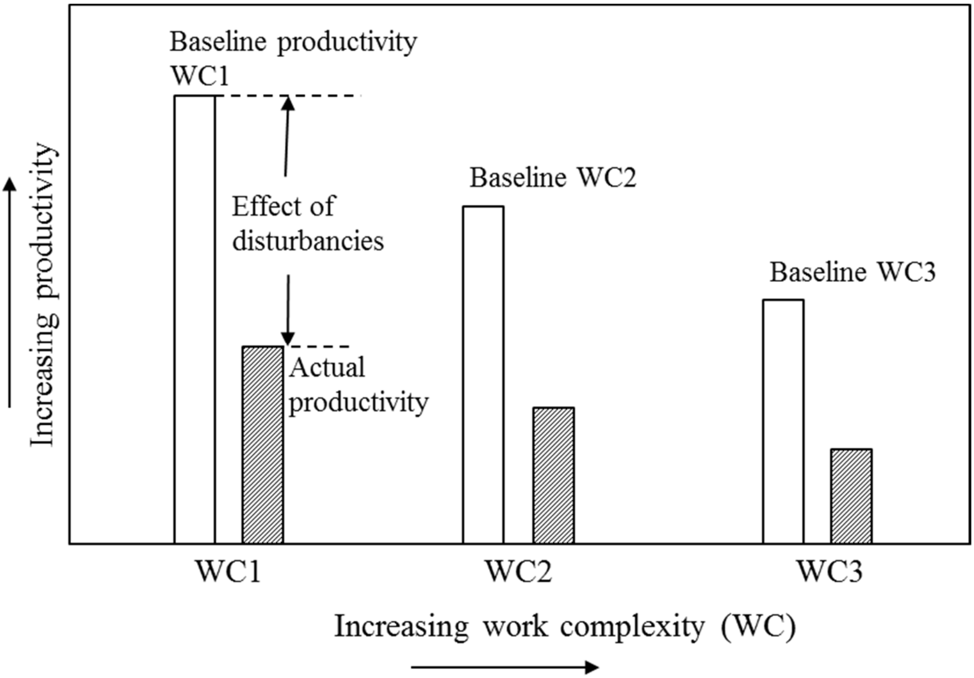


Figure 9
Illustration of baseline productivity versus actual productivity as a function of work complexity. (Modified from Thomas & Završki, 1999).

Other researchers have argued that baseline productivity should be based on normal operational performance instead of reflecting an ideal situation (Jarkas & Horner, 2015). Here, the baseline productivity is determined as the median of the inter-quartile range given by a Box-and-Whisker plot of the sampled productivity values. Jarkas and Horner (2015) relates baseline productivity to normal operational performance. Consequently, this does not reflect an ideal situation since the productivity is assumed to be influenced under normal circumstances by multiple types of factors. Therefore, in order to study the influence of individual or combinations of multiple factors, it is believed that the baseline method developed by Thomas and Završki (1999) is more appropriate. This reasoning has similarities with the factor model for productivity developed by Thomas and Yiakoumis (1987).

3.3 Factors influencing productivity

It is well known that construction productivity is influenced by a wide range of different factors, e.g. quality in design documents, motivation of labor, availability of equipment and material, weather conditions etc. Accordingly, research studies have attempted to identify those factors that are most important for productivity performance (Dai, Goodrum & Maloney, 2009), where other studies have quantified the effect of a single, or multiple, factor(s) on productivity performance (Dunlop & Smith, 2003; Jarkas, 2012).

One early attempt to structure and categorize influencing factors on a work task level, was described in Koskela (1999). Here, seven preconditions were identified as important to avoid disruptions in workflow and productivity loss. Later on, other researchers (e.g. Wambeke, Hsiang & Liu, 2011) have continued to develop the understanding of what factors that are of general importance. Wambeke divided factors into eight main categories instead of Koskela's seven preconditions. The categories proposed by Wambeke also align with other studies even though these studies have used less number of categories, e.g. Herbsman and Ellis (1990), and Rojas and Aramvareekul (2003).

Table 1 presents an overview of what factors previous research studies have mainly focused on using the eight category groups proposed by Wambeke et al., 2011. These category groups are not listed in any order of relative priority. The main focus of each study is denoted by an "x" in one or several categories.

Apparently, most research projects have attempted to study the influence of multiple factors. Only a few research studies have chosen to focus on a single type of factor. To understand, the content of each category group, a short summary of previous research is provided as follows.

1. **Design and work method:** This type of factors concern the quality in design and specifications. Complex design with high variation in technical solutions and geometrical layout reduce buildability and hampers possibilities to achieve efficient on-site construction works (Jarkas, 2012; Smith & Hanna, 1993). It also concerns the quality in design documents as such. For instance, errors in drawings or incomplete or ambiguous instructions are reasons for low productivity (Wambeke et al., 2011). Factors associated with work method and planning of work sequence are also concerned in this group. Selection of work method poorly adapted to a project's conditions, or work sequences poorly planned, are both examples that have negative effects on productivity (Smith & Hanna, 1993).

Table 1
Overview of the factors studied in previous research divided into eight main categories as suggested by Wambeke et al. (2011).

Reference (year of publication)	1. Design and work method	2. Connecting works	3. Labor	4. Tools and equipment	5. Materials and components	6. Work area/job site	7. Management & information	8. External conditions
Koehn and Brown (1985)								x
Thomas and Yiakoumis (1987)								x
Thomas et al. (1989)					x			
Herbsman and Ellis (1990)	x		x	x	x	x	x	
Smith and Hanna (1993)	x	x					x	
Christian and Hachey (1995)							x	
Proverbs et al. (1996)				x				
Koskela (1999)	x	x	x	x	x	x		x
Proverbs et al. (1999)	x		x					
Hanna and Russel (1999)							x	
Thomas et al. (1999)					x			x
Arditi and Mochtar (2000)	x		x	x	x		x	
Hassi (2002)								x
Dunlop and Smith (2003)				x	x			x
Rojas and Aramvareekul (2003)	x		x	x	x	x	x	x
Ibbs (2005)	x						x	
Noreng (2005)								x
Hanna et al. (2007)			x			x		
Thomas and Ellis (2009)								x
Dai et al. (2009)	x	x	x	x	x	x	x	x
Moselhi and Kahn (2010)								x
Hatmoko and Scott (2010)	x	x	x	x	x		x	
Jarkas (2010)	x							
Wambeke et al. (2011)	x	x	x	x	x	x	x	x
Jarkas (2012)	x							
Jarkas and Bitar (2012)	x	x	x	x	x	x	x	x
Moselhi and Kahn (2012)	x		x			x		x
Ngyen and Ngyen (2013)	x		x			x		
Hasan et al. (2018)	x		x	x	x	x	x	x
Koch et al. (2020)	x	x	x	x	x	x	x	x
Sum	**17**	**7**	**14**	**12**	**13**	**12**	**13**	**16**

2. **Connecting works:** This group concerns factors associated with disruptions and interruptions due to the complexity of work tasks' dependences. For instance, late permission to start a work task, or delays in completion of connected work tasks may cause losses in productivity (Koskela, 1999; Smith & Hanna, 1993; Wambeke et al., 2011).
3. **Labor:** The third category group concerns the work force as such. More specifically, unavailable labor, poor adaption of crew size to fit actual construction method and project conditions, restricts the ability to achieve an optimal productivity (Arditi & Mochtar, 2000). Other factors in this group are more related with the ability of labors to perform, e.g. motivation, absenteeism, skills, experience, language barriers, and learning effects (Arditi & Mochtar, 2000; Nguyen & Nguyen, 2013; Rojas & Aramvareekul, 2003).
4. **Tools and equipment:** Unavailable tools and equipment are also important factors that are mentioned to reduce productivity. Poor planning of storage areas or misplacement of equipment and tools increase the need for unnecessary movements and reduce time available for productive work (Dai et al., 2009). As pointed out by Proverbs, Olomolaiye and Harris (1996), performance of plant equipment (e.g. pumps or cranes) also influence site productivity. Moreover, poor operational planning and coordination may result in that crane resources become unavailable to work tasks which are dependent on lifting-assistance. As a result, those work tasks are interrupted and associated work crew become idle. In overall, unavailable equipment necessary to support activities are reasons for loss in productivity.
5. **Materials and components:** This group concerns factors that are associated with unavailable materials or components that are needed to perform work tasks. Delayed deliverables to construction site are common reasons for unavailable materials or components affecting productivity negatively (e.g. Hasan, Baroudi, Elmualim & Rameezdeen, 2018; Thomas, Riley & Sanvido, 1999). Wrong number or type of delivered components or damaged products are also reasons for reduced productivity. Also, poor planning of on-site logistics increases the need for double handling of materials and components (Thomas, Sanvido & Sanders, 1989).
6. **Work area/job site:** Congested work areas are also mentioned in previous research as important reason for lack of labor productivity (Hanna, Chang, Lackney & Sullivan, 2007). Poor planning and coordination of work tasks may result in labors are restricting each other's work. Having too many activities ongoing at the same work place leads to congestion of workers, tools, and materials. As a result, some work tasks may be interrupted in order to make room for other tasks. Moreover, poor planning of storage

areas in relation to work front zones result in unnecessary transportation of resources reducing available time for productive work.

7. **Management and information:** Some studies have focused on the role of management and supervision related to labor productivity. The role of supervisors or foremen to make daily planning and coordination of work tasks and resources to enable a smooth and efficient production are indisputable. Lack of skills, knowledge, or unexperienced supervisors or foremen are reasons for unproductive work (Christian & Hachey, 1995). Also, lack of supervisors may delay important operational instructions or decisions necessary for labors to do their job. In addition, poor or non-existing communication, late time changes in work scope, are other factors that reduce labor productivity (Hanna & Russel, 1999; Ibbs, 2005).
8. **External conditions:** This group of factors typically refer to the influence of weather on labor productivity. A majority of construction works are carried out outdoors exposed to varying weather conditions. For instance, hot and cold temperatures (Koehn & Brown, 1985), precipitation (Noreng, 2005), and strong winds (Moselhi & Kahn, 2010) have all negative effects on labor productivity. Therefore, weather is one factor that is commonly mentioned in literature as important for labor productivity.

As shown in table 1, the three categories that have been studied most frequently in previous research, are factors associated with external conditions, design and work method, and labor. Obviously, complexity in design, quality in design documents, work method adapted to project conditions, and external factors such as weather, are examples of factors that have been in focus when it comes to factors influencing construction productivity.

However, also factors related to management issues, availability of tools, equipment, materials, and components, have also been studied frequently indicating their importance to productivity. It should be pointed out that this overview highlights factors on a general level. Considering a specific construction method, some factors may be more important than others.

This thesis focuses on factors related to the design of the production system addressing the interdependencies between work tasks and the use of resources. These factors are partly attributed to category group 1 (design and work method), 2 (connecting works), 3 (labor), and 4 (tools and equipment) in table 1. In addition, the thesis also focuses on the impact of weather conditions which are related to category group 8 (external conditions).

3.4 Methods to measure productivity on-site

Previous research studies have in general employed two different approaches when studying the effects of various factors on productivity. The first approach attempts to identify the most important factor(s) influencing labor productivity (e.g. Arditi & Mochtar, 2000; Dai et al., 2009). In these studies, survey methods are commonly used where respondents, preferable practitioners, were asked to rank a wide range of factors in terms of their importance to labor productivity. From these rankings, the most important (highly ranked) factor could be distinguished out of many factors.

These studies are interesting as they can help identify which factors are most important. Indeed, this is important knowledge for developing methods and measures to manage negative effects on productivity. However, the survey results are dependent on contextual conditions. For instance, a survey that is targeting respondents belonging to regions with warmer climate may rank the influence of high temperature as a more important factor than respondents belong to regions with colder climates. In addition, a specific construction method also influences what type of factors that are considered to affect productivity more than others. For example, in-situ concrete methods are more sensitive to weather conditions whereas prefabricated construction methods are more sensitive to delays in deliveries of prefabricated components. Even though these studies provide important knowledge to understand what factors that influence productivity, they do not say anything about how much a specific factor influence productivity.

Therefore, the second approach employed by other researchers (e.g. Herbsman & Ellis, 1990; Moselhi & Kahn, 2010; Thomas et al., 1999) aims to quantify the effect of single or multiple factor(s) on productivity. This has been done either by analyzing historical productivity data or by on-site observations of produced units per man-hour. This also involves gathering data about those factors that are of particular interest to study. Statistical techniques (e.g. regression analysis) are utilized to establish relationship between the influencing factors and productivity data.

An advantage of measuring productivity by direct observations of ongoing works is that it provides a better understanding of unusual conditions or events that may influence the productivity output. The downside of direct measurements is that they are time consuming to perform. In addition, making reliable measurements are relatively difficult since the measured unit (productivity) is affected by a wide range of factors. To study the effect of a certain factor, other factors must also be controlled throughout the data collection phase. Due to the constantly changing conditions in construction projects, having a precise control of multiple factors are not easy to accomplish. The measurements could therefore be affected by undesired factors that happen to occur during the sample period. This problem could be solved by repeating the measurements where the increased number of data points limit the effect of other undesired factors. However, repeated measurement studies are time-consuming to perform. It’s also very difficult in practice to ensure that the same conditions prevail from one measurement to another.

To overcome the difficulties related to data collection, Alvanchi and JavadiAghdam (2019) suggested that data should be collected directly from site personnel that possess practical knowledge about how different operational factors (e.g. weather) influence work productivity. The authors argued that employing a questionnaire survey to extract the collective knowledge from many experienced individuals are less complicated and a more effective procedure than performing extensive on-site measurements.

4 Discrete-event simulation

This chapter begins with an introduction to discrete-event simulation followed by two sections describing characteristics of simulation systems and methodology for developing simulation models. The chapter ends with a section describing how discrete-event simulation has been applied to construction in previous research.

4.1 Introduction

The term simulation can have various meanings depending on its purpose and in what areas it is applied. For example, simulation of a building's indoor climate is quite different to simulation of traffic flows in urban areas. In this thesis, simulation relates to the definition formulated by Banks, Carson and Nelson (1999): "Simulation is the imitation of the operation of a real-world process or system as it evolves over time." The purpose of simulation is to either understand the behavior of the system or evaluate various strategies for operation and setups of the system.

Banks et al. (1999), states that simulation is a suitable tool if the real system of interest is either too difficult, too hazardous, or too expensive or too time consuming to study. Simulation can be used to predict the behavior of a real system. In Pedgen, Shannon and Sadowski (1995), it is mentioned that simulation is very useful for exploring new operating procedures, new machinery, or organizational setups without disturbing ongoing operations in the real system. In many cases, the cost of building and studying a model is very small compared to the cost of experimenting with the real system. Furthermore, simulation enables that time can easily be compressed or expanded according to the desired purpose of the investigation. Time-dependent events can be created on demand rather than "hoping" to encounter them in reality. Simulation experiments can easily provide knowledge about the importance of different variables on the performance of the system. Analysis of bottlenecks indicating where materials or products are delayed in the production process, or identification of critical resources which are constraining the work flow, can be performed. A simulation can be run with a particular set of inputs which can be systematically altered in order to answer what happens to the system's performance (Banks et al., 1999).

4.2 Characteristics of systems and simulation models

A system is defined as a group of objects that are joined together in some regular interaction or interdependence in order to fulfil a specific purpose (Banks et al., 1999). The main components of a system are entity, attribute, activity, state, event, and variables. An entity is an object of interest in the system. An entity can have one or more attributes which give the entity specific properties. An activity represents a time period of specified length. The state of a system is defined by a collection of variables necessary to describe the state of a system at any arbitrary time relative to the specific objective(s).

The different terms may be explained by an analogy to the construction of a concrete wall, figure 10. The system of interest is comprised by a description of the production process of the concrete wall (process steps 1-5) also including a representation of all resources needed. The system may contain different types of entities, for example carpenters (type A), formwork panel (type B), and crane (type C). Each entity can be assigned with attributes describing essential characteristics, e.g. productivity, formwork size, hoisting speed etc. Erect formwork or pour concrete are examples of activities that are executed in a specified sequence and their duration may be deterministic or random. An event can be represented by the start or finish of an activity. An event could also be randomly triggered in the system, e.g. to represent a sudden machine break-down, or a change in weather condition. The number of erected form panels or available carpenters are two examples of state variables describing the system state at a specified time. One goal with studying the system could be to identify how variations in productivity affects total lead-time.

The behavior of a system as it evolves over time is studied by developing a simulation model. A model attempts to capture the essential structure of some objects or events of a system. Therefore, a model is a simplified representation since it does not include every aspect of the system.

Systems can be categorized as discrete or continuous (Banks et al., 1999). In a continuous system, the state variables change continuously over time. In a discrete system, the state variables change only at discrete set of points in time marked as events. In practice, most systems are a combination of both continuous and discrete elements. In addition, simulation models can be either static or dynamic. In a static model, the state does not change with time unlike dynamic simulation models where the state changes over time. A simulation model can also be classified as stochastic or deterministic. Stochastic models are characterized by uncertainty usually described by random input number. On the contrary, deterministic models, do not contain variables described with random numbers.

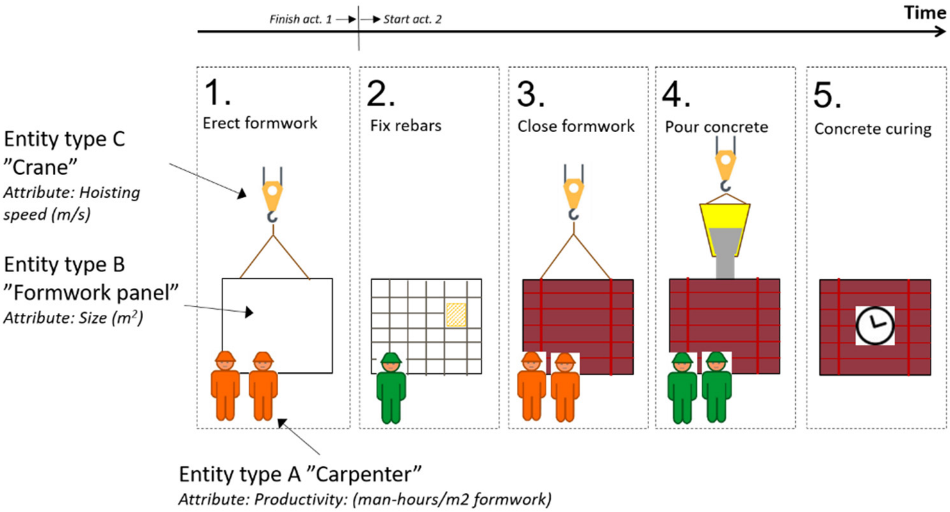


Figure 10
Analogy to construction of simulation system components.

4.3 Simulation methodology

Methodology descriptions of how to set up and carry out a simulation study is discussed by several authors in the field of discrete-event simulation, e.g. Banks et al. (1999), Persson (2003), Sanchez (2007). In Persson (2003), a synthesis of a generalized methodology description based on previous research is presented, figure 11 with 9 steps: (1) Project panning; (2) Conceptual modelling; (3) Conceptual model validation; (4) Modelling; (5) Simulation model verification; (6) Model validation; (7) Experiment; (8) Analysis; (9) Recommendation.

The first step consists of defining the problem and planning the study (1) with the stated objectives as a basis. Next, a conceptual model is developed (2) describing the system of interest. A conceptual model contains a limited description of an observed (real) system. The description may include details about the real system structure and logic. More specifically, it may contain detailed flow-chart descriptions of main activities and their dependencies. In order to create a conceptualized model, it is necessary to understand the system of interest. A number of questions have to be addressed, e.g. what are the system boundaries, what objects is the system composed of, what external factors may or may not have an impact on the system?

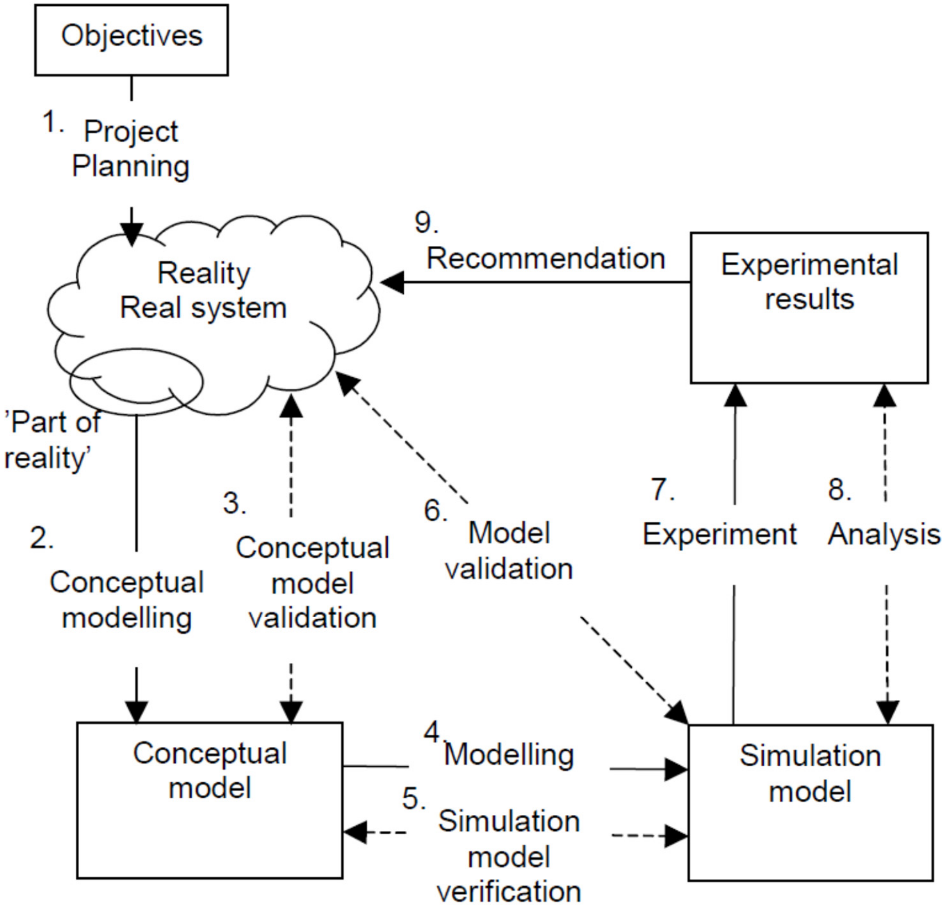


Figure 11
Activities in simulation studies and their interrelations. The numbers indicate the order of execution of activities. (Persson, 2003).

Collection of input data is often carried out simultaneously with the construction of the conceptualized model (Banks et al., 1999). Various techniques can be used to capture information about the real system, for instance direct observations of processes. Direct observations are effective to gain an initial idea of the system and its processes, resources, and influencing factors. Observations can also be complemented with time studies to collect quantitative data of operations. Interviewing individuals that possess deeper knowledge are important to understand why observed phenomena occur (or not). This kind of knowledge is usually not easy to capture using only quantitative data sampling techniques. Review of documents or historical data describing different aspects of the system are other techniques to obtain a broader understanding of the studied system. Each technique has its advantages or disadvantages, and combinations of several techniques are usually required in order to capture necessary information.

Documentation of the conceptual model is also important for the purpose of validation of the model but also as basis for coding the model into a computerized model. One way to document a conceptual model is by using a graphical notation language, e.g. some type of flowchart-technique or a more formal representation such as IDEF0 or IDEF3 (Mayer et al., 1995).

To ensure that the conceptual model is a reasonable description of the real system and the problem stated, the model has to be validated (3). Validation of the model concerns ensuring that the description of the model behavior, its entities and variables are reasonable, but also ensuring the quality of collected data (Sargent, 2013). This should include determining if the appropriate level of detail have been employed for the model's intended purpose. It also includes if appropriate structure, logic, and mathematical relationships have been used. Quality control of collected data necessary to define model input variables is also common tasks in conceptual model validation. Control of data quality is especially important when secondary data is used. In order to improve quality control, triangulation of data obtained from different sources can be used. Moreover, face validation is a technique that is commonly used for validation purpose. Face validation refers to using experts on the actual problem for evaluating if the conceptual model is correct and reasonable for its purpose. To facilitate such evaluation, graphical notation techniques could be used, e.g. flowcharts describing the modelled system and its essential parts. It is important to select a technique that domain experts can understand. In addition, using a formal notation technique to document a model also facilitates translation of the conceptual model into a computerized simulation model. Oscarsson and Moris (2002) discuss useful graphical notation methods for documentation for the purpose of developing and maintenance of simulation models.

As the conceptual model is completed and considered to be a valid representation of the real system, the next step is to build a computer-based version of the model (4). For this purpose, a simulation language (SIMUAL, GPSS), or a special-purpose simulation software such as ARENA or ExtendSim, can be used. A simulation language has a higher modelling flexibility but usually requires increased time for model development compared to a simulation software. The computerized model must be verified (5) and also validated (6). Verification deals with ensuring that the conceptual model has been translated into a computer-based model correctly. There are many techniques for verification of computerized models described in literature, e.g. in Banks et al. (1999) and Shi (2002). Most simulation software systems have integrated functions to support debugging and verification of logical behavior of a model.

Validation process aims at determining whether the computerized model's output behavior has the accuracy required for the model's intended purpose and applicability. This is where much of the validation testing and evaluation takes place. Deviations between simulated and real behavior may be caused by what was developed in any of the steps involved in building the model including having invalid data. Usually, two different validation approaches are possible. The first approach involves comparing the model and the system input-output behaviors with the use of graphs or tables. The second involves examining the output behavior of the model using statistical tests. However, in practice it is usually not possible to use statistical tests due to insufficient quantity of system data available. As a result, the use of graphs or tables is the most commonly used method for operational validity (Sargent, 2013). The same techniques as mentioned for computerized model verification can also be used for operational validation.

The simulation model is then used to run experiments (7) and the results are analyzed (8). Finally, the analyzed results constitute the basis for conclusions and recommendations (9).

4.4 Applications in construction research

This section first provides an introduction to the use of discrete-event simulation in construction research followed by a more focused description of applications which are of interest for the scope of this thesis.

4.4.1 Introduction

Discrete-event simulation has been proposed by researchers as suitable to analyze the complex systems such as construction-related production systems (Lucko et al., 2008; AbouRizk et al., 2011). It offers powerful capabilities to logically and quantitatively model construction processes, its resources, surrounding environment, and any external factors that may impact it. Simulation can output multiple performance indicators, such as time, cost, resource utilization, and waiting time, which can be used to analyze the system.

The idea of using DES to analyze construction-related systems are not new (AbouRizk et al., 2011). The pioneer in construction simulation was Professor Daniel T. Halpin who developed the CYCLONE-system in the end of 1970 (Halpin, 1977). The main focus at that time was to improve earth moving operations. Since then, the CYCLONE-methodology has been refined and applied in many other applications. In addition, other computer-based tools for simulation of construction processes have also been developed, e.g. STROBOSCOPE (Martinez, 1996) and Simphony (Hajjar & AbouRizk, 2002). Also general-purpose simulation packages, e.g. ExtendSim, have been used in order to analyze construction systems (Peña-Mora, Han, Lee & Park, 2008; Polat, Arditi & Mungen, 2007).

DES has been used in research projects to study a wide range of different construction application problems, e.g. earth moving operations (Lee et al., 2010), viaduct construction (Chan & Lu, 2008), tunneling projects (Alarcón, Rodríguez & Mourgues, 2012). Other research has focused on the integration of discrete-event simulation and building information models to enhance 4D planning, visualization, and scheduling (Kamat & Martinez, 2002). In Kamat et al. (2011) different visualization concepts were described together with advances in techniques related to those concepts. Vidalakis, Tookey and Sommerville (2011) used simulation to perform a logistical analysis of construction supply chains. DES has also been used for project scheduling and productivity estimation (Song & AbouRizk, 2008), improving vertical transportation of manpower in high-rise building projects (Shin, Cho & Kang, 2011, Park et al., 2013). Moreover, crane operations have been simulated to detect spatial conflicts on construction sites (Kim, Al-Hussein, Niaz, & Yu, 2006; Tantisevi & Akinci, 2008). Discrete event simulation has also been used to simulate offsite construction systems.

4.4.2 Applications related to on-site concrete construction and weather

On-site construction of reinforced concrete frames (RC frames), which is of primary interest of this paper, has also been addressed in simulation research, either as a basis for demonstrating new simulation methodologies or for the study of specific construction operations.

For instance, gang form operations during erection of RC frameworks were studied by Huang, Chen & Sun (2004). In this paper, a model was used for simulation of different reuse schemes of temporary formwork. The aim was to find the formwork reuse scheme that resulted in lowest cost and/or shortest duration. As a result, the model was limited to simulate the progress of formwork, rebar, and concrete operations constrained by the availability of formwork, form crew, and cranes. However, the modelled workflow assumed that formwork, rebar, and concrete operations were isolated from other works and resources that typically are integrated in the workflow of in-situ concrete frameworks, e.g. installing prefabricated structural elements, or placing MEP systems that are being poured into concrete slabs and walls. As a result, the description of the on-site workflow underlying the simulation model was not complete neglecting effects on on-site workflow due to interactions with other important work tasks and resources.

Wang, Weng, Wang and Chen (2014) also focused on construction of RC frameworks. However, the focus in this research was to demonstrate a new methodology integrating discrete-event simulation and building information model (BIM). Despite the successful demonstration of the system, the model description exhibited similar limitations as were found in the model presented in Huang et al. (2004).

The supply of materials to the construction site have also been studied using DES in several research projects. The main focus in these projects were either to study the off-site production and delivery processes of concrete or reinforcement materials, or the interactions between supply of materials and the work taken place at the construction site. Zayed and Halpin (2001) developed a model to define optimum supply areas around a concrete batch plant in terms of productivity and costs for a given resource setup. In a more recent study, simulation was used to analyze the relation between concrete truck mixers' dispatching interval and resources' waiting time on site (Park et al., 2011). Lu, Anson, Tang and Ying (2003) used simulation to study production operations and need for resources of a ready-mix concrete plant to meet the daily demand from multiple construction sites. Polat et al. (2007) simulated the supply of rebar to a multi-story RC building in order to study different delivery strategies considering effects of lot sizes, variability in construction durations, and time buffers. Obviously, the models used in these studies are generally focused on studying upstream processes rather than the on-site workflow. The system boundary in these models is typically set to the entry point of materials to the construction site. As a result, description of the on-site workflow deals with the initial handling of RC materials. Therefore, these models generally lack capability to consider effects on the overall workflow of the construction of RC frameworks.

Using simulation for production analysis, the emphasis in previous studies has mainly been on analyzing different resource setups using time and cost as the primary performance indicators (e.g. Chan & Lu., 2008; Huang et al., 2004; Polat et al., 2007). This is of course essential since these two measures are typically used for evaluating construction projects. However, simulation models have capabilities to produce other workflow measures which could be useful when analyzing construction systems, such as queue waiting time and resource utilization (Sadeghi, Robinson Fayek & Gerami Seresht, 2015). Queue waiting times and resource utilization can provide detailed knowledge about hidden problems such as bottlenecks and inefficient use of resources. Indeed, there are studies where resource utilization and waiting times have been used, e.g. to dynamically control resources as in (Park et al., 2011), or as a performance indicator of resource usage (Lu et al., 2003; Wang et al., 2014). However, there are very few examples where waiting time and resource utilization are used in combination with time and cost as a basis to propose changes for improvements.

Discrete-event simulation has also been used to study the impact of weather on construction projects. Shahin, AbouRizk and Mohamed (2011) developed a framework to simulate the effects of weather in construction projects. The study model was focused on simulating the effects on a weather-sensitive construction process, namely laying of pipes in soil. Therefore, the weather effects accounted for by the model were specific for the actual construction method, e.g. trenching, placing and fusion of pipes. As a result, the model is not suitable to describe effects of weather for other construction methods such as RC construction.

Jung et al. (2016), studied the effects of changing weather conditions due to increasing working altitude in high-rise RC construction projects. For this purpose, a simulation model was developed integrating a vertical weather profile. This model is interesting, but it only describes the effect of adverse weather resulting in work stoppages. This is of course important, but it underestimates the true effect by not considering loss in productivity due to normal weather conditions. In addition, the model does not consider effects of weather on concrete curing. Instead, it is assumed that concrete strength is unaffected by changing temperature and wind conditions.

5 Synthesis of previous research and research questions

This chapter provides a synthesis of chapters 2, 3, and 4 forming the basis to identification of research gaps and formulation of research questions.

The first section addresses influence factor 1 which was introduced in section 1.1. Knowledge about the challenges associated with complexity of the production method as described in chapter 2 is combined with the review presented in chapter 3 describing factors that influence on-site productivity. The possibilities of employing DES to support modelling and analysis of the production system is then addressed based on insights from chapter 4.

The second section address influence factors 2 and 3 according to section 1.1. This section combines knowledge about how weather influence productivity of concrete methods including the use of climate-improved concrete described in chapter 2 with knowledge about how the effects of specific factors can be determined as discussed in chapter 3. Again, chapter 4 provides valuable insights describing previous attempts where discrete-event simulation has been employed to study the effects of weather on construction-related production systems.

The third section addresses factor 2 once again, but now based on the need to collect additional data describing how weather conditions affect the productivity of concrete works. Here, chapter 2 provides insights about the effects of weather on work task productivity based on previous research. Chapter 3 contributes with knowledge on different methods to collect data describing how a specific factor, such as weather, affects work task productivity.

5.1 Systematic analysis of resource usage in on-site concrete production system

As described in section 2.2, the on-site production process of concrete frameworks is associated with challenges related to the many interactions between work tasks and different resources such as labor, machinery, materials, equipment (Löfgren, 2002). A missing resource may result in delays which may cause further disruptions to downstream processes (Howell et al., 1993). Since the production method normally is divided in multiple work locations sharing common resources (e.g. workers, formwork, crane) also add to the complexity in managing the interactions between tasks and resources (Larsson, 2010). A delayed task that holds certain resources at one location may prevent a scheduled start of tasks at another location and so on. Obviously, the availability of shared resources and a timely allocation of these to work tasks will be decisive for a continuous and uninterrupted progress of the overall workflow. As described in chapter 3, unavailable resources and poor sequencing of tasks have been pointed out as important reasons for low productivity by other researchers (e.g. Dai et al., 2009; Koskela, 1999; Smith & Hanna, 2003). To study the effects of resource availability on workflow, it is necessary to have a sufficiently detailed description of the production system. For instance, it requires that the description of the workflow is decomposed at a work task level specifying task's dependences and explicitly describing the use of different resources (Lucko et al., 2008). Without a detailed description of workflow, it is not possible to foresee inherent problems such as bottlenecks or resource allocation conflicts. However, descriptions of the dependencies between tasks and resource may quickly become complex even with relative few tasks and resources. Therefore, a systematic approach is needed to make modelling and analysis of the production system manageable.

Discrete-event simulation as introduced in chapter 4 has been proposed by researchers as suitable to analyze the complexity associated with construction-related production systems (AbouRizk et al., 2011). Parts of on-site concrete production methods focusing on the availability of resources have been analyzed using discrete-event simulation (Huang et al., 2004; Wang et al., 2013). Indeed, these two studies clearly address the benefits of using simulation to systematically analyze the construction workflow constrained by the availability of resources. However, the descriptions of the workflow in these studies are either not complete or missing important aspects of concrete production methods. For instance, focusing on the resource availability in the core activities (formwork, rebar, concrete) neglecting that other interconnected works also compete for the same resources, e.g. installing prefabricated components requires crane resources. Neglecting other works that are a part of the workflow limits the possibility to describe the true implication of resource availability. In addition, there is also a lack of knowledge about how DES can facilitate a systematic analysis of production workflow using multiple output variables. The traditional approach is to use time and cost as the main performance indicators. However, as pointed out in Sadeghi et al. (2015), statistics on resource utilization and process waiting times are also useful indicators to identify inherent problems in a production system.

To address the challenges associated with resource availability on the on-site workflow and to provide new insights about how DES can facilitate systematic analysis of construction-related production systems, the following research question is formulated:

RQ1: How can the on-site construction workflow of concrete frameworks be modelled in a discrete-event simulation model to facilitate a systematic production analysis focusing on resource usage?

5.2 Effects of weather on concrete construction and climate-improved concrete

The on-site production of a concrete framework is normally carried out in an unprotected environment. As a result, the workflow is affected by current weather, e.g. cold temperature or snow reduce working pace and high winds prohibit the use of crane resources as discussed in section 2.3.1. The implication on workflow is either a reduced work task productivity, or a complete loss due to work stoppage. In addition, cold temperatures may also delay formwork removal which also contributes to lower productivity as discussed in section 2.3.2.

Therefore, to account for the impact of weather, the effects on reduced work task productivity and delays related to slower curing process must be considered in an integrated way. Unfortunately, existing knowledge about the effects of weather on labor productivity and concrete curing is divided in two separate research domains with limited interdisciplinary transfer of knowledge. For instance, the effects of weather on labor productivity have been frequently studied within construction management research. Here, several research projects have studied the effects of different weather factors on manual or machine-assisted works, e.g. Koehn and Brown (1985), Thomas and Ellis (2009), Moselhi and Kahn (2010). However, the implications on concrete curing have not been explicitly addressed in these research studies.

On the other hand, the effects of ambient climate on concrete curing have been a major research topic by material scientists for decades (e.g. Freiesleben Hansen & Pedersen, 1977; Jonasson, 1985; Nurse, 1949; Saul, 1951). Indeed, these studies have made important contributions to the theoretical foundation describing the maturity-strength relationships under varying conditions. Other material scientists have employed a more practical approach of using maturity method to study formwork removal times. For instance, Bagheri-Zadeh et al. (2007) studied the potential of using the maturity method to assess formwork removal in cold weather. Other researchers integrated sensor data and BIM modelling to analyze formwork removal for different weather conditions (Hamooni, Maghrebi, Majrouhi Sardroud & Kim, 2020). However, a limitation in material-related research studies is that they do not consider effects on work tasks' productivity, e.g. due to a slower work pace, or the need for additional work to shield concrete against ambient climate. This is especially important as the interest in using climate-improved concrete is growing rapidly. Climate-improved concrete is more sensitive to cold weather compared to concrete mixtures containing only ordinary Portland cement as the binder material (Lothenbach et al., 2011). Productivity may be affected by delays in formwork removal, but also due to the need for extra curing measures to shield concrete against cooling. The combination of a slower initial curing rate and extra work-tasks reinforces the need to consider effects of weather on both working process and concrete curing when planning concrete production. Current practice when it comes to employing curing methods to enable formwork removal according to desired production cycles may not be fully applicable when new concrete types are introduced.

In addition, planning of production have traditionally focused on time and cost as the main performance indicators. However, to evaluate the effects of introducing new concrete types to reduce carbon emissions during the production of concrete structures, CO_2-emissions should be introduced as a third indicator. In this way, evaluations of different construction methods can be made more holistically. Despite, the general interest in climate-improved concrete, there has not been many attempts to develop methods to support decisions-making considering multiple performance indicators such as time, cost, and carbon emissions.

Since different weather factors affect productivity in different ways, e.g. snowfall reduce work pace, cold temperature slows down concrete hydration, the description of all effects become complex. The description becomes even more complex by the fact that weather conditions vary due to season and geographical differences. Accordingly, a systematic approach is needed which can provide means to describe and study the complexity associated with weather.

Again, discrete-event simulation can be used as a tool to systematically model and study such complexity. For instance, it has been successfully employed in (Jung et al., 2016) to account for varying weather conditions as a result of changing project conditions in high-rise building projects. Other researchers (Shahin et al., 2011), have used DES to study effects of weather on other weather-sensitive construction methods. These studies have shown on the potential to model and systematically simulate effects of weather. However, these attempts have not addressed how weather can be integrated in DES to account for the combined effects of weather on working processes and concrete curing.

To summarize, to make analysis of weather effects on concrete construction productivity more comprehensive, it is needed to combine existing knowledge describing the effects on both working processes and concrete curing. Such analysis should also consider the use of climate-improved concrete and the implications on construction time, cost, and carbon emissions. To manage the complexity in such analysis, it is suggested to use discrete-event simulation. However, there is a need to develop the understanding of how to describe and study these effects using discrete-event simulation. These insights lead to the formulation of the second and third research question:

RQ2: How can the impact of weather on working processes and curing of concrete be modelled in a discrete-event simulation model?

RQ3: How is construction of concrete frameworks affected by varying weather conditions and what are the implications in terms of time, cost, and CO_2*-emisssions when climate-improved concrete is used?*

5.3 Assessment of weather factors on concrete work tasks' productivity

To be practically useful, knowledge about the effects of weather on productivity must be related to specific types of work that are common for concrete construction. Obviously, different work tasks are more or less sensitive to different weather conditions. For example, lifting of formwork is more sensitive to wind compared with placing rebars. The intensity of a weather factor also influences how much productivity is affected. Obviously, heavy snowfall affects work tasks more than light snowfall. Therefore, to account for weather when planning concrete construction, it is necessary to understand how different weather factors influence specific work tasks. As mentioned in section 2.3.1, the need to differentiate the effects of weather have been highlighted by several researchers (McDonald, 2000; Nguyen et al., 2010; Smith & Hancher, 1989).

Although the importance of weather on productivity is well documented and recognized, detailed knowledge about which weather factors that are most important, or how much certain weather factors reduce productivity are still limited. A few studies have focused on comparing (or ranking) a wide range of factors (including weather) based on their relative importance to productivity (Dai et al., 2009; Moselhi & Kahn, 2012; Rojas & Aramvareekul, 2003). In general, these rankings are made on a general level where contextual conditions are not clearly specified, e.g. type of method (steel or concrete works), or weather condition (wind or snow). Therefore, these studies do not provide any deeper understanding about the relative importance of different weather factors to a specific construction method, e.g. formwork, pouring concrete.

Other studies have focused on quantifying the effect of weather on productivity. However, these studies have focused on construction works at an aggregated level, e.g. masonry (e.g. Koehn & Brown, 1985; Thomas & Yiakoumis, 1987), erection of steel frameworks (e.g. Thomas et al., 1999; Thomas & Ellis, 2009), formwork (e.g. Ballesteros-Perez, del Campo-Hitschfeld, Gonzalez-Naranjo & Gonzalez-

Cruz, 2015; Moselhi & Kahn, 2010). As a result, these studies lack necessary level of detail to distinguish the effects of certain weather factors on specific work tasks. To determine the precise relation between a factor and productivity usually requires a large amount of data. The most straight-forward method to collect necessary data is through direct observations of productive work. However, as discussed in chapter 3.4, this type data collection method is very time-consuming, but also difficult to perform in practice. A less complicated and more effective method is to collect data directly from site personnel as proposed by Alvanchi and JavadiAghdam (2019). The idea is to take advantage of experts' practical knowledge and experience. It is reasonable to assume that experts (e.g. site managers) responsible for operational planning and execution of construction works have sufficient knowledge about how weather affect productivity.

To summarize, existing knowledge describing the effects of weather on construction productivity is based on a relatively limited amount of data. In general, the data is collected at an aggregated level which do not fully reflect the effects of weather on concrete work tasks' productivity. In addition, previous research studies have not fully acknowledged the possibility to collect detailed information from the extensive source of knowledge that is collectively possessed by industry experts.

With this background, a fourth research question is formulated as follows:

RQ4: How do contractors quantify the influence of weather on concrete work tasks' productivity, and rank the importance of weather factors (temperature, wind, and precipitation)?

6 Research design and methods

This chapter starts with describing the overall research process and the four studies that have been undertaken during the research project. Next, each study is described at a more detailed level focusing on the preconditions, the research methods employed, and reflections on the research quality.

6.1 Research process

The research project is outlined in figure 12. Based on the research scope and overall research questions the project was divided in four studies each addressing a specific topic.

Study 1 is related to RQ1 and covers a simulation-based approach for systematic production analysis of in-situ concrete framework. The outcome of study 1 is paper 1 which have been published as an LTH Research Report (Larsson & Rudberg, 2020). This paper describes the simulation model as such and how it can be used for systematic production analysis using multiple performance indicators. The work with the model and simulation experiments has been carried out during this research project. However, most of the data used for conceptual model development and validation process were collected during the work with the Licentiate Thesis during the years 2006 to 2010 (Larsson, 2010). The early ideas of the simulation model have also been presented at two conferences: the "*16th annual conference for Lean Construction - IGLC 16, 2008*", and the "*European Conference on Product and Process Modelling in the Building Industry (ECPPM, 2008)*".

Study 2 on the other hand, is related to the first part of RQ2 and focus on the impact of weather conditions on manual and machine-assisted work task productivity. Also here, simulation is used to model and study the effects of weather. Study 2 resulted in paper 2 which presents a simulation-based approach for considering weather effects on concrete wall operations. The paper has been published in *Journal of Construction Engineering and Management* (Larsson & Rudberg, 2019).

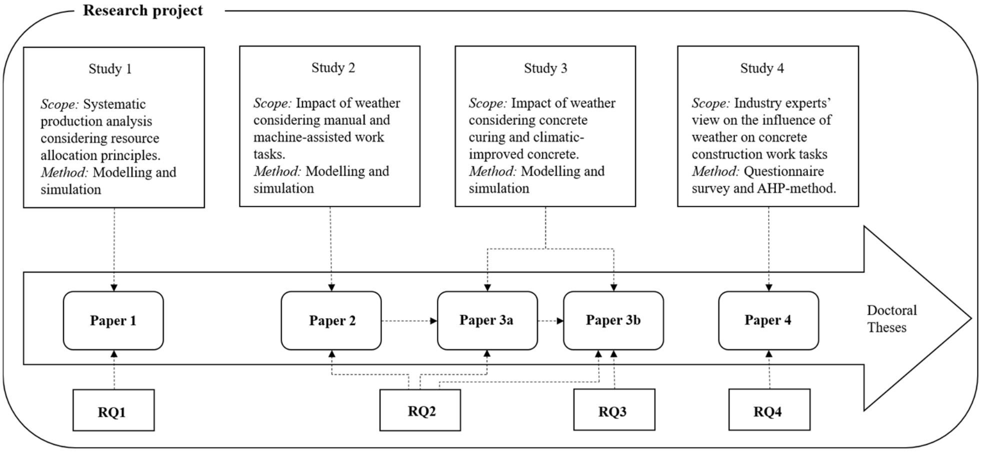


Figure 12
Overall research process.

Study 3 continues to build on the knowledge gained in study 2 but extends the focus to also include how weather affects the curing of concrete, especially considering the use of new climatic-improved concrete types. Study 3 is related to address both RQ2 and RQ3. The early work in study 3 resulted in a conference paper (paper 3a) presented at the "*35th CIBW78 Conference: IT in Design, Construction, and Management 2018*" (Larsson, 2019). The paper deals with how the influence of weather on concrete curing process can be modelled and studied using discrete-event simulation. The model presented in this paper was limited to consider only concrete wall operations and the effects of vertical formwork removal. Therefore, the model was then further developed in order to contain a more comprehensive description of the in-situ concrete framework process, e.g. also curing of concrete slabs and removal of horizontal formwork systems. The extended model was presented in paper 3b. Since the paper included both detailed description of the model as such but also a comprehensive study of how weather influence concrete construction, the length of the paper was not suitable for journal publication. Therefore, it was decided to publish the paper as an LTH Research Report (Larsson, 2020).

Study 4 is related to study 2 and 3 but aims to collect quantitative data regarding how industry experts estimate the influence of weather on common concrete works' productivity. Here, a questionnaire survey is used including pairwise comparisons based on the Analytical Hierarchy Process (AHP) method. Study 4 is related to RQ4. The findings of study 4 is presented in paper 4 which has been published in *Construction Innovation* (Larsson & Rudberg, 2021).

The four studies involved different methods to collect necessary data. A description of methods and what type of data that were collected in each study are outlined in table 2. As seen, several field studies were used both for developing practical knowledge about the production process and for collection of real-process data.

Table 2
Overview of data collection methods.

Data collection method	Data collection method	Type of data collected
Study 1	Interview-based survey	Construction methods for in-situ concrete frameworks.
	Field study A: Interviews, process mapping	Mapping of activities and their logical sequence during concrete framework construction. Special attention on resource usage.
	Field study B: Interviews, process mapping	Same as in field study A.
	Field study C: Process mapping, interviews, time studies, activity sampling	Same as in field study A and B, but also special focus on collecting statistics on resource usage.
	Field study D: Process mapping, interviews, time studies, activity sampling, cost-follow up	Same as in field study A-C, but also special focus on documentation of relevant cost items.
Study 2	Field study E: Interviews, process mapping, review of project documents, weather statistics.	Mapping of activities and their logical sequence focusing on concrete wall cycles. Weather statistics from SMHI's databases.
	Field study F: Process mapping, time-studies.	Time studies of durations of work tasks in concrete wall construction cycles.
Study 3	Field study E: Interviews, process mapping, review of project documents.	Common practice for formwork removal and measures to shield concrete against weather. Collection of data on resource costs and CO_2-emissions from project documents and material suppliers.
	Field study G: On-site sensor measurements. Review of project documents.	Measurements of air temperature, wind, and concrete temperature. Documentation of concrete pours including curing measures.
Study 4	Questionnaire survey	Ranking of the importance of weather factors on concrete framework productivity. Assessments of weather conditions on concrete work task's productivity.

More details about the field study objects are described in table 3. All field studies involved construction of multi-story residential buildings of various size. Hybrid concrete methods were employed in all field studies to build the structural framework. The methods used in field studies A-D and F had somewhat higher degree of prefabrication compared to field studies E and G. It should be mentioned that the data collection in field studies A-D were performed during the work with the licentiate thesis (2006-2010). The other field studies were done during the work with the doctoral thesis (2016-2020). In overall, the field studies were considered to be relevant for documentation of the on-site production process of hybrid concrete frameworks.

Table 3
Overview of field study objects.

Field study	Object description	Construction method	Time period for data collection
A	Residential building, 6-8 floors, 64 apartments. Location: Malmö	Hybrid concrete: In-situ walls, precast slabs with in-situ topping. Precast columns, stairs, balconies.	Winter (Jan-Feb)
B	Residential building, 2-4 floors, 19 apartments. Location: Landskrona	Hybrid concrete: In-situ walls, precast slabs with in-situ topping. Precast columns, stairs, balconies.	Spring (April)
C	Residential building, 8 floors, 85 apartments. Location: Malmö	Hybrid concrete: In-situ walls, precast slabs with in-situ topping. Precast columns, stairs, balconies.	Autumn (Sep-Oct)
D	Residential building, 6 floors, 64 apartments. Location: Lund	Hybrid concrete: In-situ walls, precast slabs with in-situ topping. Precast columns, stairs, balconies.	Winter (Nov-Dec)
E	Residential building, 8 floors, 74 apartments Location: Kristianstad	Hybrid concrete: In-situ walls and slabs. Precast columns, stairs, balconies.	Winter/Spring (Feb-March)
F	Residential building, 4 floors, 126 apartments Location: Gothenburg	Hybrid concrete: In-situ walls, precast slabs with in-situ topping. Precast columns, stairs, balconies.	Winter (Oct-Jan)
G	Residential building, 8 floors, 44 apartments, Location: Norrköping	Hybrid concrete: In-situ walls and slabs. Precast columns, stairs, balconies.	Spring (March-April)

6.2 Study 1: Description of research process

6.2.1 Preconditions

The first study focused on the use of labor and crane resources during the on-site production process of a multi-story concrete framework. A simulation-based approached is employed to model the interaction between different types of work tasks and resources. Multiple simulation output measures are used to make in-depth analysis of the workflow and resource usage for a given setup of the production system.

6.2.2 Research process

The research process consisted of three stages according to figure 13. The first stage aimed at developing a conceptual model describing the essential aspects of the on-site production process focusing specifically on the use of labor and crane resources.

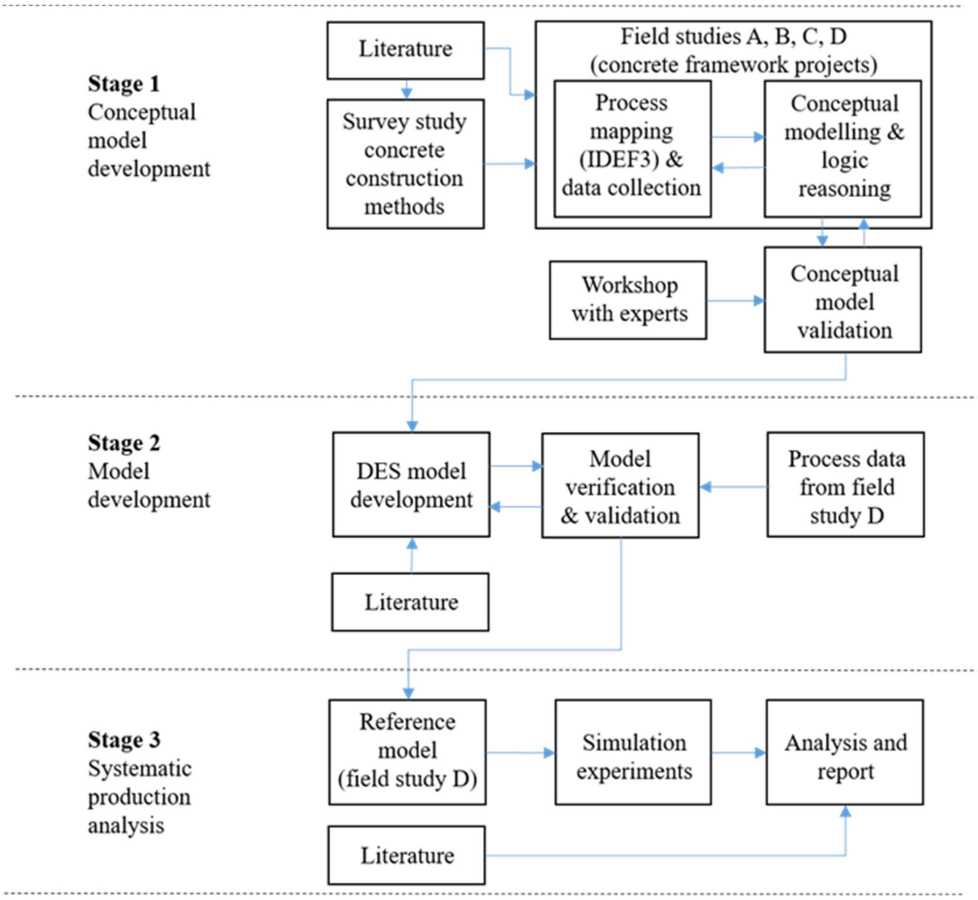


Figure 13
Research process for study 1.

To obtain necessary background information, a literature review and an interview-based survey was carried out. The literature review and the survey aimed at mapping the current use of production methods for in-situ concrete frameworks. These insights were used to select four field study projects (A to D) which were representative in terms of structural solution (in-situ concrete), and the use of production methods. The field studies were used to document the on-site production process focusing on core activities, their interrelations, and the use of resources. For consistency the IDEF3-notation language (Mayer et al., 1995) was used to describe the essential aspects of the studied system. Experts involved in each field study were also consulted to verify that all essential aspects have been correctly described.

In field studies C and D, activity durations and associated man-hours, and resource usage were measured using time study and activity sampling methods (Jenkins and

Orth, 2003). Data about material quantities were also documented which, combined with measured man-hours, were used to determine productivity rates. In field study D, the cost of resources was also obtained from project documents.

The descriptions from each field study were then combined into one generalized conceptual model. The conceptual model contains a logical representation of the observed production process focusing on the main activities, interdependencies, and the use of resources. As a final step, the model was validated by presenting it to a group of industry experts.

The second stage consisted of developing a discrete-event simulation model using the conceptual model as input. The model was implemented in a general-purpose simulation software. The workflow was described using a set of pre-programmed block elements which were connected to each other to resemble the desired logical behavior. Parallel to the model development, real process data collected from field study D was structured according to the required input variables in the model. The reason project D was chosen was that available data was more comprehensive for this field study compared to the others.

Verification of the simulation model was carried out iteratively during the development phase. In this sense, verification deals with both debugging any model development errors and by comparing the computerized model behavior with logical descriptions of the conceptual model (Sargent, 2013; Shi, 2002). For instance, the logical behavior was visualized in detail using built-in animation features and the allocation and release of resources to activities were closely examined using traceability reports automatically generated by the end of the simulation. When the verification process was successfully completed, an operation validation of the model was performed by comparing simulated outputs with real process data collected from field study D.

In stage 3, the validated simulation model was used to demonstrate how it could facilitate a systematic analysis of the on-site production process. For this purpose, field study D was once again, used as a basis for comparisons of experiment results. To analyze the existing production setup, typical simulation statistics such as queue waiting times and resource utilization were collected at the end of the simulation. In this way, location of bottlenecks and inefficient use of resources could be identified. This information was then used in order to suggest and formulate scenarios containing operational changes in order to improve the overall workflow. Each scenario was then simulated and evaluated using the indicators time, cost, waiting time, and resource utilization.

Selecting the most favorable scenario, the analysis continued with conducting a fine tuning of the production setup by systematically altering the allocation of resources. This process was automatized using a scenario-manager functionality provided by the simulation software. In this way, the resource allocation that yielded the best outcome considering all indicators could be determined. In overall, the procedure in stage 3 provided valuable knowledge about the benefits and limitations of DES as a tool to support a systematic production analysis.

6.2.3 Research quality

Measures to ensure reliability were employed at different stages in the study. To ensure high reliability in data collection, documentation of processes was carried out using flowchart techniques and a formal IDEF3-denotation language. In addition, data about resource usage and activity durations were measured using established sampling and time study techniques. For this purpose, structured protocols were used for consistent reporting of measurements.

Measures to ensure reliability of the simulation model concerned having the computerized model examined by an external simulation expert. To ensure consistency of the model outputs, the model was run multiple times and the results were closely examined to ensure that the results were replicated. A list of input and output variables were here used to ensure identical conditions between each simulation. To simplify the analysis, the model was run in a deterministic mode excluding the influence of variability. In this way, the model's response to changes in input variables could be analyzed without the influence of undesired disturbances caused by variability.

The construct validity of the study is related to the scope of the model and the variables included. The model simulates the effect of availability of labor and crane resources on the overall construction time and cost. The model has been developed by observing the ongoing process in four field study projects. These projects were chosen to be representative for hybrid concrete construction methods in Sweden. The scope and logic behavior of the descriptions underlying the model, were validated by a group of industry experts. Here, the focus on labor and crane resources were considered valid as these are critical for the overall progress of the workflow. The computerized version was reviewed by a simulation specialist to ensure that the logical behavior have been modeled correctly. The simulation model's outputs (cycle time and resource usage), were also compared with measured data. The internal validity of the model was tested by studying how changes in resource availability affected resource utilization and the occurrence of process bottlenecks. Lack of a specific resource type was clearly shown in the simulation outputs in terms of high resource utilization and occurrence of bottlenecks (waiting times) located in modelled activities which are dependent on those resources.

A limitation of the model is that it is focused on hybrid concrete construction and the use of a few resource types under non-disturbed conditions. Obviously, this is a limitation considering the many factors that may influence real production. However, it is still useful as a tool to set a baseline for the design of the production system. It is possible to adjust the model to be applicable to other methods and add other influencing factors to the model in order to increase its external validity.

6.3 Study 2: Description of research process

6.3.1 Preconditions

The second study addresses how different weather conditions influence concrete construction duration by employing a simulation-based approach. The study is limited to consider concrete wall production cycles and the effects of weather on manual and machine-assisted work task productivity. The knowledge gained from study 1 regarding modelling and simulation techniques have been utilized to adjust the existing model and for developing new capabilities to account for weather.

6.3.2 Research process

The research process consisted of five stages as illustrated in figure 14. In the first stage, a literature review was performed focusing on research papers and industry reports that have described the influence of weather on construction productivity. In addition, the theory of baseline productivity (Thomas & Završki, 1999) was studied in order to estimate ideal work productivity. These two parts formed the theoretical base for how to describe the effects of weather conditions.

Based on the knowledge gained in stage 1, it was concluded that temperature, wind speed and precipitation are the most significant weather factors. Accordingly, in stage 2 weather statistics including these parameters were obtained from the Swedish Meteorological and Hydrological Institute (SMHI). The data records covered hourly readings over the past 20 years for the city of Stockholm in Sweden. The data records were statistically analyzed in order to identify specific years that either could be representative as normal or unusual in terms of temperature, wind, and precipitation. As a final step, each data set was controlled with respect to completeness and formatted so it could be used by the simulation model (stage 4).

In stage 3, the concrete wall cycle in field studies E and F were documented through site observations and by interviews of site personnel. In project F, also time studies of work tasks were carried out to collect productivity data. This data was compared with similar studies and discussed with site personnel in field study E to confirm its validity. The measured productivity was also used to determined baseline productivity.

Based on the knowledge gained from stages 1-3, a simulation model was developed in stage 4. The model developed in study 1 is used as a basis but adopted to solely focus on concrete wall operations. It also contains specific algorithms to account for weather on work tasks' durations involving both labor and crane resources. Similar methods for verification and validation as were used in study 1 were also employed here. In addition, the model's response on work task duration for specific values of weather factors were validated by closely examine input and response values. Simulated wall cycle times were also compared to real data collected in field study F.

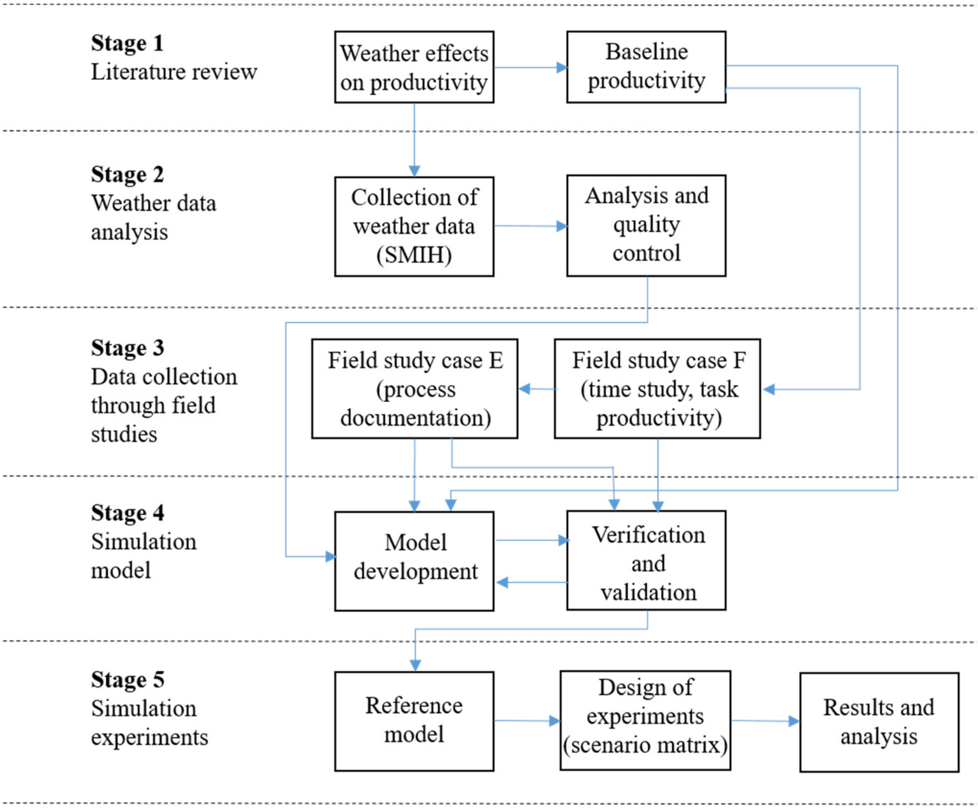


Figure 14
Research process for study 2.

In stage 5, simulation experiments were conducted in order to study the effect of various weather on construction duration of concrete walls. Here, a reference model was determined using data collected from field studies E and F. The reference model was used as a baseline for making experiments where different scenarios related to weather conditions were simulated. To facilitate a systematic approach, a matrix was developed describing the conditions for each scenario. The simulated results were compiled and compared to the baseline scenario (no effect of weather) leading to conclusions on how different weather conditions influence construction durations.

6.3.3 Research quality

Also in this study, various measures were employed at different stages to ensure reliability. Again, using established methods to collect process information (e.g. flowchart techniques, interview and time study protocols etc.) ensured transparency and consistency in collected data. In this study, weather data was an essential input variable. Therefore, data were obtained from the Swedish Meteorological and Hydrological Institute's (SMHI) databases. Similar to study 1, the coding of the simulation model was checked for errors by a simulation specialist. The model was also simulated multiple times in a deterministic mode in order to make sure that the results could be reproduced without any systematic or random deviation.

The construct validity of this study is related to the scope of the model and the type of data collected needed by the model. The model simulates the effect of varying weather conditions on manual and machine-assisted work tasks involved in construction of in-situ concrete walls. The model was developed based on practical knowledge obtained by studying ongoing work process in two field study projects. Construction of in-situ walls are a common method in most residential projects and it's also time-critical to keep up with the overall production cycle. The process consists of multiple work tasks performed in a standardized sequence which are repeated between wall units. Therefore, it is a process that is relatively easily to observe and to measure activities' durations and overall cycle times. Interviews of site personnel and the review of previous research studies resulted in a comprehensive understanding of what weather factors that are important to consider. It also gave ideas how to describe the effects of weather on productivity. To ensure validity of the weather conditions used for simulation, data were statistically analyzed in collaboration with a meteorologist at SMHI. The internal validity of the model was tested by closely studying the effects of changing weather parameters on duration of activities. For instance, wind speed above stoppage criteria forced lifting operations to stop, or cold temperatures reduced work task productivity.

The model is limited to study the effects of varying weather conditions on the duration of a typical work sequence (in-situ concrete walls) that usually have an important influence on the overall production cycle in multi-story buildings. The model simulates varying weather conditions on an hourly basis which improves the possibility to account for natural variations more realistically. It is applicable to study the effects on the duration of concrete walls. Since this is a construction method that is commonly used in many types of construction projects, e.g. residential, commercial, and educational buildings, the model can be used to study the effects in a variety of construction projects. By adjusting the input weather variables, it can be used in geographical regions with different climate as well. To improve the external validity, the model has to be extended to consider a complete working process of a concrete framework and also to consider effects of concrete curing. Moreover, the underlying relationships used to describe the effects of weather are based on previous research findings reflecting a variety of work methods. These findings need to be validated against more specific data reflecting the influence on concrete work tasks.

6.4 Study 3: Description of research process

6.4.1 Preconditions

The third study extends the focus on how weather influence concrete construction by also considering the effects of weather conditions on formwork removal. The existing model in study 2 was therefore further developed covering a more comprehensive description of the framework construction process including curing of concrete and removal of formwork. To facilitate a more comprehensive analysis, the model was added with functionality to simulate time, cost, and CO_2-emissions. This was used later on to study the effects of using climate-improved concrete types for different weather conditions and curing methods.

6.4.2 Research process

The research process consisted of six stages as illustrated in figure 15. In stage 1, a literature review was conducted focusing on concrete maturity theory, available tools for prediction of concrete strength as well as sensor systems for real-time in-situ measurements. The review also included reports covering costs of resources and Environmental Product Declarations (EPD) documents specifying CO_2-emissions of cementitious materials. In overall, the literature review provided valuable information to identify and structure data needed in later stages.

In stage 2, data were collected in two field studies (E and G). Field study E was once again revisited. However, this time the focus was on mapping the complete construction cycle of a concrete framework. In addition, operational methods for shielding concrete curing were also documented. Data on cost items were collected from various sources. For instance, by reviewing projects documents but also through direct information from site manager and suppliers involved in field study E. Other sources were reports where costs of concrete frameworks have been documented, but also official price lists specifying costs of relevant items. Data on CO_2-emissions were mainly collected from EPD-documents focusing on sourcing and manufacturing of concrete. However, also data on emissions related to curing measures were collected.

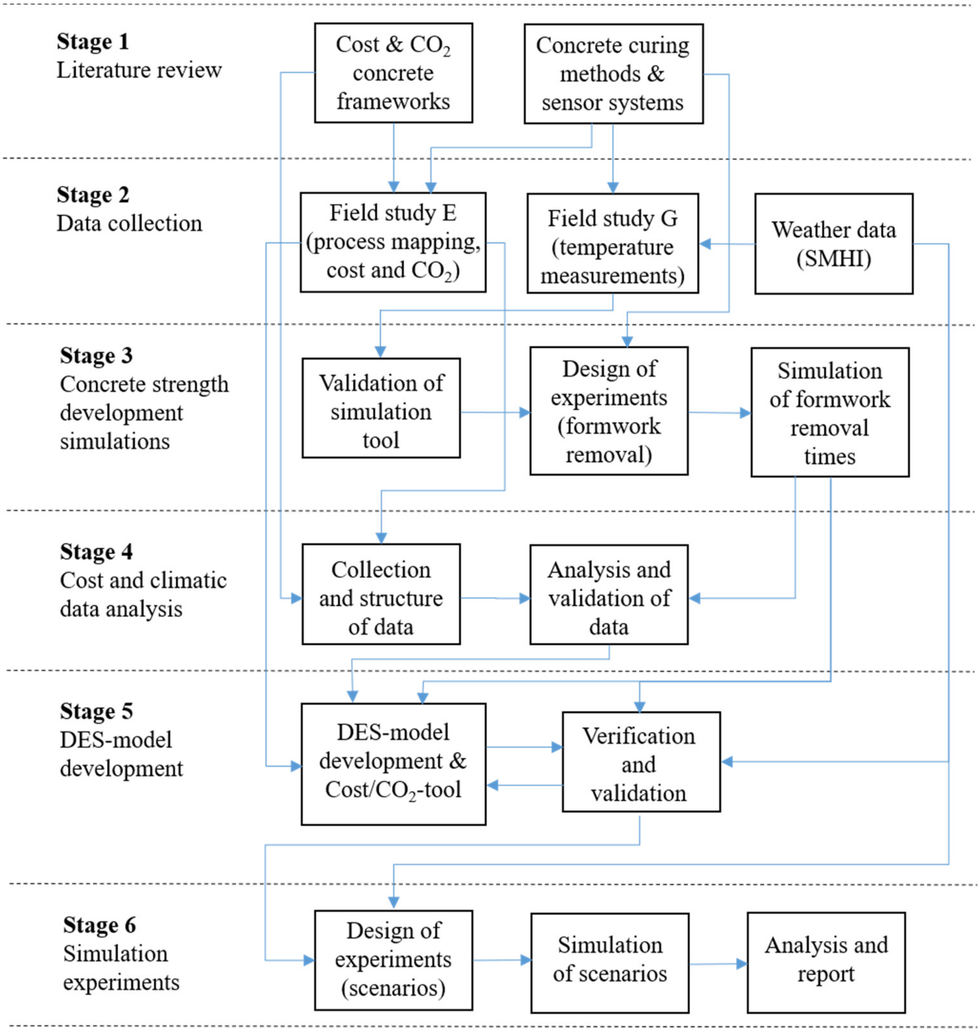


Figure 15
Research process for study 3.

In field study G, concrete temperatures and ambient climate were measured using a commercial sensor system. Each measurement was also documented in terms of operational measures employed prior and after concrete pouring. All data collected in field study G were later used to validate the simulation tool used to predict formwork removal times (stage 3). Stage 2 also included collection of weather data from SMHI covering records for three geographical locations in Sweden.

In stage 3, removal times of both vertical and horizontal formwork were simulated using a special-purpose simulation tool. The work started with validating the simulation tool by comparing simulated concrete temperatures with measurements performed in field study G. Thereafter, a matrix was composed containing 150 scenarios describing different combinations of concrete mixtures, curing measures, and weather conditions. The results were then structured and prepared to be integrated into the discrete-event simulation model.

In stage 4, data on cost items collected from different sources were structured, analyzed, and compared to check for consistency. Data covered both fixed and time-dependent costs of typical resources (material, labor, equipment) used during the construction phase. Data on CO_2-emissions were structured and analyzed to be representative for the concrete mixtures and curing measures which were used as preconditions for the formwork removal times simulated in stage 3.

Based on the work in previous stages, a simulation model was developed in stage 5. The same procedure as were employed in study 2 were also used here to build the model. The formalized process description documented in field study E was translated into a computerized model. The algorithms developed in study 2 describing how weather influence work task productivity were reused. In addition, functionality was added to the model to consider the effects on formwork removal time depending on weather, concrete type, and curing measures. A tool for calculating costs and CO_2-emissions were also developed. The methods employed for verification and validation purposes were similar to the methods used in study 1 and 2. Underlying process descriptions visualized with the help of flowcharts were discussed with site personnel. The computerized model was controlled using built-in animation and debugging features. The algorithm that determines formwork removal time based on actual weather were also closely examined by extracting values of weather input variables and corresponding formwork removal time. The final validation was done by comparing simulated floor cycle times with floor cycles that were reported from field project E using the same conditions regarding resource setup and durations of specific work tasks.

In stage 6, the model was used to study how weather affects concrete construction by considering both effects on work task's productivity and formwork removal. Multiple scenarios were simulated covering different combinations of weather conditions, concrete types (traditional and climate-improved), and curing measures. Each scenario was compared against a reference scenario in terms of time, cost, and CO_2-emissions.

6.4.3 Research quality

Similar to study 1 and 2, various measures to address reliability have been employed in both data collection and model development. Again, established methods were used for documentation of the production process. Weather statistics covering three different locations in Sweden were obtained from SMHI:s databases which ensured high data quality. Important input variables were formwork removal times. These were simulated using a special-purpose simulation software (PPB). To reduce the risk of errors due to many manual operations when inserting input data into the software, a structured protocol was used where all input variables were documented for each scenario together with simulated formwork removal time. This procedure facilitated a better overall control and by that reducing the risk of missing variables or having wrong values inserted.

To ensure consistency in cost data, comparisons of cost items from different sources were made. To make comparisons reliable, cost items were index-adjusted according to Swedish annual price factor index in cases when data was derived from different time-periods (SCB, 2020). Data on CO_2-emissions were obtained from EPD-documents which are compliant with the ISO-standard 14025 for life cycle assessments of environmental impact (ISO, 2006). It is believed that EPD:s are the most trustworthy and reliable sources to describe carbon emissions from building materials.

The simulation model was developed based on formal IDEF3-descriptions of the observed process ensuring consistency in representation of work tasks and logical sequences. The computerized model was controlled for internal errors in the same way as in study 1 and 2. In addition, special attention was given to the algorithm which dynamically determines formwork removal time due to actual weather conditions.

The construct validity is related to the model’s ability to capture the effects of weather on concrete construction in terms of time, cost, and carbon emissions. Therefore it is concerned with the measures employed to validate the model structure and its variables such as formwork removal times, cost of resources, and CO_2-emissions. The model is based on knowledge gained from documentation of the process in multiple field studies (A to F). Therefore, the production process and its characteristics are well understood and have been repeatedly validated. The algorithm developed in study 2 to account for the influence of weather on work task productivity, have also been reused here.

However, to address the scope of this study, the model has been added with capability to also consider effects of weather on formwork removal. To accomplish this, the model was further developed to consider a complete production cycle of a concrete framework. Documentation of a complete production cycle including curing measures was performed in field study F by direct observations and interviewing site personnel.

As a result, the model accounts for the combined effects of weather on work task’s productivity and removal of vertical and horizontal formwork. For a given combination of concrete mixture, curing methods, and weather conditions, the model simulates implications on construction time, cost, and CO_2-emissions.

Formwork removal times were simulated using a specific-purpose software tool. The tool's capability to predict temperature and concrete strength has been validated by many years of practical use in Sweden. It was also validated in this study by comparing simulated temperatures with measurements performed in field study G. The tool enables to precisely estimate removal times of vertical and horizontal formwork systems for different combinations of weather, concrete types, and curing measures. To ensure relevance in selected combinations of concrete types and curing measures, industry guidelines (Cementa, 2014; Svensk Betong, 2019) and practical views from site personnel and specialists involved in the field studies F and G were used.

The relevance of different cost items was validated by site personnel and material suppliers involved in field study F. Both fixed and time-dependent cost items were incorporated into the model to reflect the economic implications of weather-related delays, and the use of different concrete mixtures and curing methods. Data on CO_2-emissions are limited to concrete mixtures and curing measures. This is reasonable since this study only consider the implications on carbon emissions by using different levels of climate-improved concrete mixtures and necessary curing methods.

Weather statistics were obtained from SMHI:s databases and statistically analyzed in collaboration with a meteorologist. This procedure ensured a valid description of weather conditions representative for the three different geographical locations included in the study.

The internal validity was tested by studying how changes in input variables affected output indicators, e.g. colder weather resulted in extended durations, or increased the risk of early freezing if climate-improved concrete were used without sufficient curing measures. These were all reasonable model responses showing the causality between input and output variables. To ensure that the model could replicate the real process, simulated floor cycle times were compared with reported floor cycles in field study F using the same settings regarding availability of resources and productivity rates.

The model is valid to study the effects of Swedish weather conditions on the construction of hybrid concrete framework typically used in multi-story residential buildings. The formwork removal times are valid for concrete types commonly used in Sweden. However, the insights of how to model the effects of weather in DES, but also the specific implications on concrete construction due to varying weather and combinations of different concrete types and curing measures are believed to be of a general interest.

6.5 Study 4: Description of research process

6.5.1 Preconditions

In this study, the effects of weather on work task productivity were studied by employing a questionnaire survey. The target group is industry experts that are believed to possess practical knowledge about how weather affects concrete-related work tasks. This study is related to study 2 and 3 since it concerns the effect of weather on work task productivity.

6.5.2 Research process

The research process was divided in four stages according to figure 16. In the first stage, a literature review was performed. The effects of weather on construction productivity were once again studied focusing on updating the review performed in studies 2 and 3. The review also covered theoretical and practical aspects of designing and conducting a survey. In addition, structured methods for making rankings and comparisons were studied. For instance, the analytical hierarchy process (AHP) was examined to understand how it could be used for making pairwise comparisons of weather factors within a questionnaire survey.

Stage 2 consisted of planning the questionnaire survey. First the aim and scope of the survey was defined. The aim of survey was on ranking the relative importance of individual weather factors (temperature, wind, rain, snow), but also to quantify the effects of specific weather conditions on work tasks' productivity. The scope was limited to focus on typical concrete work tasks involved in the erection of concrete frameworks in multistory residential buildings.

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

Next, the target group was analyzed in terms of size and how to access individuals using data from a market survey company[4] specialized in collecting information about the Swedish construction market. By searching the market survey company's database, 4265 individuals currently involved in construction of multi-story residential buildings could be identified. Compared to the total size of the target

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[4] Sverige Bygger, www.sverigebygger.se

group which was estimated at a maximum of 5000 individuals, the search result indicated on a high coverage.

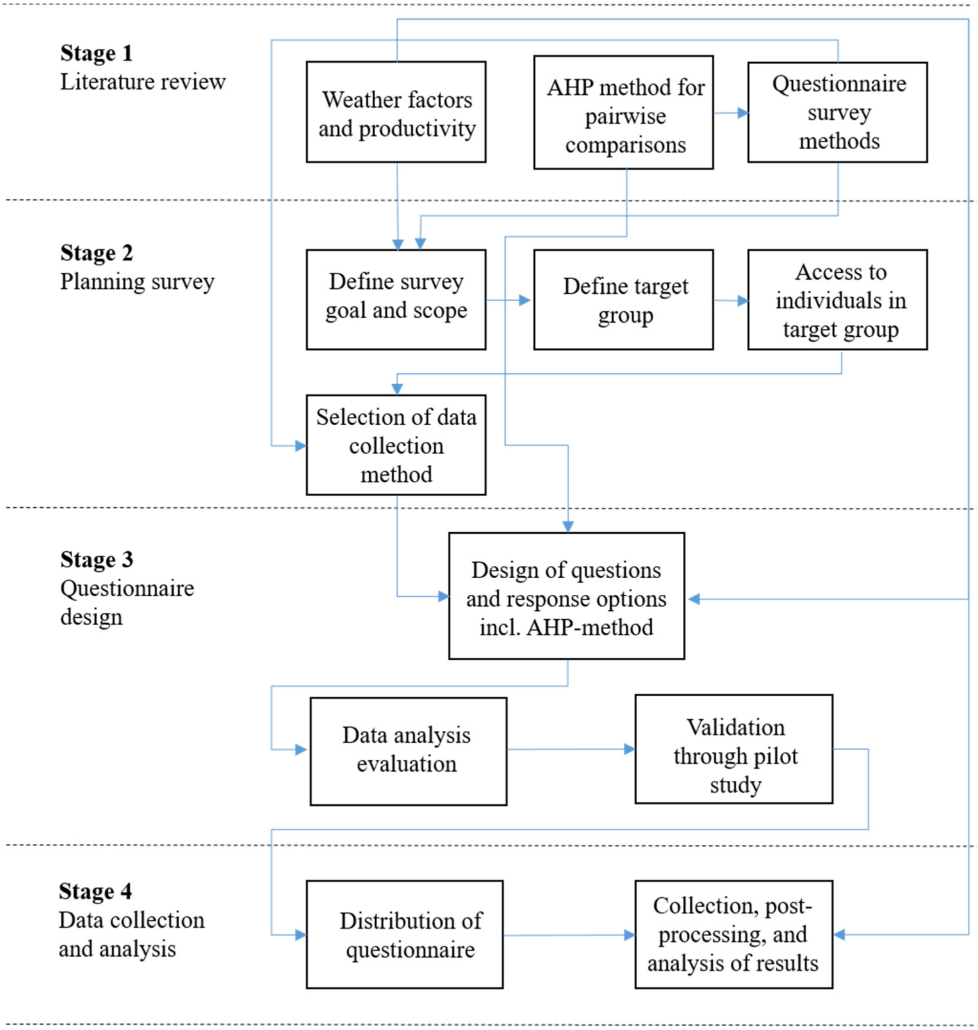

Figure 16
Research process for study 4.

Next, selection of appropriate data collection method was performed. In this study, a digital distributed questionnaire was used since it enables large scale-distribution at a low cost. It was here decided to make a complete survey rather than making a sampled survey. The extra cost for a complete survey is relatively small when employing a digitally distributed questionnaire. Moreover, since the knowledge about the total target population is based on estimations, statistical sampling technique becomes less useful.

In stage 3, the design of the questionnaire was performed. Selection, structure and phrasing of questions were closely linked to the overall objective and was done in an iterative process. 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, Koczkodaj and Szarek (2010) and Pecchia et al. (2013) to assess the importance of one factor relative to another. Comparisons were made for a summer and a winter case separately resulting in two unique correlation matrices for each respondent. The priority of each weather factor was given by the priority vector of each matrix which was calculated by the geometric mean of rows (Yoon & Hwang, 1995). 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 respondent was asked to estimate the loss in productivity for typical work tasks due 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%). The use of an uneven scale was a consciously choice to study if there was 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 (M. Asp, personal communication, March 16th, 2018). As a result, the following weather types were included; wind speed (range between 10-20 m/s), low and high temperature (-10 °C and +25°C), light and heavy rain (4 and 32 mm per day), 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 recognized. Each question and response option were carefully formulated and revised until they were considered to be relevant, clear, and easy to interpret.

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. The time to complete the questionnaire was also examined.

Distribution of the questionnaire was performed in November 2018 (stage 4). 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 in order to make respondents feel comfortable with providing answers. The expected time to complete the survey (about 10 minutes) was also indicated.

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

6.5.3 Research quality

Reliability of this study is influenced by the fact that the questionnaire approach limits the interaction with respondents. Therefore, the scientist has less control of how respondents interpret questions and how answers are provided. In addition, it can be difficult to make assessment of the impact of weather if the stated questions are not precisely defined and contextual information clearly stated. To address these difficulties, the questionnaire was focused on specific but typical work tasks such as handling of formwork, pouring concrete etc. These work tasks are believed to be well recognized and understood by the target group. In addition, each question was carefully formulated to facilitate the assessment of productivity loss due to a specific weather condition. To minimize the risk of misinterpretations, the questions were supplemented with both numerical and textual descriptions explaining the meaning of a certain weather condition. In addition, respondents had always the possibility to click the option “do not know” reducing the risk of providing uncertain answers. To control the consistency in pairwise comparisons, a consistency index was calculated for each comparison matrix (Saaty, 1990). In cases where this index was not satisfying, the comparisons were excluded from the overall results.

The questionnaire was also tested on a group of site managers in a pilot study where questions and response options were evaluated in terms of clarity and comprehensibility. The digital survey tool also facilitated that answers were compiled and visualized automatically. In addition, calculations of priority vectors were automated by an Excel-algorithm. In this way, errors due to manual processing of data were eliminated.

In overall, it is believed that the measures described above contributed to reduce the risk of random and/or systematic errors. Nevertheless, variations in assessments are to be expected since these are based on personal knowledge which obviously vary among respondents.

The construct validity of this study is related to the design and planning of the questionnaire survey. The survey measures how industry experts assess the importance of individual weather factors and to what extent a specific weather condition reduce work tasks’ productivity. Therefore, it was critical to ensure that the respondents were qualified to make such assessments.

The target group were selected to represent personnel in construction companies with job functions that required practical knowledge about managing concrete construction works, e.g. site managers. The collaboration with the MS-company also enabled to identify individuals responsible for ongoing (or recently completed) construction projects involving residential buildings. The control questions confirmed that the respondents had desired job titles and their experience of concrete construction were substantial. In addition, the questionnaire was distributed and completed during November which typically can offer harsh weather conditions in Sweden. Therefore, the general awareness of weather among respondents should be higher as it would be a more present issue in daily management of works. In overall, the respondents were believed to have necessary background knowledge and experience to make assessments feasible.

The weather types to be included were selected to be representative for Swedish conditions but also to be contrastive in order to reflect the influence of varying weather conditions, e.g. light versus heavy rain. The contrasting levels of intensity were also used as an internal validity of the survey. For instance, heavy rain should typically result in higher loss in productivity compared to light rain. This causality was confirmed in the survey results for all work tasks. The relevancy of selected weather types was also confirmed in discussions with a meteorologist at SMHI.

The relevancy of the questionnaire was also confirmed in advance by performing a pilot study involving six site managers.

The survey results are foremost valid for Swedish weather conditions. However, the weather types included are not unique, but could be valid in other regions with similar climate as in the Scandinavian countries. Moreover, since the assessments have addressed concrete work tasks that are commonly used in many other countries, the results are interesting also in a wider perspective. The findings in this study can be compared against own data or experiences. In addition, the survey can be replicated using an identical questionnaire to verify the results in this study, or a modified version to study other weather types or work tasks. Finally, it is believed that the methodology employed in this study also can be used to assess the impact of other important factors.

7 Research findings

In this chapter, research findings from the five papers are presented answering the research questions of the dissertation.

7.1 Modelling and systematic analysis of resource usage in on-site concrete production systems (RQ1)

The first research question focuses on how to describe on-site production of concrete frameworks in a discrete-event simulation model to enable systematic analysis of resource usage. To answer the research question, this section is divided in three parts. The first part describes a conceptual model of a typical on-site production system focusing on its essential construct elements and how they are interrelated. The second part addresses how the conceptual model could be described (modelled) in a discrete-event simulation model. The third part focuses on how the model can be used to enable systematic analysis of the production system focusing on resource usage. The findings presented here are based on the work performed in study 1 and presented in paper 1.

7.1.1 Conceptual model of the production system

The most elementary construct elements to describe the on-site production system are work locations, network of linked work tasks, and resources. Work locations are defined as physical units of a construction project at where production takes place, e.g. a framework of a building. In the context of on-site concrete production, a physical production unit is equal to the size of a pour unit, e.g. a floor slab of a framework. In addition, each floor slab may consist of multiple concrete wall units poured separately on daily basis. As a result, work locations can be defined on different levels of aggregation, e.g. framework, floor slab, or wall unit. The production process can be described as a network of linked work tasks performed in a predefined sequence. The construction sequence is typically repeated at each work location (e.g. at each floor level) as the erection of the framework evolves. In addition, multiple work tasks are usually performed simultaneously both within the same work location or between different work locations sharing common project resources. Each work task involves different types of resources, e.g. materials, machinery and labor. Since resources typically are shared between work tasks and work locations, their availability become decisive for the continuous progress of work. Any missing resource input either prohibit the start of a work task or reduce the working pace.

Conceptually, the production system can be modelled according to figure 17. A building is divided into the work locations WLX and WLY. The working process is described by a network of linked work tasks (WT1-WT*N*). Work tasks represents primary works that are needed to erect the concrete framework, e.g. erecting formwork, pouring concrete etc. Work tasks are linked together indicating a process related dependency. Ideally, no time buffers exist between two consecutive tasks indicating a finish-to-start dependency. However, the opposite may occur as do other more complex dependencies, e.g. when the finish of a task triggers multiple other tasks. Typical for the production system is the need for concrete to develop necessary strength to enable removal of formwork. This curing process is important to describe since it determines when following work can proceed. The curing process also holds certain resources (e.g. temporary formwork) making them unavailable for use in other pour units.

Different types of resources are needed to execute work tasks, e.g. labor, equipment, and materials denoted as R1, R2, and R3 in figure. The interplay between resources and work tasks is illustrated by the vertical incoming and outgoing arrows for each work task. Resources are allocated to a work task where they remain until the work task is finished and the resources are released and become available for use in other tasks. If several tasks simultaneously request the same resource (and the resource has limited capacity), an allocation conflict occurs. The tasks that are not assigned with required resources have to wait until the requested resources become available. The time a work task has to wait for resources is represented by the time buffers B1-B*N* in figure 17. Waiting time indicates the existence of workflow bottlenecks due to resource allocation conflicts. These bottlenecks can be solved by adding more resources or by changing the sequence of work tasks.

A detailed process description of a typical production process is presented in paper 1. The process description covers the logical sequence within a work location but also between locations to resemble that production takes place simultaneously at multiple work locations. For instance, when all wall units are finished at WLX1 in figure 17, the formwork and labor crew is moved to WLY1 where they continue to build concrete walls. At the same time, another work crew starts to build the next floor level at WLX2. This overall sequence of workflow is repeated floor by floor until the framework is completed.

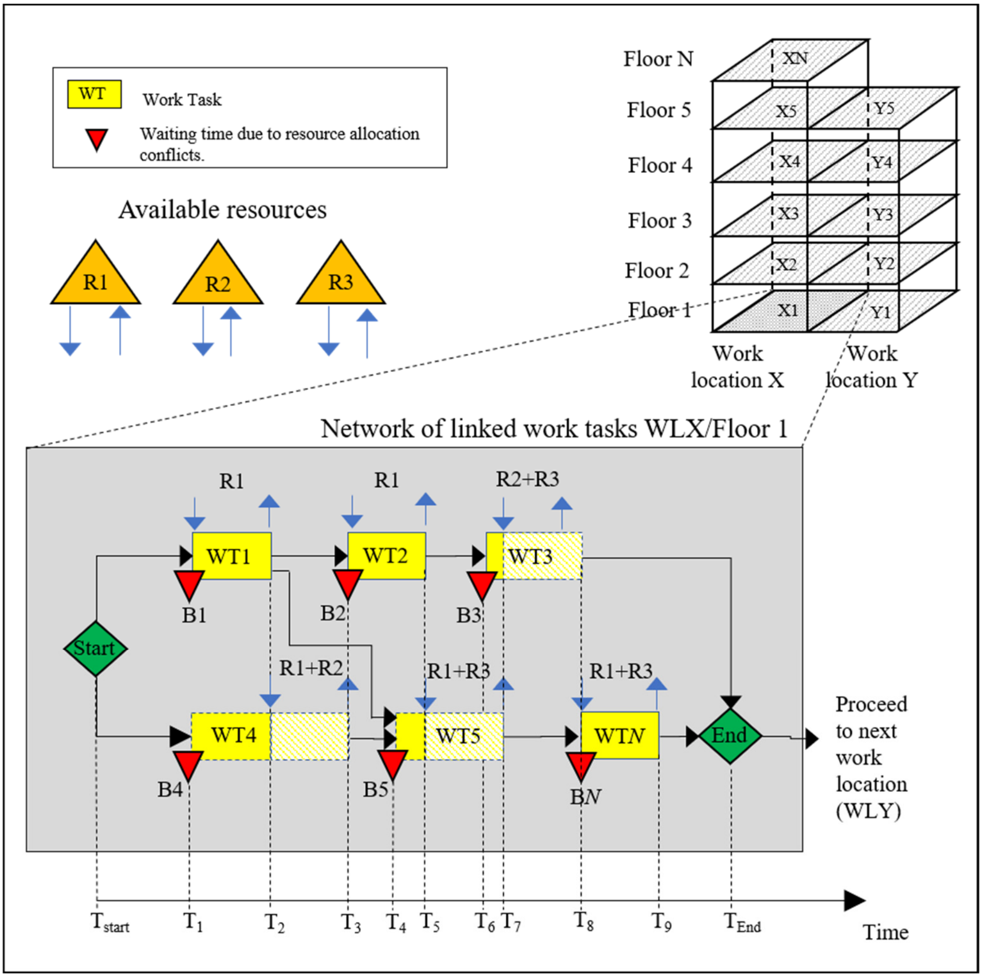

Figure 17
Conceptual model of a on-site concrete concrete framework (revised from paper 1).

7.1.2 Discrete-event simulation model

The conceptual model has been implemented in a commercially available discrete-event simulation system. In this case, ExtendSim[5] was chosen which is a commercial general-purpose simulation software. In ExtendSim, a system is modelled using a library of predefined construct elements (denoted as blocks) which are configured to perform highly specific tasks. Blocks are then connected to each other to resemble the desired functionality of the system. In figure 18, a layout of

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[5] ExtendSim®, www.extendsim.com

the discrete-event simulation model is presented. The model has a hierarchical structure consisting of three levels of detail.

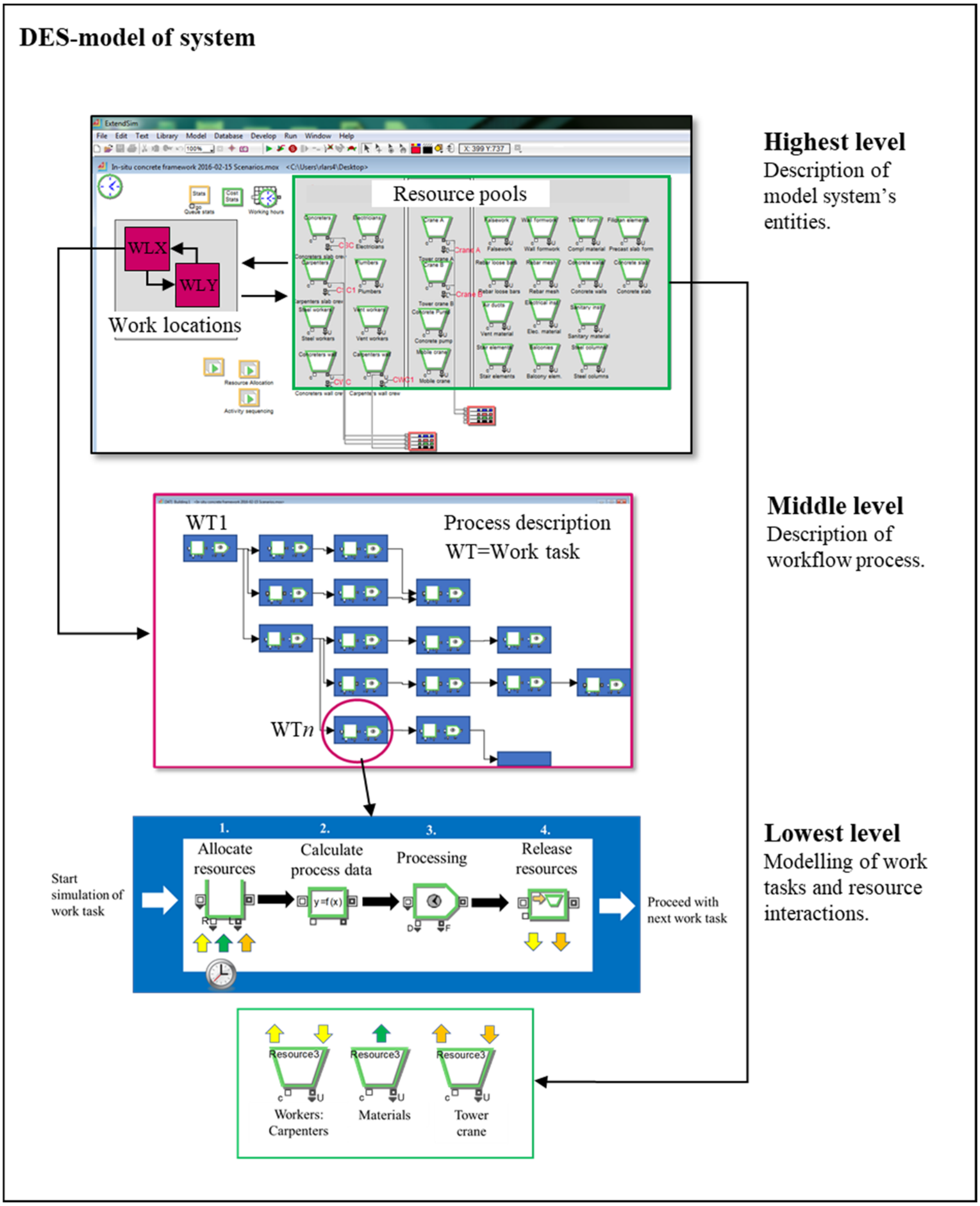


Figure 18
Discrete-event simulation model of a on-site concrete framework.

The highest level consists of a representation of the construct elements defining the overall model structure. For instance, the two sub-models denoted WLX and WLY represents the structures to be built, e.g. two separate concrete frameworks. Each sub-model is analogous to a work location and contains a description of the production process of a concrete framework. The arrows between the two sub-models indicate a mutual dependency since the state of the workflow in one sub-model affect the state in the other sub-model. The different resource types are also modelled at this level. Each resource type is defined by a unique resource pool block, e.g. a tower crane, or a concrete slab crew etc. These resource pool blocks hold information about available resources at any time during the simulation. The arrows between the work location sub-models and resource pool blocks represent the interactions between work tasks and resources.

The middle level of the model contains a description of the workflow process according to the formal description as presented in paper 1. The process is modelled using a set of different types of block elements that are interconnected forming the overall structure of the workflow. Items are flowing through the modelled system of blocks via the interconnecting links to resemble the desired order of execution of work tasks.

The lowest level of the model contains a group of blocks that are arranged in a specific order to resemble the execution of a work task and the interaction with resources. In general, all work tasks are modelled using four block elements (1 to 4 in figure 18) arranged in a specific order. Basically, the initiation of a work task is triggered by the entrance of an item to a resource queue block. Here, a request to allocate necessary resources (type and number) is sent to the resource pool blocks located at the highest level of the model structure. If all resources are available, they are allocated to the queue block and the item is then allowed to proceed. However, if some of the resources are busy serving other work tasks, the item waits until all resources become available. The time an item waits in a queue block is recorded during the simulation. This information is used to identify bottlenecks in the workflow due to resource allocation conflicts. The next block (equation block) calculates the duration of the work tasks based on work quantity, number of resources, and productivity rates. Thereafter, the item enters an activity block which holds the item and the allocated resources equal to the calculated duration time. Finally, the item enters a block that releases allocated resources back to the pool blocks as they were allocated from in the first place. During simulation, the passage time for an item to travel between blocks 1 to 4 is analogous to the lead time of a work task.

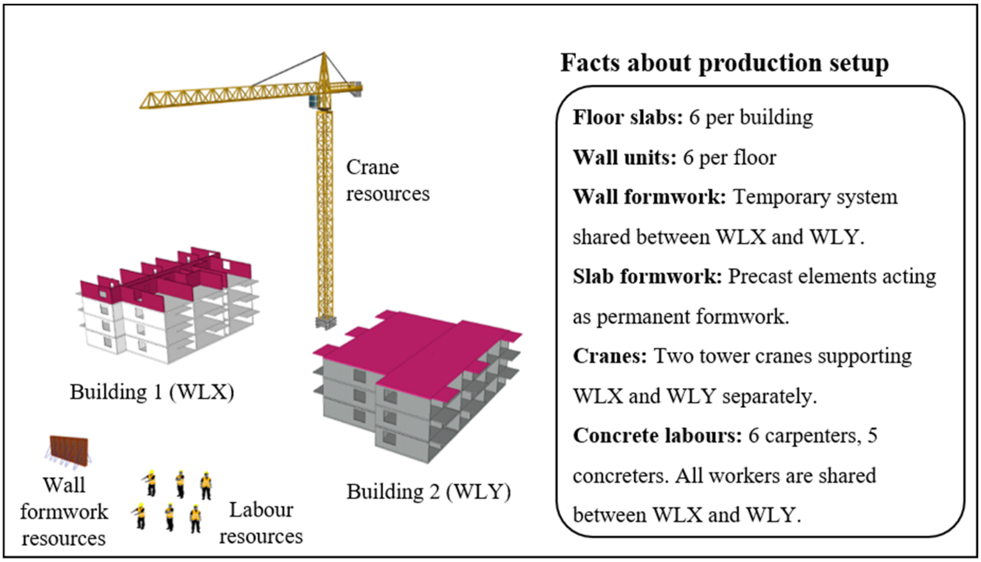
The model input variables consist of general project information and work-task specific information. General information consists of production units such as number of floor and wall units, available resources, working-hour schedules, costs of resources etc. Work task-specific information consists of productivity data, number of resources needed, and actual workloads. More details about input variables are described in paper 1. The model output variables are described in table 4 and includes both traditional construction metrics such as time and cost, but also metrics that can be used to analyze workflow bottlenecks and the use of resources, e.g. queue time and resource utilization.

Table 4
Overview of model output indicators.

Output indicator	Unit	Description
Queue time	Hours	Average time a work task has to wait to receive requested resources.
Total Queue time	Hours	Sum of average queue time for work tasks in a Work Location (e.g. WLX or WLY).
Resource Utilization (RU)	%	Relation between the average time a resource type has been used and the total available time during simulation.
Total time	Hours	Total simulated time. The time elapsed between start of the first and finish of the last modelled work task in the model.
Total cost	EUR (or SEK)	Total cost of resources (material, equipment, labor).

7.1.3 Systematic analysis of production system focusing on resource usage

The simulation model could be used to support a systematic analysis of a production setup in different ways. Here, the use of the model to analyze an existing production setup in terms of bottlenecks due to resource allocation conflicts, and to perform systematic analysis of alternative production configurations are discussed. To demonstrate the use of the model, the production setup based on field study D are used as a reference. An overview of the actual production setup is given in figure 19 whereas more details about model input variables and the actual production process is described in paper 1.



Facts about production setup

Floor slabs: 6 per building

Wall units: 6 per floor

Wall formwork: Temporary system shared between WLX and WLY.

Slab formwork: Precast elements acting as permanent formwork.

Cranes: Two tower cranes supporting WLX and WLY separately.

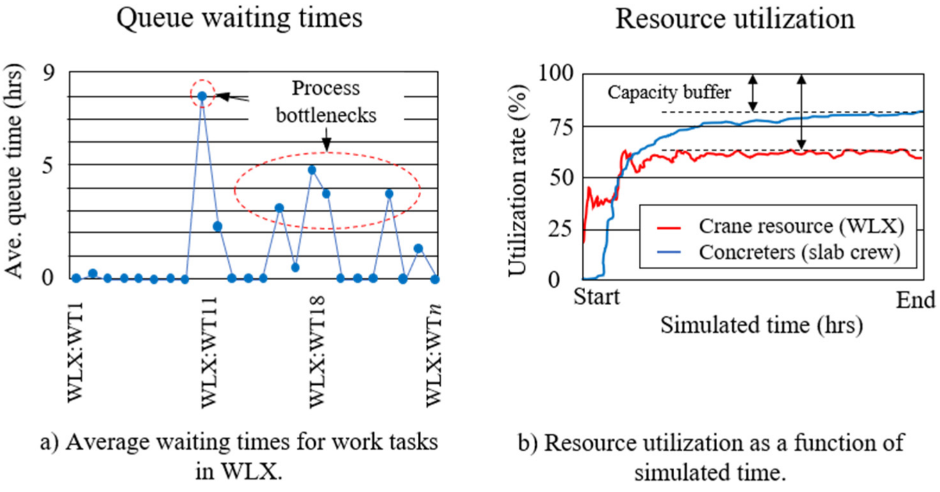
Concrete labours: 6 carpenters, 5 concreters. All workers are shared between WLX and WLY.

Figure 19
Overview of production setup that are analyzed by employing the simulation model.

7.1.3.1 Bottleneck analysis due to resource allocation conflicts

The simulation model reports queue waiting times for each modelled work tasks, see figure 20 (diagram a). In this model, waiting times are a symptom of bottlenecks due to resource allocation conflicts. Since all queue blocks have a unique identity in the model, it is easy to trace which work tasks that report waiting times. From the resource queue blocks, it is also possible to identify which resource types that are requested by the actual work tasks. Supplementary time stamped data from the same queue blocks also reveal that several work tasks request the same resource types (crane and concreters) simultaneously. Obviously, the design of the production system contains parallel processing of work that result in resource allocation conflicts. This would not be a problem if the number of available cranes and concreters were unlimited resources. However, in practice these resources are expensive, and a common goal is therefore to maximize the use of as few resources as possible.

To understand the use of resources, the model also reports statistics on utilization of each resource type (figure 20, diagram b). As seen in diagram, concreters have a higher utilization rate in average compared with the crane resource. Even though, the unused capacity of the crane resource is high (about 50%), it can temporarily become a critical resource if several work tasks are requesting crane assistance simultaneously. Having identified both the work tasks and the resource types that are responsible for the occurrence of bottlenecks, the next step is to use the model to analyze different scenarios to improve the use of resources and ultimately the overall performance of the production system.



a) Average waiting times for work tasks in WLX.

b) Resource utilization as a function of simulated time.

Figure 20
Queue waiting time statistics (diagram a) and resource utilization statistics (diagram b), revised from paper 1.

7.1.3.2 Systematic analysis of alternative production configurations

The simulation model supports implementation of various methodological and organizational changes. To analyze new construction methods, the model structure has to be adjusted to resemble the process of a particular construction method and additional resources may also be required. Indeed, this requires some efforts related to redesign and new verification and validation of the model. However, the model's hierarchical structure containing standardized components (groups of block elements) which can be copied and modified may reduce the efforts needed.

Organization changes, or minor modifications of existing working process, are thus more easily implemented. For instance, changes in how workers are dived to perform specific tasks are done by configuration of settings in block elements controlling the availability, request, allocation, and release of resources. New resources can easily be added to the model structure and then configured to be integrated into the workflow. Time buffers can be introduced between work tasks in order to change the timing of initiation of work tasks and also when resources are requested.

The simulation model also enables analysis of large numbers of different resource allocation combinations by systematically altering the variables describing the allocation of workers to different work tasks. Manually operated, this is a complex and time-consuming task, but the simulation model has in-built capabilities to automize this procedure. This procedure was tested on a production setup where the traditional division of workers into specialized crews (e.g. carpenters and concreters) were replaced by one group of multiskilled workers. The creation and simulation of all possible combinations were divided in two separate rounds to reduce the number of simulated runs required. In total, 64 combinations (2^6) were simulated in the first round and 4096 (2^{12}) combinations in the second round. More details about the procedure are described in paper 1.

Simulated total time and cost for each resource combination are presented in figure 21. The best resource combination (id: 4026) resulted in a 15% reduction in total time compared to the reference. Total cost was reduced only by 5% due to the additional resources employed. The total queue waiting time for scenario 4026 was 69% lower compared to the reference and the resource utilization RU (table 4) of the multi-skilled workers was found to be 71% which is 13% higher than the average utilization of workers in the reference case.

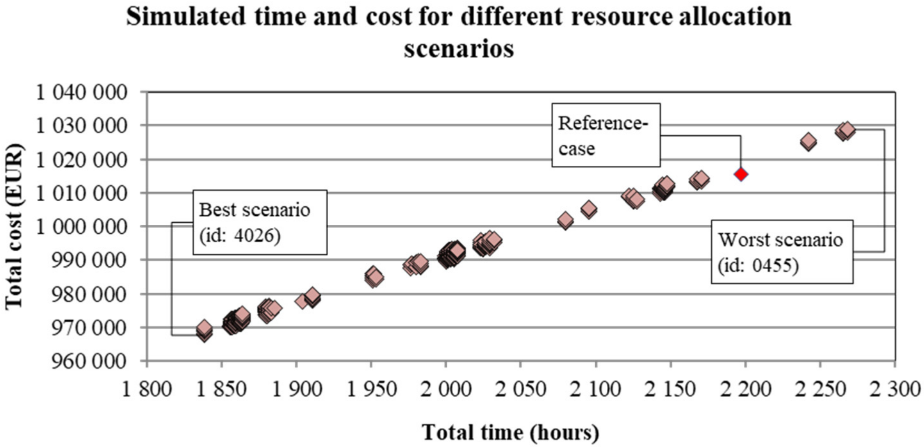


Figure 21
Simulated time and cost for 4096 resource allocation combinations (paper 1).

Even though the tested alternative production setup only resulted in minor time and cost reductions it demonstrates the powerful capabilities of the model to perform systematic analysis of the use of critical resources in an efficient way. Other model variables can be systematically altered in the same way.

In summary, to respond to RQ1, the conceptual model (figure 17) outlining the essential construct elements as well as the computerized version (figure 18) both illustrate how the on-site production process can be modelled in a discrete-event simulation model. In addition, figure 20 illustrates how queue waiting times together with statistics on resource utilization can facilitate systematic production *analysis. It is also demonstrated, as shown in figure 21, how discrete-event simulation can facilitate a systematic analysis of resource usage improving the overall production performance in terms of time and cost.*

7.2 Modelling the impact of weather conditions in a discrete-event simulation model (RQ2)

The second research question (RQ2) focuses on how the influence of weather conditions on productivity of concrete frameworks can be described in a discrete-event simulation model. The findings addressing RQ2 are based on work that has been published in papers 2, 3a, and 3b. This section is organized in the following order. First, the final DES-model is introduced on a general level describing the main components and the type of information needed. This model is also described in detail in paper 3b. The next sub-section describes the type of weather data needed as model input variable and how it was analyzed to identify data sets that were representative to describe different weather conditions. This procedure to analyze and compile weather data was first introduced in paper 2 and reused in papers 3a and 3b. The two following sub-sections describe how the effects of weather conditions on work task productivity (paper 2) and concrete curing process (papers 3a and 3b) are described and implemented in the model. Finally, the model output variables are described.

7.2.1 Overview of model structure

The structure of the discrete-event simulation model is outlined in figure 22. The model consists of two sub-models (work locations) representing the construction of concrete frameworks in two separate multi-story buildings. More specifically, each sub-model contains a detailed description of the concrete framework production process as described in paper 3b. The model simulates the duration of individual work tasks as well as the overall construction process. During simulation, the model continuously keeps track of the status of working process (number of finished floors/wall units, start and finish of work tasks etc.), and the use of different resources. In addition, the model also keeps track of current weather conditions which are used to dynamically determine the effects on productivity addressing both physical work tasks and concrete curing. This procedure is further described in the next following sub-sections.

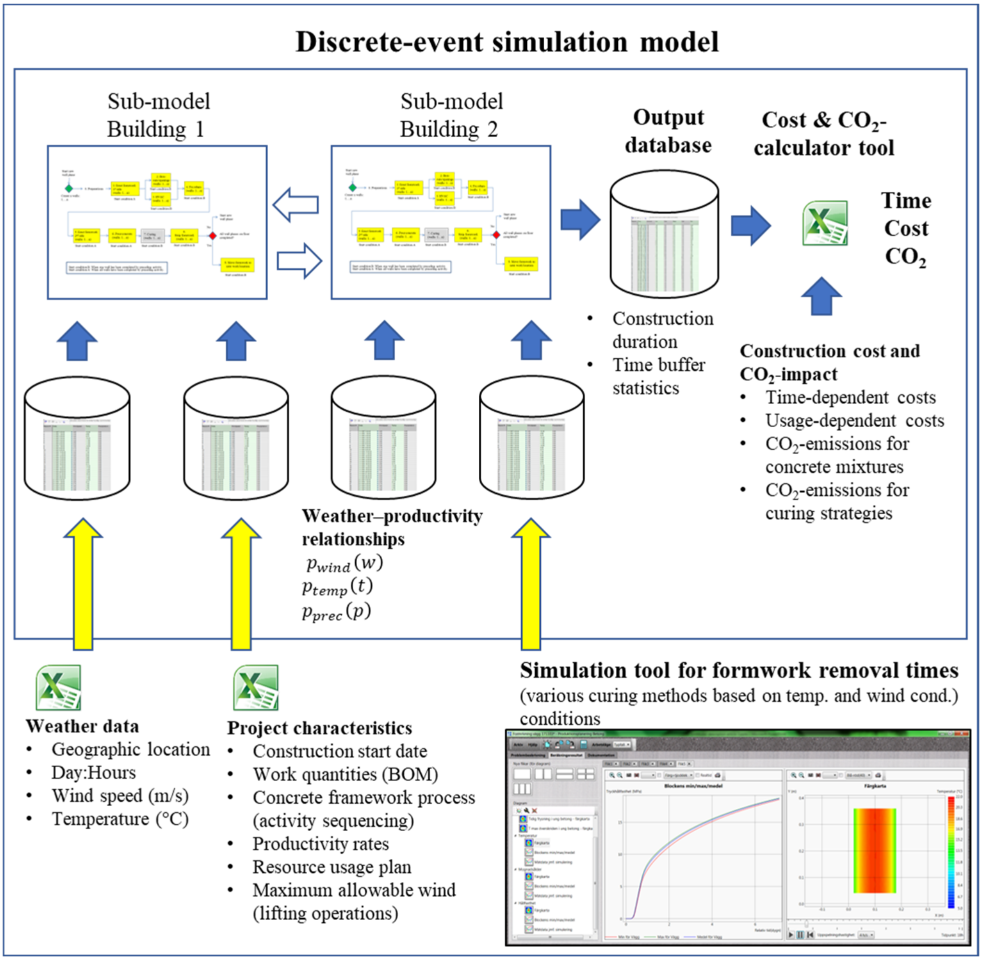


Figure 22
Overview of discrete-event simulation model developed to study the effects of weather (paper 3b).

The model is connected to four databases containing different type of information needed during a simulation. For instance, one database contains weather data for different geographic locations specifying temperature, precipitation, and wind speed on an hourly basis. Collection, analysis, and preparation of weather data is discussed in the next sub-section. The second database contains project information, e.g. start date of construction, work quantities, maximum wind speeds for lifting operations, productivity rates, and allocation of resources etc. The third database contains relationships used to determine the influence of weather conditions on work task productivity as is described in section 7.2.3. The fourth database contains simulated formwork removal times for different concrete types, curing strategies, and weather conditions as described in section 7.2.4.

The model outputs total construction duration and time buffer statistics which are stored in an output database during the run of the simulation. It is also possible to extract more detailed timing data from a simulation, e.g. duration of each work task, or duration of a complete floor cycle. In addition, the cost and CO_2-calulator tool calculates corresponding cost and carbon-emissions for the simulated production setup. As a result, each scenario studied can be evaluated considering implications on time, cost, and CO_2-emissions. Model output variables are further described in section 7.2.5 whereas additional details about the cost and CO_2-calculator tool is given in paper 3b.

7.2.2 Weather data

Weather data reflecting Swedish weather conditions are an important model variable. Weather conditions can be described at an aggregated level, e.g. monthly or daily average values. However, weather conditions change on very short basis. For example, temperature is normally lower at night, the intensity of precipitation or winds speeds may vary on an hourly or even minute basis. Sudden changes in weather may have significant implications for certain work tasks. For example, wind speed may vary significantly on hourly basis compared to average wind over a 24-hour period (figure 23). Neglecting the influence of short-term variations may result in wrong conclusions regarding the possibility to perform certain activities which may be time critical, e.g. lifting formwork or lifting prefabricated elements directly from a truck where any delays may result in penalty costs. Therefore, to account for weather on a short term basis, it is necessary to have a high resolution in weather data, preferable with an hourly resolution.

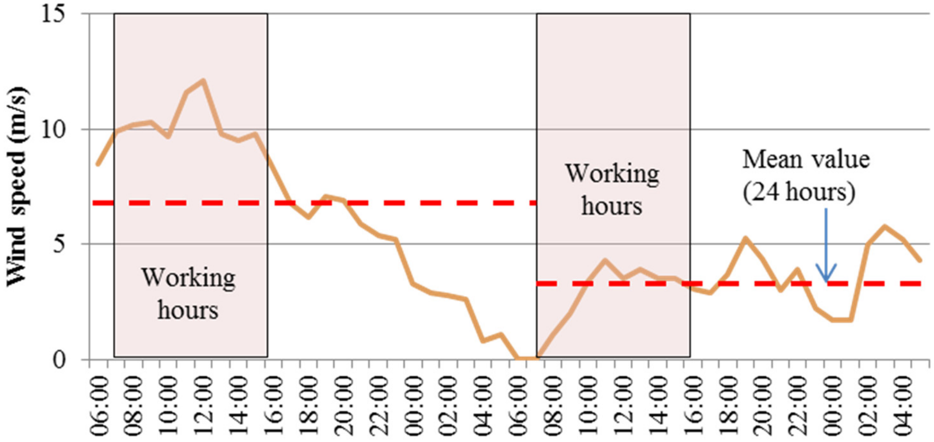


Figure 23
Hourly wind speed variation versus average wind speed (paper 2).

To ensure validity and quality in weather data, it was collected from the Swedish Meteorological and Hydrological Institute's (SMHI) databases consisting of hourly readings of temperature, precipitation and wind speed. These data sets represent different geographical locations in Sweden, e.g. Malmö, Stockholm, and Umeå. In this way, it is possible to study the effects of varying weather conditions due to different geographical locations. Data records covering longer time periods (10 or 20 years) were statistically analyzed to identify years that could be considered as normal and unusual in terms of annual temperature, wind, or precipitation for an actual location. More details about the analytical procedure are presented in papers 2 and 3b. Since precipitation is measured in melted form it must be converted to rain or snow depending on actual air temperature. This is done automatically in the model. In addition, since snow is measured in melted phase, the resulting snow depth must be adjusted to actual temperature since depth of a snowfall increases with colder temperature according to the fluffiness factor (SMHI, 2013). Each record of precipitation in the climate data sets is therefore adjusted to reflect the influence of increased snow depth at colder temperatures.

7.2.3 Modelling the effects of weather on work task productivity

Based on previous research findings, the most significant weather factors influencing construction productivity are temperature, wind, and precipitation (rain and snow). Different weather factors affect construction works in different ways. For instance, labors are affected by cold or hot temperatures, machinery such as tower cranes are affected by strong winds, and so forth. A brief summary of the effects of different weather factors on work task productivity is given in table 5.

Several researchers have attempted to establish relationships between specific weather factors and work task productivity. For example, the relationship between temperature and productivity based on three different studies are outlined in figure 24. As seen, these show on different effects, especially at cold and warm temperatures. The differences could be a result of that these studies consider different types of construction works. Another reason could be that these studies have been performed in regions with different climate conditions. Other researchers have published results describing the relative effects of precipitation and wind speed on work task productivity. An overview of these can be found in paper 2. These types of weather-productivity relationships can be used to model the effect of weather on work task productivity.

Table 5
Summary of documented effects of weather on construction productivity (revised from paper 2).

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 relationsships are given in figure 24.	Curing of concrete is affected by temperature which determine the time when formwork can be removed. Also wind speed may be of importance due to wind-chill effects.
Rain	Most type of works involving individuals	Labor productivity is reduced even at light rain. Light rain (above 0.2 m/h): 40% loss. Rain above (0.5 mm/h: 50-60% loss.	Pouring concrete skab 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 slab are more sensitive to snowfall than walls. Actions to protect and clean working areas must be carried out due to snowfall. Materials have to be protected and cleaned from snow.
Wind	Work at heights, lifting operations (e.g. formwork)	Lifting operations cancelled at wind speeds > 20 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 Kahn (2010).	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. Additional safety measures may be required at high winds.

Since construction works typically are influenced by many external factors, the individual effect of weather must be distinguished. To determine the single effect of weather on work task productivity, the concept of baseline productivity (Thomas & Završki, 1999) was used. The baseline productivity reflects ideal conditions in a project, i.e. when no significant interruptions occur. Baseline productivity as such, is considered only to be affected by work complexity. However, for a specific project it is reasonable to assume work complexity as a constant. More details about how baseline productivity data for work tasks were determined are given in paper 2.

To describe the impact of a specific weather factor on work task productivity, baseline productivity for the actual work task is multiplied by a weather factor (*wf*). The weather factor (*wf*) describes the combined effect of wind speed, temperature, and precipitation according to equation 3.

$$wf = p_{wind}(w) \times p_{temp}(t) \times p_{prec}(p) \qquad (3)$$

Where:

$p_{wind}(w)$ defines the effect on productivity as a function of wind speed according to figure 5 in paper 2, and $0 \leq p_{wind}(\mathrm{w}) \leq 1$; $p_{temp}(t)$ defines the effect on productivity as a function of temperature according to figure 24, and $0 \leq p_{temp}(t) \leq 1$; $p_{prec}(p)$ defines the effect on productivity as a function of precipitation intensity according to the approximated curve in figure 4 in paper 2, and $0 \leq p_{prec}(p) \leq 1$; w is wind speed (m/s), t is temperature (°C), p is precipitation intensity (mm/hour).

The weather factor (wf) varies between 1 and 0, where 1 indicates no loss in productivity due to weather effects and 0 means a 100% loss in productivity (equal to work stoppage).

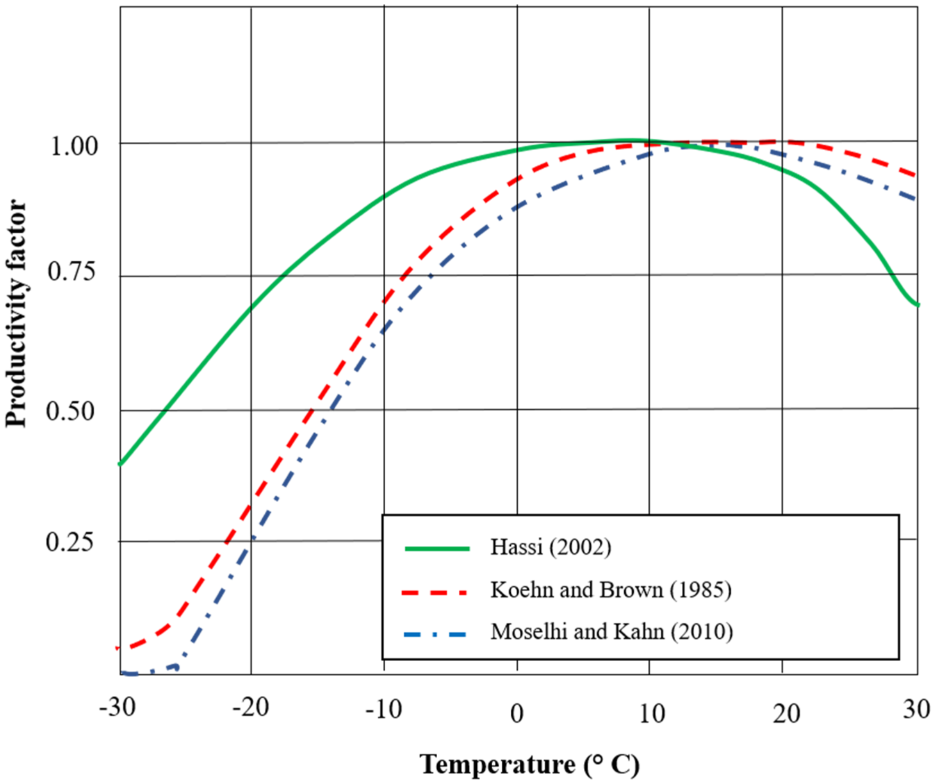


Figure 24
Relation between temperature and productvity loss based on Moselhi and Kahn (2010), Koehn and Brown (1985), and Hassi (2002), revised from paper 2.

A schematic layout of the overall principle to account for weather on work task productivity is given in figure 25. Productivity data is collected for work tasks and analysed to determine ideal, or baseline, productivity (A in figure). During simulation, the model updates weather on hourly basis and at the start of a specific task (t_{now}), most recent weather conditions are retrieved corresponding to a set of temperature, wind, and precipitation data (B in figure). These parameters are used to adjust lead time of a work task using the weather factor, wf, and the underlying weather-productivity relationships (C in figure). If some weather parameter triggers a threshold for work stoppage, the work task is cancelled until next hourly update of weather. A more detailed description of the algorithm is presented in paper 2.

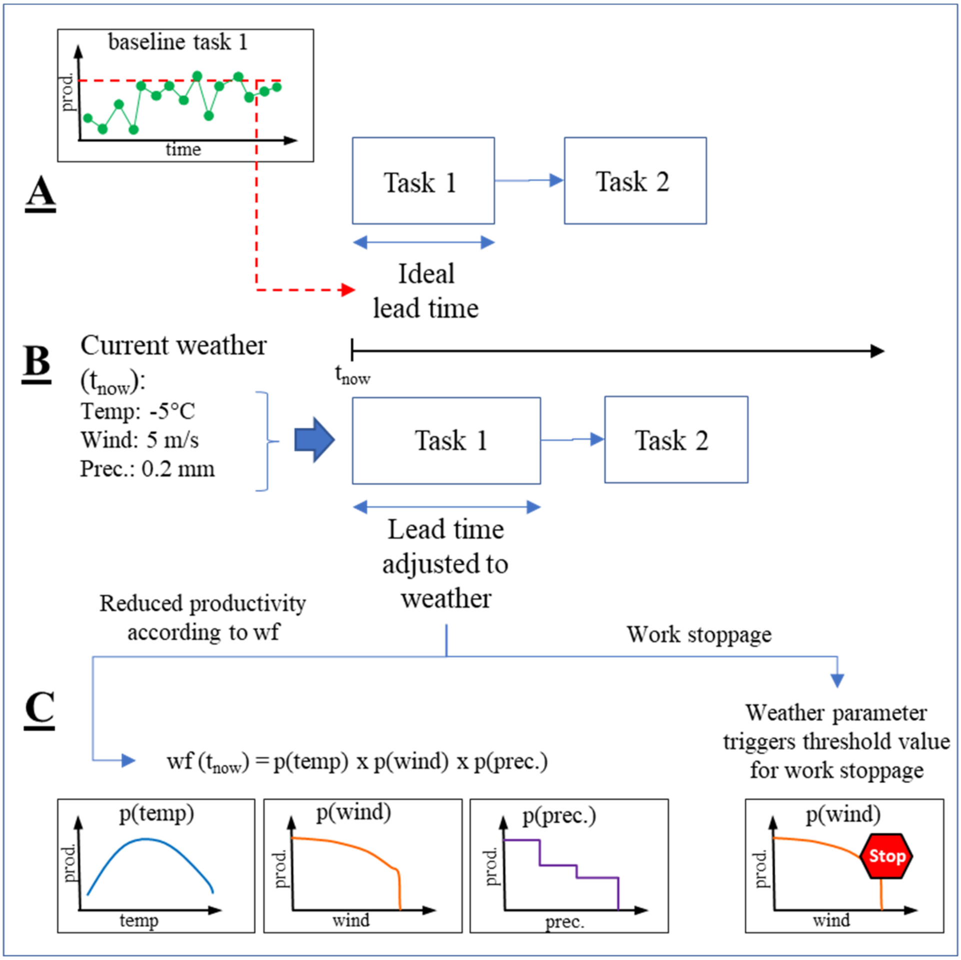


Figure 25
Schematic layout describing the overall procedure to account for weather on work task productivity.

7.2.4 Modelling the effects of weather on concrete curing process

To account for weather conditions on concrete curing process, the simulation model is connected to a database consisting of formwork removal times. More specifically, the database holds information about vertical and horizontal formwork removal times for different combinations of concrete types, curing conditions, and ambient weather conditions. Formwork removal times have been estimated using a special-purpose simulation tool (PPB[6]) which is designed to simulate temperature and strength development in concrete structures. To validate the simulation tool, simulated temperatures for both concrete walls and slabs in field study G were compared with temperatures measured in-situ using temperature sensors. The simulation tool was provided with details about actual conditions documented in the field project, e.g. details about concrete structure, concrete mixture, formwork, isolation and heating methods. Ambient air temperatures measured on-site together with data records of wind speeds retrieved from the closest located weather station, were used as input variables to the simulation software for validation purpose. Using the on-site conditions as input variables to the simulation tool, it was concluded that the simulated temperature profiles corresponded with measured temperature profiles. Figure 26 (left diagram) shows an example of simulated and measured concrete temperatures in a concrete floor structure. Simulated strength development based on simulated and measured temperatures are given in diagram b). More details about the simulation software and sensor measurements are described in paper 3b.

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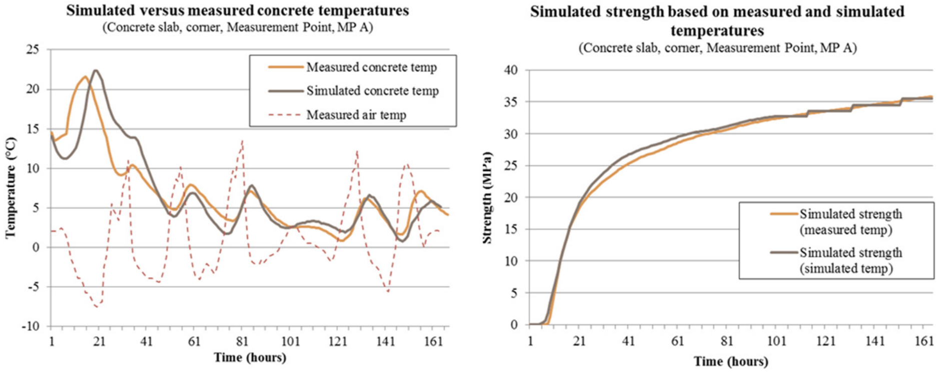

Figure 26
Comparisons between simulated and measured concrete temperatures and associated concrete strength development (paper 3b).

The algorithm for considering effects of weather on horizontal formwork removal in the DES-model is outlined in figure 27. Prior to initiation of simulation, the user selects a desired combination of concrete configuration and curing strategy for both walls and floor slabs. In this way, the model has access to corresponding formwork removal data for various weather conditions during the simulation.

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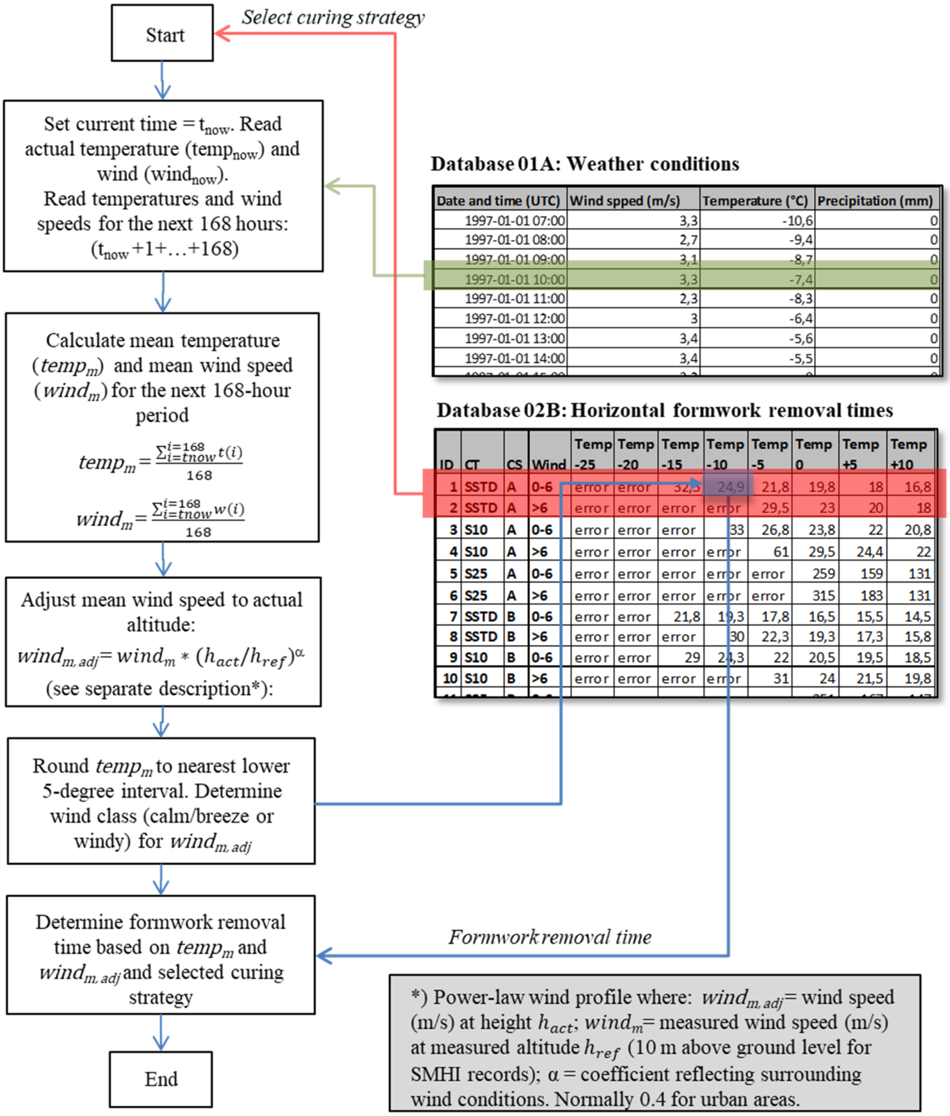
[6] PPB, Produktions Planering Betong; www.byggforetagen.se

As mentioned earlier, the model continuously keeps track of the status of the workflow, e.g. when it is time to pour concrete walls or slabs. Referring to figure 27, when a floor slab is ready to be poured (i.e. when preceding work tasks are finished), current time is set to t_{now}, actual temperature ($temp_{now}$), and wind speed ($wind_{now}$) are obtained from the climate database. The model also reads temperatures and wind speeds for the next seven days (168 hours).



Database 01A: Weather conditions

Date and time (UTC)	Wind spped (m/s)	Temperature (°C)	Precipitation (mm)
1997-01-01 07:00	3,3	-10,6	0
1997-01-01 08:00	2,7	-9,4	0
1997-01-01 09:00	3,1	-8,7	0
1997-01-01 10:00	3,3	-7,4	0
1997-01-01 11:00	2,3	-8,3	0
1997-01-01 12:00	3	-6,4	0
1997-01-01 13:00	3,4	-5,6	0
1997-01-01 14:00	3,4	-5,5	0

Database 02B: Horizontal formwork removal times

ID	CT	CS	Wind	Temp -25	Temp -20	Temp -15	Temp -10	Temp -5	Temp 0	Temp +5	Temp +10
1	SSTD	A	0-6	error	error	32,5	24,9	21,8	19,8	18	16,8
2	SSTD	A	>6	error	error	error	error	29,5	23	20	18
3	S10	A	0-6	error	error	error	33	26,8	23,8	22	20,8
4	S10	A	>6	error	error	error	error	61	29,5	24,4	22
5	S25	A	0-6	error	error	error	error	error	259	159	131
6	S25	A	>6	error	error	error	error	error	315	183	131
7	SSTD	B	0-6	error	error	21,8	19,3	17,8	16,5	15,5	14,5
8	SSTD	B	>6	error	error	error	30	22,3	19,3	17,3	15,8
9	S10	B	0-6	error	error	29	24,3	22	20,5	19,5	18,5
10	S10	B	>6	error	error	error	error	31	24	21,5	19,8

*) Power-law wind profile where: $wind_{m,adj}$ = wind speed (m/s) at height h_{act}; $wind_m$ = measured wind speed (m/s) at measured altitude h_{ref} (10 m above ground level for SMHI records); α = coefficient reflecting surrounding wind conditions. Normally 0.4 for urban areas.

Figure 27
Algorithm used in DES-model for estimating formwork removal times based on current weather (paper 3b).

Next, mean temperature ($temp_m$) and wind ($wind_m$) is calculated for the upcoming seven days. Calculated wind speed is also adjusted to actual working height based on the power-law wind profile. A similar procedure is used for determining removal of wall formwork except that the time-period for future weather conditions is based on the next 12 hours instead of 168-hours. The algorithm for vertical formwork used in the model is described in paper 3a.

The model also accounts for the need of additional works associated with a specific curing method when pouring concrete in cold weather conditions. For example, installing heating cables before pouring a concrete wall or covering a concrete slab after pouring. Prior to pouring a concrete wall or a slab, the model updates current and future weather conditions. If temperature is less than zero degrees, or if temperature is below 5 degrees and the wind speed is above 6 m/s, winter measures are employed according to the selected curing strategy. In this way, the extra work associated with a selected curing strategy is also reflected during the simulation. The logical modelling and coding describing the need for winter-related curing measures as a function of actual weather conditions are described in paper 3b.

7.2.5 Model output variables

The simulation model framework enables to analyze a production setup using the following output indicators:

1. *Time*: This variable refers to total duration of the on-site production phase and is defined as the time elapsed between the start of the first work task in the framework erection process and the last modelled work tasks. It is also possible to obtain intermediate time statistics such as lead time of work tasks or lead time between two consecutive floor slabs (also denoted as floor cycle time). In cases where early freezing of concrete occurs due low concrete strength in combination with cold temperature, the model automatically stops the simulation and reports an error-message. The model also outputs information about when (time) and where (location) the problem has occurred. In similar way, if concrete temperature becomes too high (> 60°C), the model automatically stops and outputs an error-message.
2. *BuffTime*: BuffTime denotes the time between when concrete strength allows for removal of formwork (material-related condition) and when the working process is ready to remove formwork (process-related condition). As such, it is a measure of the synchronization of a concrete-related production system. In a perfectly synchronized production system, the working process and material-related conditions are fulfilled simultaneously. However, if the working process is ready to remove formwork but the actual concrete strength prohibits removal, then the working process is interrupted. On the other hand, if the concrete strength

enables removal of formwork but the working process is not ready, it may indicate an unnecessary use of project resources, e.g. use of too high-quality concrete and/or too extensive curing measures. The mathematical formula used to determine the BuffTime variable for removal of horizontal formwork is described in paper 3b. The conceptual idea of BuffTime was initially introduced on vertical formwork as described in paper 3a.

3. *Cost*: Cost of the on-site production is calculated using an Excel-based calculation tool. The tool is limited to include cost items (labor, material, equipment) typically used during the erection of a concrete framework. More specifically, it accounts for time-dependent and usage-dependent costs. Accordingly, the cost calculation tool does not provide a complete cost analysis. Time-dependent costs refer to variable costs for general site resources (labor, rental costs for cranes, tools, facilities, equipment), and rental costs for different types of formwork systems. The calculation tool uses simulated time as an input variable to calculate time-dependent costs. The usage-dependent costs refer to variable costs due to selection and actual use of different curing methods and concrete types for pouring walls and floor slabs. For this purpose, the tool uses output information from the simulation model regarding the number of walls or slabs where a specific curing method has been employed which in turn is dependent on prevailing weather conditions. More details about the different cost items and the equation used by the cost calculation tool are described in paper 3b.
4. *CO_2-emissions*: The Excel-based tool also calculates carbon-emissions related to the use of different concrete types and curing methods. The calculation tool uses data on carbon emissions for different concrete types based on EPD-documents (A1-A3). In addition, carbon emissions related to different curing methods are also included. More details describing how carbon emissions have been determined are also given in paper 3b.

The simulation model and the associated cost and CO_2-calculation tool can be used to study the implications on construction time, cost, and carbon emissions of a concrete framework due to varying weather conditions and different combinations of concrete types and curing methods.

Referring to RQ2, figure 22 outlines the overall structure of a simulation-based approach to consider the effects of weather. At a detailed level, figure 25 describes the overall procedure to account for weather on work task productivity. To account for weather on a work task level, baseline productivity is adjusted using a weather factor according to equation 3. The weather factor is a function of several specific relationships as exemplified in figure 24. In addition, an algorithm as described in figure 27 is also used to define the impact of weather on concrete curing processes. As such, this algorithm dynamically accounts for when formwork can be removed considering actual weather conditions and the specific curing method applied. The *simulation model also accounts for the implications on productivity due to the work needed for winter preparations as a certain curing method entails.*

7.3 Simulated effects of weather during production of concrete frameworks (RQ3)

The third research question (RQ3) focuses on the effects of varying weather on concrete frameworks in terms of time, cost, and CO_2-emissions by also considering the use of different concrete types and curing methods. To address the research question, the simulation model described in section 7.2 was used. The setup of simulation experiments and results are based on paper 3b. This section is organized as follows. First, details about the simulation setup and experiments are provided. Thereafter, the effects on construction time, cost, and CO_2-emissions for different geographical locations, seasons, concrete types, and curing methods are presented. Supplementary BuffTime statistics are provided in the next section showing the synchronization between working process and concrete curing as a result of different concrete types, curing methods, and weather conditions. The final section presents the best configurations of concrete types and curing methods for different locations and seasons considering construction time, cost, and CO_2-emissions.

7.3.1 Design of simulation experiments

Field study E (table 3) was used as a basis for conducting simulation experiments. The field study involves construction of two six story concrete frameworks being erected simultaneously. Details about how the production setup was implemented in the simulation model are described in paper 3b.

The simulation experiments involved three different geographical locations (Malmö, Stockholm, and Umeå), two different seasons for construction (autumn and winter), five combinations of concrete types, and three curing strategies. Start dates for the two seasons were set to October 1st (autumn) and January 1st (winter). Normal weather conditions are simulated using weather data for representative years according to table 6.

The different combinations of concrete types as were simulated are outlined in table 7. Here, denotation WS-STD refers to the use of standard concrete (STD) in both walls (W) and slabs (S). In similar way, WS-10 refers to the use of concrete types in walls and slabs with 10% lower CO_2-emissions compared with standard concrete (WS-STD) whereas WS-25 refers to the use of concrete mixtures in walls and slabs with 25% lower emissions. Denotation W25-SSTD refers to the use of concrete mixtures with 25% lower CO_2-emissions in walls, but with standard concrete in slabs. A Portland fly-ash cement CEM II/A-V 52.5 N is used in all concrete mixtures.

Table 6
Overview of selected years used as input for simulation of normal weather conditions for Malmö, Stockholm, and Umeå.

Location	Weather condition	Time period for analysis	Selected year
Malmö	Normal	1997-2016	2006
Stockholm	Normal	1997-2016	1997
Umeå	Normal	2007-2016	2007

Table 7
Overview of combinations of concrete types used in concrete framework's walls and slabs (paper 3b).

Denotation of concrete configuration	Concrete walls		Concrete slabs	
	Strength class	Cement content (kg/m3)	Strength class	Cement content (kg/m3)
WS-STD	C30/37	360	C40/50	420
WS-10	C28/35	325	C35/45	380
WS25	C25/30	270	C25/30	320
W25-SSTD	C25/30	270	C40/50	420
W25-S10	C25/30	270	C35/45	380

Simulated curing strategies A, B, and C are outlined in table 8. Curing strategy A is assumed to be included in standard operations meaning that this method does not influence duration time of production. However, both curing methods B and C implies, to various extent, that additional works on both walls and slabs are required which may influence duration of production cycles. A large number of scenarios were simulated covering different geographical locations, concrete configurations, and curing methods. Details about the simulated scenarios are further described in paper 3b.

Table 8
Description of curing measures associated with curing strategies A-C (paper 3b).

Curing strategy	Concrete walls	Concrete slabs
A	• Initial concrete temperature = 20°C • Formwork panels: 19 mm plywood, 50 mm intermittent EPS isolation • Cover of formwork top one hour after pouring (removed next morning, 17 hours after pour)	• Initial concrete temperature = 20°C • Table forms: Plywood, no isolation • Concrete surface cover: 10 mm high-performance insulation placed 1 hour after pouring and removed after 24 hours • 50 mm isolation along the edge of concrete slab
B	• Intital concrete temperature = 25°C • Formwork panels: Same configuration as A • Cover of formwork top after pouring • Heting cables (30W/m) placed in top and bottom of wall	• Initial concrete temperature = 25°C • Table forms: Plywood, no isolation • Concrete surface cover: 10 mm high-performance insulation placed 1 hour after pouring and removed after 24 hours • 50 mm isolation along the edge of concrete slab
C	• Same measures as B	• Initial concrete temperature = 25°C • Table forms: Plywood, no isolation • Concrete surface cover: 10 mm high-performance insulation placed 1 hour after pouring and removed after 24 hours • 50 mm isolation along the edge of concrete slab • Use of heaters (100W/m^2) from the underside of the concrete slab. Heaters are operated until 7 days after pouring.

7.3.2 Effects of normal weather conditions in Malmö

Figure 28 presents the simulated effects of normal weather conditions for Malmö when construction of the two frameworks is performed during the autumn period. The diagram shows simulated time, cost, and CO_2-emisssions when employing different combinations of concrete types and curing methods relative to a reference scenario where effects of weather are neglected. The reference scenario is set to 1 for all indicators. In the diagram, the x-axis denotes concrete configuration (e.g. WS-STD, WS-10 etc.) and the curing strategies A-C according to tables 7 and 8.

As seen in figure 28, the construction duration is extended by 8-20% compared to the reference scenario. All curing methods are capable of shielding concrete curing against freezing indicating that both strategy B and C are unnecessary. In fact, curing strategy C is even inappropriate resulting in high temperature when standard concrete types are used in floor slabs. High concrete temperatures may also result in delayed formwork removal times as indicated by the extended duration when using WS-25 in combination with method C. It can also be noted that concrete configurations WS-10 or WS25 in combination with curing method A result in a slightly increase in duration due to delays in formwork removal compared with using standard concrete configuration (WS-STD).

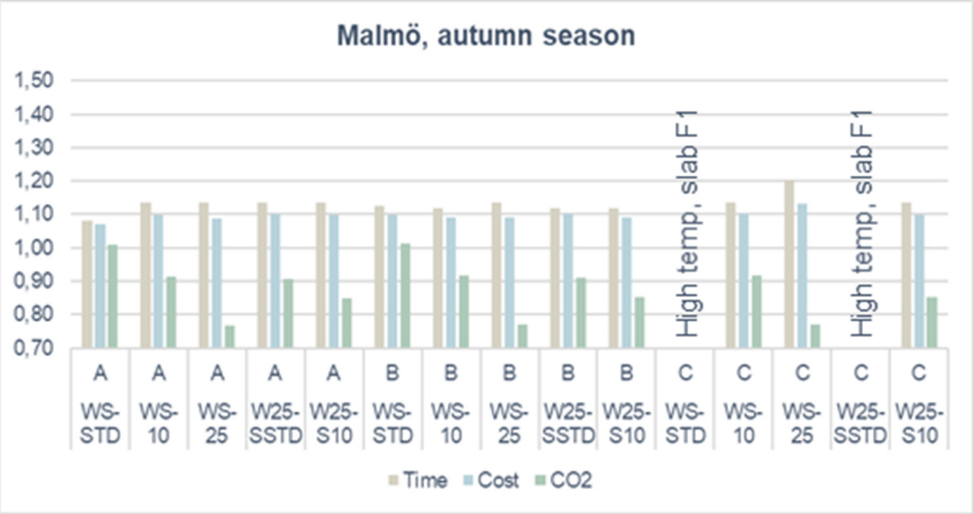


Figure 28
Simulated effects of normal weather on constructtion time, cost and CO_2-emissions for Malmö during autumn season (paper 3b).

The cost of construction is increased by 8-13% which mostly is an effect of an extended duration. In the model, variable costs related to wages for site personnel, rental costs of crane resources, machinery, tools etc., comprise for about 60% of the total cost included in the model. Accordingly, extended duration (due to weather) means higher variable costs which then directly influence the total cost. The remaining costs in the model are mostly related to different combinations of concrete types and to some extent also related to different curing methods. Differences in costs of concrete are foremost related to different qualities of the concrete mixture. In the model, the cost of a concrete type is dependent on the concrete quality. A lower concrete quality means a reduced cost due to a lower content of cement in the mixture. As a result, concrete mixtures with reduced carbon emissions also means reduced costs of concrete. However, since the time-dependent costs are more dominant in the model, the combination of concrete types and curing methods that result in shortest duration (WS-STD and method A) also means lowest cost. Accordingly, the combination that result in longest duration (WS-25 and method C) means highest cost even though this combination has the lowest costs related to concrete materials.

Carbon emissions are reduced by up to 23% when concrete configuration WS-25 is used compared to the reference scenario based on standard concrete (STD) configuration. Clearly, selecting concrete mixtures with lower carbon footprint has a positive impact on total emissions of the framework.

The effects of changing the construction period to winter is presented in figure 29. As seen, the construction duration is extended by 29-41% compared to the reference scenario. This is a direct result of cold weather reducing work task productivity and implies the need for extra winter measures to protect the concrete curing process. As seen, winter conditions also mean that early freezing of concrete becomes a problem when curing method A is used in combination with climate-improved concrete. However, curing methods B and C are both capable of shielding concrete against early freezing except for when concrete configuration WS-25 is used. However, the need for extra works associated with curing methods B and C are responsible for further increasing duration up to 41%.

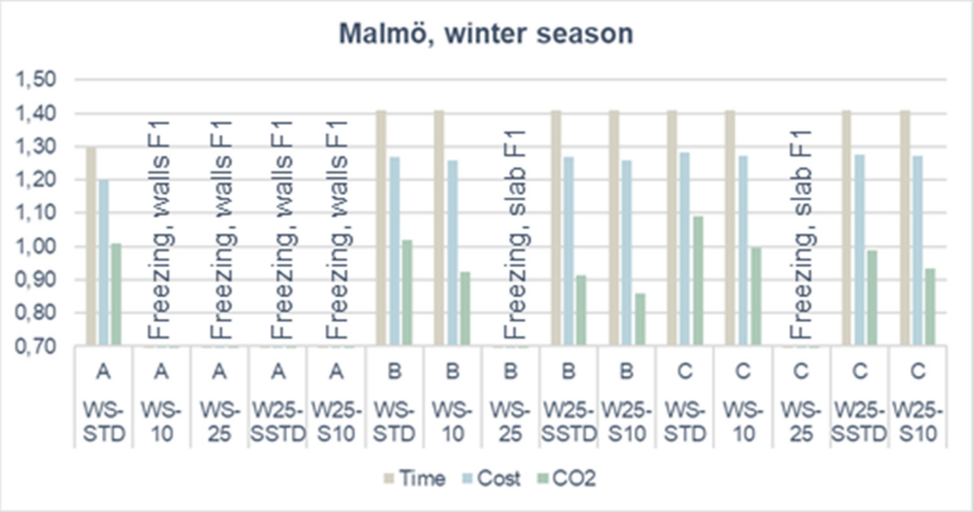


Figure 29
Simulated effects of normal weather on construction time, cost and CO_2-emissions for Malmö during winter season (paper 3b).

The cost is increased by 20-28% during the winter period. In the same way as for the autumn period, the combination that result in shortest duration also means lowest cost, in this case WS-STD and method A. The costs for the other options are in the range of 26-28% mainly due to longer duration.

During the winter period, carbon emissions are reduced by up to 14% for W25-S10 combined with curing method B. However, employment of unnecessary extensive curing methods may increase CO_2-emissions above the reference scenario.

7.3.3 Effects due to normal weather conditions in Stockholm

The simulated effects of weather in Stockholm during autumn season is presented in figure 30. By accounting for weather, the duration is increased by 16-27%

depending on concrete types and curing methods. Again, standard concrete and curing method A result in shortest duration whereas climate-improved concrete (WS-25) in combination with curing method C results in the highest increase. The latter is an effect of delays in formwork removal increasing duration by 27%.

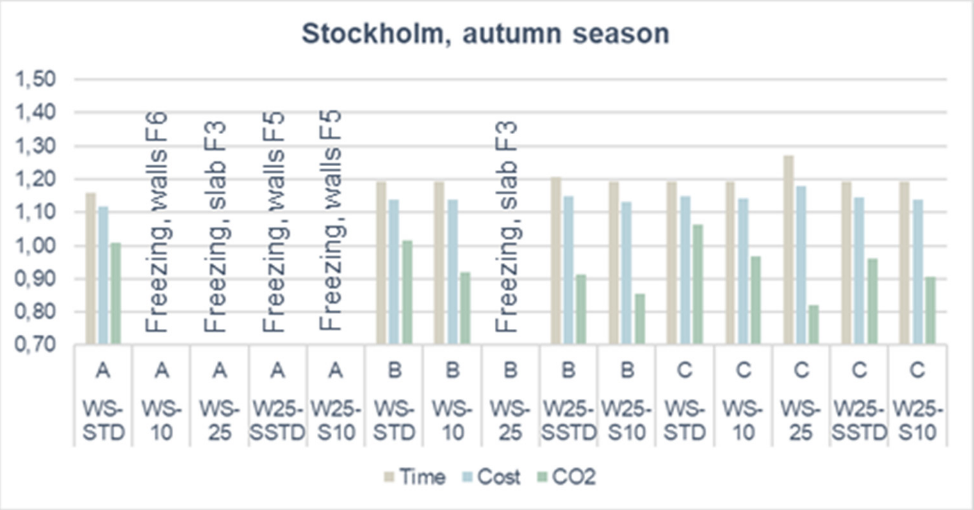


Figure 30
Simulated effects of normal weather on construction time, cost and CO_2-emissions for Stockholm during autumn season (paper 3b).

At this location, early freezing becomes an issue when curing method A is employed in combination with climate-improved concrete types. As seen, early freezing occurs at higher floor levels which are constructed in the later stage of the project when weather conditions are becoming colder as autumn turns into winter. The working altitude may also be of importance since the wind chill effect increases at higher altitudes. This means that employing one curing method during the whole project is not suitable but has to be adjusted to changing weather conditions.

Construction costs are increased by 12-18%. Again, the combination of concrete types and curing methods that result in shortest duration also means lowest increase in costs.

Carbon emissions are reduced by up to 18% when employing WS-25 in combination with curing method C. Again, the use of standard concrete types in combination with unnecessary extensive curing methods increase emissions.

Starting construction January 1st, the duration is increased by 42% compared to the reference scenario (figure 31). The results show that curing method A is not capable of shielding concrete against early freezing. Instead, at least curing method B should be employed. It can also be noted that more extensive measures than strategy C are needed to shield combinations of concrete types with low carbon footprint corresponding to WS-25.

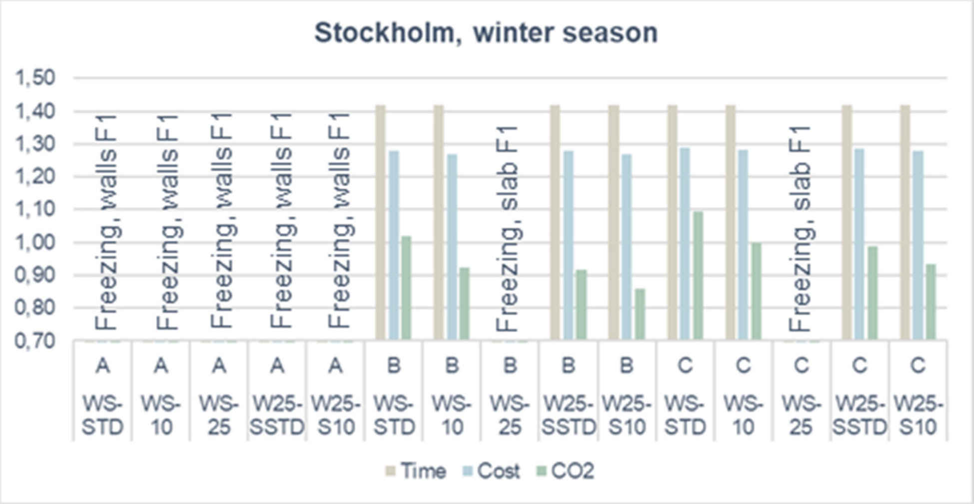


Figure 31
Simulated effects of normal weather on construction time, cost and CO_2-emissions for Stockholm during winter season (paper 3b).

The construction cost is increased by 27-29%. Highest cost occurs for the scenario involving standard concrete types (WS-STD) and curing method C. However, the difference is very small compared to the other scenarios. Carbon emissions are reduced by up to 14% when employing W25-S10 in combination with curing method B.

7.3.4 Effects due to normal weather conditions in Umeå

Turning to Umeå, the duration is increased by 20-24% if the construction takes place during the autumn period (figure 32). Similar to Stockholm (figure 30), early freezing occurs for most cases when curing method A is employed, but also for curing method B in combination with WS-25. For Umeå, early freezing also occurs at the end of the construction phase (floor level 5) when climate-improve concrete (WS-25) is used in combination with curing method C. Costs are increased in the range 15-18% depending on the actual use of concrete and curing methods. Carbon emissions are reduced by up to 14% when employing W25-S10 in combination with curing method B.

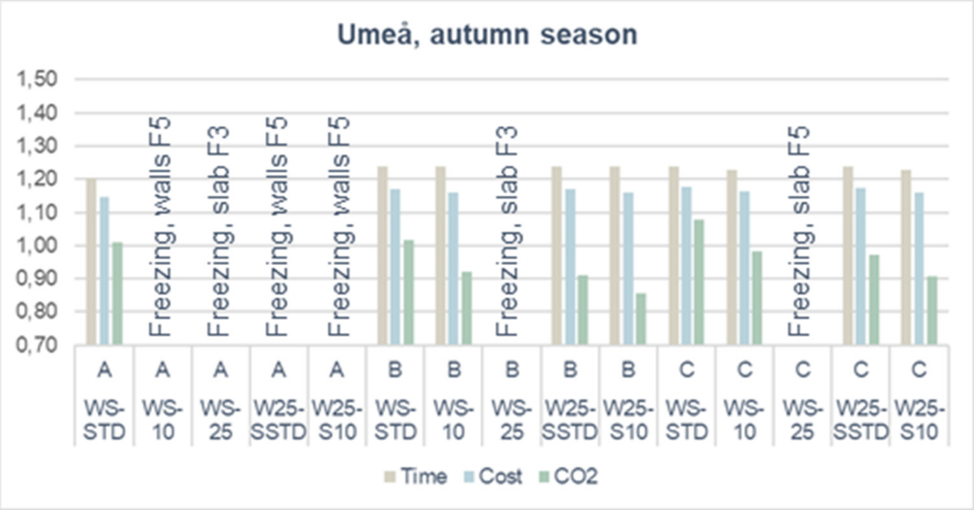


Figure 32
Simulated effects of normal weather on constrcution time, cost and CO_2-emissions for Umeå during autumn season (paper 3b).

The effect of colder weather conditions due to northern location become more obvious when considering construction during the winter period (figure 33). As seen, early freezing occurs for most cases except for when standard concrete types (WS-STD) are used in combination with curing methods B or C.

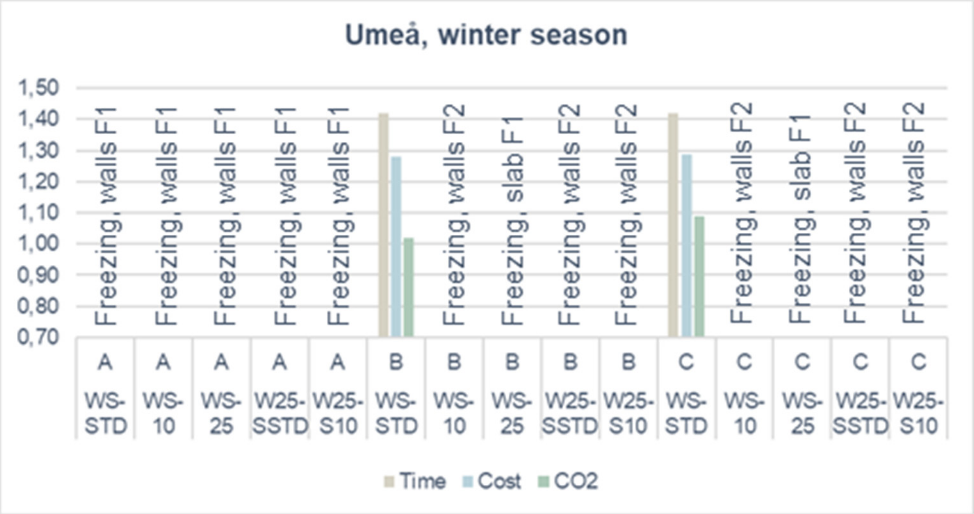


Figure 33
Simulated effects of normal weather on constrcution time, cost and CO_2-emissions for Umeå during winter season (paper 3b).

Obviously, more extensive curing methods than studied here are needed to allow for the use of concrete types with reduced carbon footprint at this location during winter period. Simulated costs of the framework are increased by almost 30% during the winter period. As mentioned before, this is mostly attributed to an extended duration due to cold weather. Since only options involving the use of standard concrete types (WS-STD) in combination with curing methods B or C were capable of protecting concrete against early freezing, no reduction in carbon emissions compared to reference scenario was achieved.

Considering the effects of winter conditions between the three geographical locations, it may appear somewhat surprising that there is no difference in maximum duration (figures 29, 31, and 33). This can be explained by the extra work associated with curing methods B and C are more important reasons for an extended duration compared with effects caused by formwork delays or reduced work task productivity. Especially winter preparations related to concrete walls are more likely to extend duration since these are more time critical for the studied production setup. Moreover, since execution of work tasks related to a certain curing method is triggered by a specific threshold condition (e.g. temperature below 0 °C) means that the difference in climate conditions becomes less significant. This is reflected by examining the model output more closely. For instance, the model outputs statistics on the ratio between the number of times a curing method has been employed at a pour unit and the total number of pour units. The results reveal that the ratio related to walls are about the same for Malmö (0.5) and Umeå (0.6) despite that the winter conditions are rather different at these two locations.

However, the geographical effect is still reflected in the results since more extensive curing methods than C are needed in Umeå. For the same reason, an intermediate option (between A and B) would have been enough to shield concrete in Malmö during winter which may have resulted in a less impact on construction duration. As mentioned earlier, the production cycle of concrete walls in the studied production system consists of close-linked work tasks with no intermediate time buffers. Therefore, extra work tasks needed to shield the concrete curing process may result in extended duration of work cycles. The working process of concrete floor slabs consists of more parallel works that are not fully synchronized leading to the existence of intermediate time buffers. As a result, the working process of floor slabs has better possibilities to absorb the extra works associated with a specific curing method. This also explains why there is no difference in duration between curing method B and C despite that the latter method involves more extensive works.

In overall, this highlights the importance to consider implications of winter protection measures on production cycles.

7.3.5 Synchronization of floor cycles and concrete curing

Considering the synchronization between the framework working process and the curing of concrete floor slabs, time buffer statistics for each simulated scenario are presented in table 9. Time buffer values are expressed in days and are an average of 12 floor slabs (6 floors in each of two buildings). No values are given for cases where early freezing occur, denoted "n/a" in table. A positive value means that the minimum concrete strength to allow removal of formwork occurs before the working process is ready to remove formwork. A negative value indicates that the working process must wait until concrete has reached required strength to allow removal of formwork. A value close to zero means that working process and curing process are synchronized, i.e. they occur almost simultaneously.

Table 9
Time buffers in days for different combinations of concrete types and curing methods.

Curing methods / concrete configuration	Malmö		Stockholm		Umeå	
	Autumn	Winter	Autumn	Winter	Autumn	Winter
Curing method A						
WS-STD	5,9	8,0	7,0	n/a	7,2	n/a
WS-10	6,4	n/a	n/a	n/a	n/a	n/a
WS-25	1,3	n/a	n/a	n/a	n/a	n/a
W25-SSTD	6,6	n/a	n/a	n/a	n/a	n/a
W25-S10	6,4	n/a	n/a	n/a	n/a	n/a
Curing method B						
WS-STD	5,4	8,6	6,6	8,0	6,7	6,9
WS-10	6,7	8,5	6,5	7,8	6,5	n/a
WS-25	0,8	n/a	n/a	n/a	n/a	n/a
W25-SSTD	6,7	8,6	7,0	8,4	6,7	n/a
W25-S10	6,6	7,4	6,5	7,8	6,7	n/a
Curing method C						
WS-STD	n/a	8,9	6,9	8,8	7,0	7,5
WS-10	6,6	8,7	6,6	8,6	6,9	n/a
WS-25	0,8	n/a	0,2	n/a	n/a	n/a
W25-SSTD	n/a	8,8	6,9	8,8	6,9	n/a
W25-S10	6,6	8,8	6,6	8,6	7,1	n/a
Min	**0,8**	**7,4**	**0,2**	**7,8**	**6,5**	**6,9**
Max	**6,7**	**8,9**	**7,0**	**8,8**	**7,2**	**7,5**

As seen, the results reveal high positive time buffer values in general. This clearly indicate that, when early freezing is not an issue, the working process determines the duration of floor cycles, not the curing process. Measures employed to protect concrete curing against early freezing result in a rapid concrete strength development as indicated by high buffer times (almost up to 9 days).

In general, high buffer times indicate an unnecessary extensive use of resources increasing project costs and environmental impact. It may also indicate an opportunity to reduce floor cycle time which may reduce total construction time. However, this require that the overall working process is accelerated. The results also show that when using concrete types with reduced carbon emissions (WS-25) in floor slabs, time buffer values are significantly reduced for some conditions (e.g. autumn season in Stockholm) indicating improved synchronization between working and curing process. However, bear in mind that this specific configuration resulted in highest duration and cost due to delays in duration of concrete wall cycles. Accordingly, using only time buffer statistics on horizontal formwork to achieve better synchronization may lead to wrong conclusions on what is a suitable solution at a system level. Time buffer statistics related to horizontal formwork should therefore be analyzed together with implications on time, cost, and CO_2-emissions to avoid risk of sub-optimization. Moreover, to make analysis of production synchronization more comprehensive, buff time statistics should also consider removal of vertical formwork as described in paper 3a.

7.3.6 Selection of optimal solution adopted to weather

An overview of combinations of concrete types and curing methods that resulted in shortest time, lowest cost, or lowest carbon emissions for different seasons and locations, are outlined in table 10. Each value of time, cost, and CO_2 given in table 10 corresponds to minimum value based on figures 28-33. As seen, the combination that includes standard concrete types (WS-STD) and curing method A result in both shortest duration and lowest cost for all three locations during the autumn period. Obviously, standard concrete types in combination with the least extensive curing method are to be selected if time and cost are of highest priority.

However, if lowest carbon emissions are most important, WS-25 can be selected for Malmö and Stockholm.

For Malmö all curing methods are applicable indicating that prevailing weather conditions during the period do not require the use of curing methods to any significant extent explaining why all three methods result in lowest CO_2-emissions. For Stockholm, the most extensive curing method (C) is needed to shield concrete against freezing. For Umeå, concrete configuration W25-S10 in combination with curing method B result in lowest carbon emissions.

Considering winter conditions, standard concrete types (WS-STD) and curing method A result in shortest duration and lowest costs for Malmö. However, this configuration is not possible for Stockholm due to early freezing. Instead several other concrete configurations (WS-STD, WS-10, W25-SSTD, and W25-S10) result in shortest duration when combined with curing methods B or C. Lowest cost is obtained for WS-10 or W25-S10 in combination with curing method B. For Umeå, standard concrete configuration (WS-STD) in combination with curing methods B or C result in shortest duration but considering lowest cost, the least extensive curing method (B) should be selected. When it comes to lowest carbon emissions, concrete configuration W25-S10 in combination with curing method B are preferable for both Malmö and Stockholm. For Umeå, this option is not possible due to risk of early freezing. Instead standard concrete configuration in combination with curing method B result in lowest emissions.

Table 10

Most favorable combination of concrete configuration and curing strategy in terms of time, cost, and carbon emissions (paper 3b).

Location	Value	Autumn CC: Concrete config. (CS: Curing strategy)	Value	Winter CC: Concrete config. (CS: Curing strategy)
Malmö				
Time (min)	1,08	CC: WS-STD (CS: A)	1,29	CC: WS-STD (CS: A)
Cost (min)	1,07	CC: WS-STD (CS: A)	1,20	CC: WS-STD (CS: A)
CO_2 (min)	0,77	CC: WS-25 (CS: A, B, C)	0,86	CC: W25-S10 (CS: B)
Stockholm				
Time (min)	1,16	CC: WS-STD (CS: A)	1,42	CC: WS-STD (CS: B, C) CC: WS-10 (CS: B, C) CC: W25-SSTD (CS: B, C) CC: W25-S10 (CS: B, C)
Cost (min)	1,12	CC: WS-STD (CS: A)	1,27	CC: WS-10 (CS: B) CC: W25-S10 (CS: B)
CO_2 (min)	0,82	CC: WS-25 (CS: C)	0,86	CC: W25-S10 (CS: B)
Umeå				
Time (min)	1,20	CC: WS-STD (CS: A)	1,42	CC: WS-STD (CS: B, C)
Cost (min)	1,15	CC: WS-STD (CS: A)	1,28	CC: WS-STD (CS: B)
CO_2 (min)	0,86	CC: W25-S10 (CS: B)	1,02	CC: WS-STD (CS: B)

The different combinations outlined in table 10 show that there is no combination that provide the best solution considering all three indicators. Obviously, there exist a contradiction between time, cost, and CO_2-optimization. Therefore, selecting an optimal option must be evaluated against project or company priorities.

Referring to RQ3, the simulation results as summarized in figures 28-32 reveal that construction duration of concrete framework is extended by 8-42% compared to if weather is not accounted for. The variations in extended duration are due to different seasons (autumn and winter) and geographical location (Malmö, Stockholm, and Umeå). The costs increase by 8-29% and are mostly referred to an extended duration (due to weather), and to a less extent due to the use of different types of concrete and curing methods.

The results also show on the positive effects of using climate-improved concrete types to reduce carbon emissions of the concrete structure. Reductions up to 23% were achieved for the simulated scenarios. Since these concrete types are more sensitive to colder weather, the results also highlight the importance of appropriate selection of curing methods to avoid issues related to early freezing and delays in formwork removal. In addition, the simulation results also reveal that extra work associated with a certain curing method is more important reason for extended duration and its implications on duration of production cycles should therefore be examined more closely.

7.4 Estimated effects of weather on concrete work task productivity (RQ4)

The fourth research question (RQ4) focuses on how practitioners estimate the influence of weather at a work task level. To address the research question, a questionnaire survey study was performed as a part of study 4. The survey was targeting site personnel in Swedish construction companies.

7.4.1 General facts about survey respondents

The questionnaire survey resulted in that 232 respondents completed the questionnaire. The respondent group consisted of individuals in construction companies with different job functions, e.g. site managers (41%), construction managers (29%), site engineers (13%), project managers (12%), foremen (4%), and other job titles (11%). Most of the stated job functions require practical knowledge of managing construction works including planning and follow-up of projects. These types of activities assume knowledge about productivity and what factors that might be of importance, e.g. weather. In addition, almost 75% of respondents stated that they have more than 10 years of experience of concrete construction and 90% have at least 5 years of experience. Obviously, the respondents as a group possess a considerable amount of experience related to concrete construction. More details about the survey are described in paper 4.

7.4.2 Importance of weather parameters on productivity

Table 11 presents the aggregated rankings (priority vectors) made by respondents of weather parameters in terms of their relative importance to concrete framework productivity. The rankings are based on pairwise comparisons for different settings of temperature, wind, and precipitation typical for Swedish summer and winter conditions. Only consistent pairwise comparisons are included (consistency ratio, CR, ≤ 0,1) (Saaty, 1990). The number of consistent comparisons underlying the rankings in table are denoted by the variable N. The values for each weather parameter represent its weight (or importance) in relation to the other parameters, e.g. rain is ranked as the most important (0.38) weather parameter for concrete productivity during summer conditions. Another way to express this relation is to determine the relative importance of parameters by dividing each parameters value with the value of the lowest ranked parameter. The relative importance of parameters is given by the numerical values in brackets in table 11.

Apparently, the respondents rank rain as the most important weather parameter influencing productivity of concrete frameworks during summer conditions whereas temperature is ranked as least important. Similar rankings apply also during winter conditions where snowfall is ranked as most important, followed by wind and finally temperature.

Table 11

Aggregated priority vectors based on pairwise comparisons with consistency ratio (CR) ≤ 0.1. Priority vectors are valid for summer and winter conditions (paper 4).

	Aggregated priority vectors (CR≤0.1)	
Weather factor	**Summer condition N=178**	**Winter condition N=175**
High/low temperature[7]	0.30 (1.00)	0.29 (1.00)
Rain/snow[8]	0.38 (1.27)	0.40 (1.38)
Wind[9]	0.32 (1.07)	0.31 (1.07)

The relative rankings indicate that rain is ranked 1.27 times, and snow 1.38 times, more important than temperature. Wind is ranked 1.07 times more important than temperature for both summer and winter conditions. These findings are in contrast with previous studies (e.g. Moselhi & Kahn, 2012) where temperature was found to be most important, followed by wind and precipitation. The results presented in table 11 suggest that precipitation should be given more attention. However, bear in mind that the rankings are influenced by the actual values used to describe each weather conditions and the type of construction method considered. This could explain differences in rankings between different studies.

However, the rankings in table 11 do not reveal any details about the effects of weather in terms of reduced productivity. The respondents were therefore asked to

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[7] Summer: Temperature = +25 °C; Winter: Temperature ≤ 0 °C

[8] Summer: Rain = 10 mm during 8 hours; Winter: Snow = 8 cm during 8 hours

[9] Wind speed between 10 and 14 m/s

estimate the loss in productivity for different work tasks due to specific weather conditions.

7.4.3 Estimated effects on productivity due to wind

Estimated maximum wind speeds when different lifting operations are cancelled for safety reasons are presented in figure 34. As seen, there is a relatively large span in maximum wind speed where a majority of estimations are between 13-19 m/s regardless of type of lifting operation. About 80-85% of respondents state that lifting operations are cancelled a wind speed above 19 m/s. A closer look indicates that lifting of wall formwork, table forms, and frame finishing material (e.g. windows) are more sensitive to wind compared to lifting heavier objects, e.g. precast element or a skip filled with concrete. For example, 45-50% of respondents estimate that lifting of wall panels, table forms, and frame finishing materials are cancelled at wind speeds above 15 m/s. At the same wind speed, only 35% of respondents estimate that lifting of precast elements or pouring concrete are cancelled. It seems reasonable given the differences in lifting objects sensitivity to wind conditions, e.g. large light-weight form panels against heavy precast units.

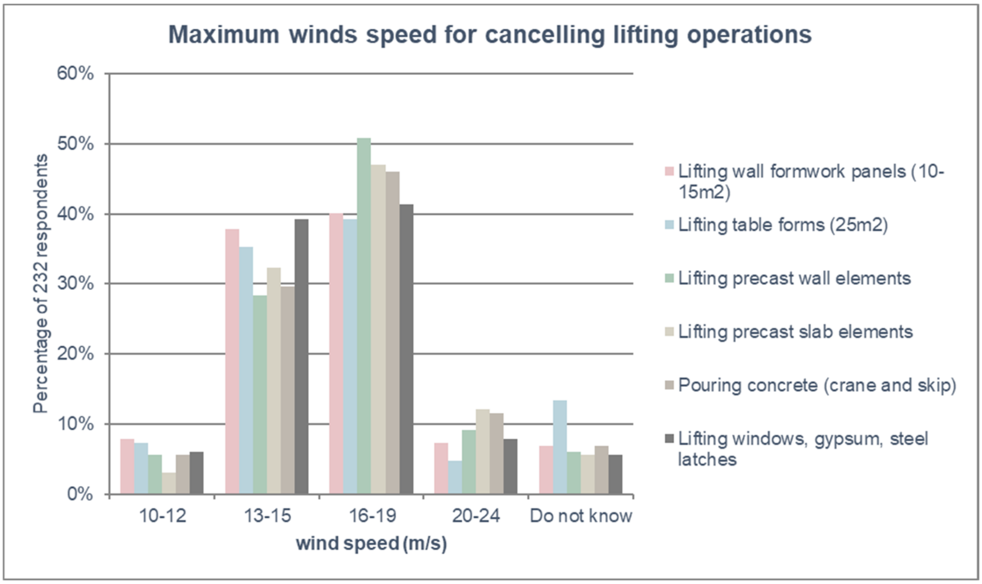

Figure 34
Estimated maximum wind speed for cancelling lifting operations (paper 4).

7.4.4 Effects of rain on work task productivity

The effects of rain on work task productivity depends on its intensity, e.g. light or heavy rain. Figure 35 presents the estimated loss in productivity for different types of work due to light rain. In general, light rain seems to have a limited effect regardless of type of work considered.

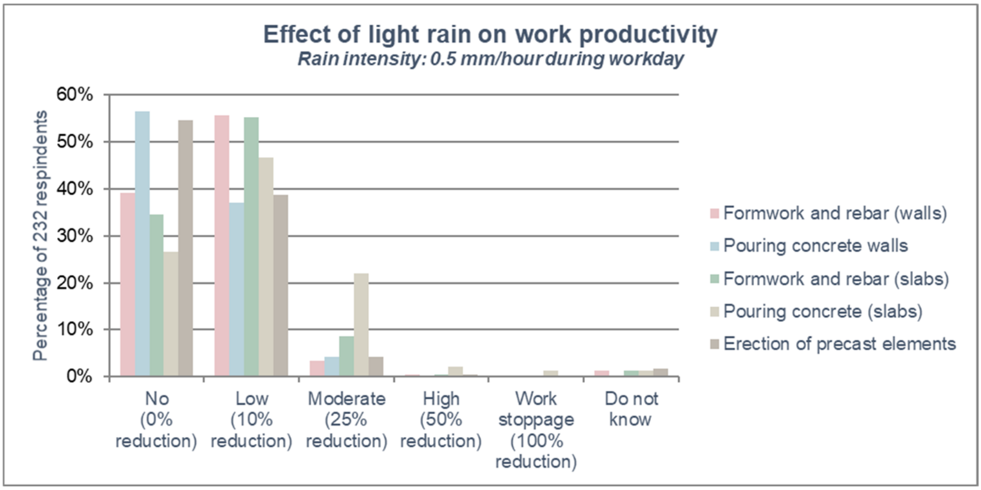

Figure 35
Estimated loss in productivity for different work tasks due to light rain (paper 4).

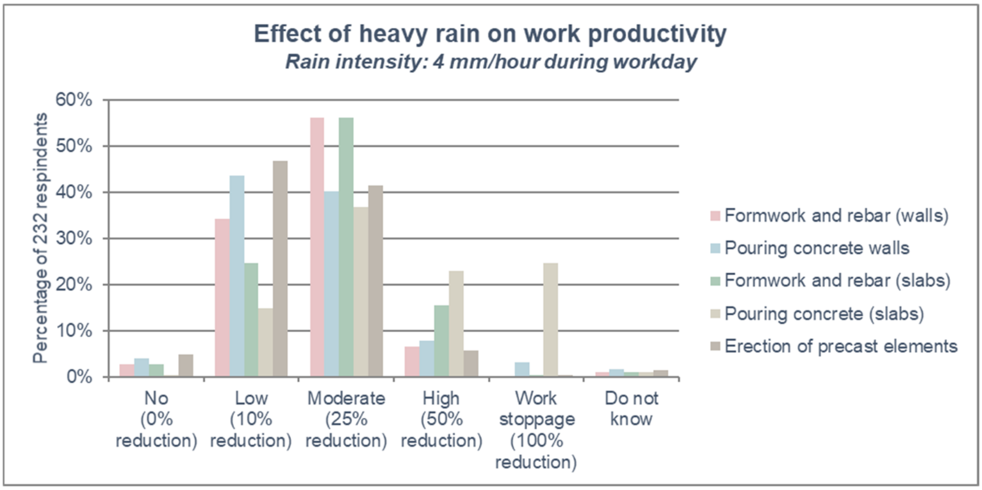

Figure 36
Estimated loss in productivity for different work tasks due to heavy rain (paper 4).

A majority of respondents estimate either zero or a 10% reduction in productivity. However, pouring of concrete slabs seem to be a little bit more affected where about 20% of respondents estimate a 25% reduction. As expected, the reduction in productivity increases with increasing intensity of rainfall.

Figure 36 shows the estimated reduction in productivity due to a heavy rain. Under these conditions, most respondents estimate losses in the range 10-25%. However, about 15% of respondents state a 50% reduction for formwork and rebar operations performed on floor slabs. In addition, pouring of concrete slabs is even more affected where 25% of respondents estimate a 100% reduction equal to work stoppage. The results indicate that work tasks performed on horizontal areas, e.g. on a floor slab, are more sensitive to heavy rain compared with tasks that are performed vertically, e.g. on concrete walls.

7.4.5 Effects of snow on work task productivity

The estimated effects of light snowfall on productivity losses are presented in figure 37. A majority of respondents estimate 10% reduction in productivity. However, more respondents estimate a higher (25%) reduction compared to light rain. It is also here more obvious that certain tasks are more sensitive to snowfall compared to rain, e.g. formwork and rebar operations on floor slab. Indeed, a snowfall on a reinforced floor slab may require substantial efforts to remove snow from the work area.

Considering heavy snowfall, estimated loss in productivity is in the range 10-50% for work tasks performed on concrete walls and erection of precast panels (figure 38). Estimated loss for formwork, rebar, and concrete operations performed horizontally (on floors) are in the range 25-100%. Apparently, heavy snowfall accentuates that different types of work are affected differently. It should 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 pouring concrete must be cancelled at this weather condition.

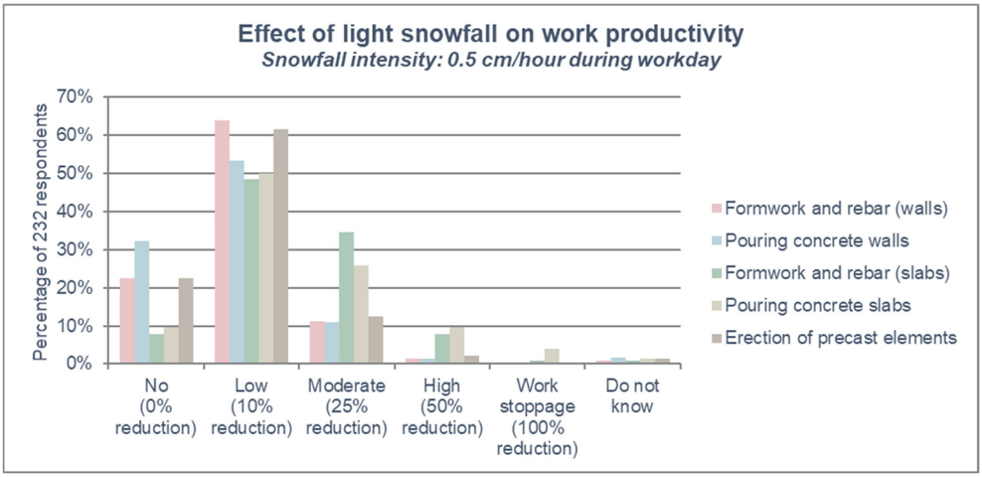

Figure 37
Estimated loss in productivity for different work tasks due to light snowfall (paper 4).

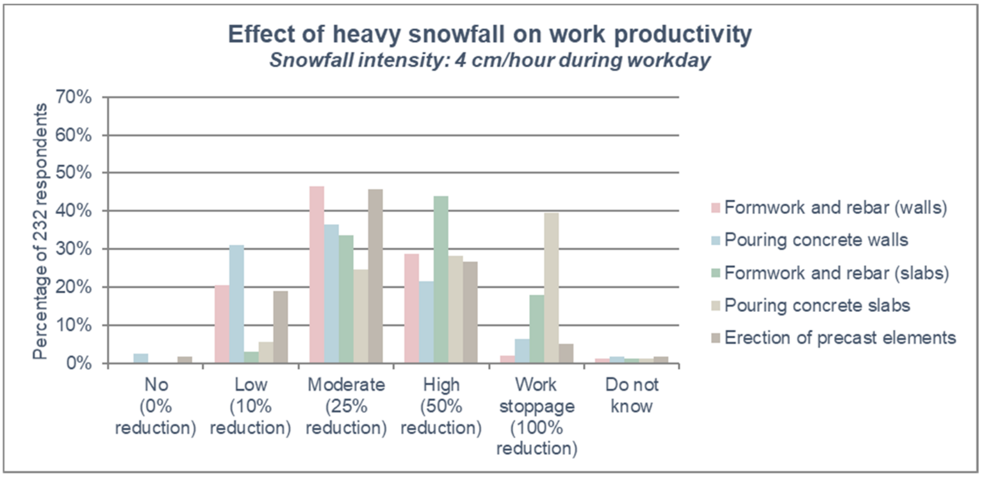

Figure 38
Estimated loss in productivity for different work tasks due to heavy snowfall (paper 4).

7.4.6 Effects of temperature

The estimated loss in productivity due to low temperature (-10 °C) is given in figure 39. Almost 80% of respondents estimate either a low or a moderate loss in productivity for formwork and rebar operations. The loss in productivity for pouring concrete walls are estimated to be higher compared with formwork and rebar operations. Once again, pouring of concrete slab is estimated to be affected the most.

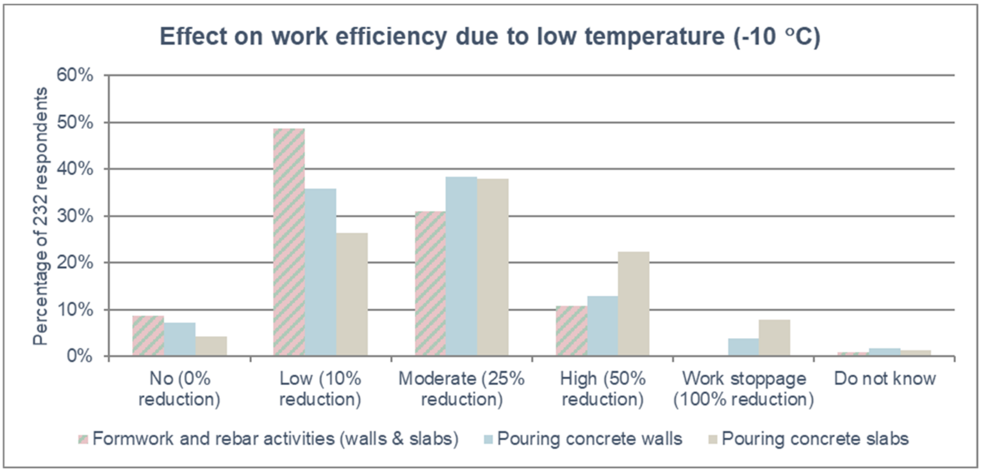

Figure 39
Estimated loss in productivity for different work tasks due to low temperature (paper 4).

The results clearly show on the difference in how work types are affected, e.g. concrete operations are more affected in cold temperature conditions compared to formwork and rebar works.

The effect of high temperature (+25 °C) is presented in figure 40. In general, the loss in productivity is either zero or low for all work tasks. Comparing with estimations in figure 39, it is obvious that high temperature has a more limited impact on productivity compared to cold temperature.

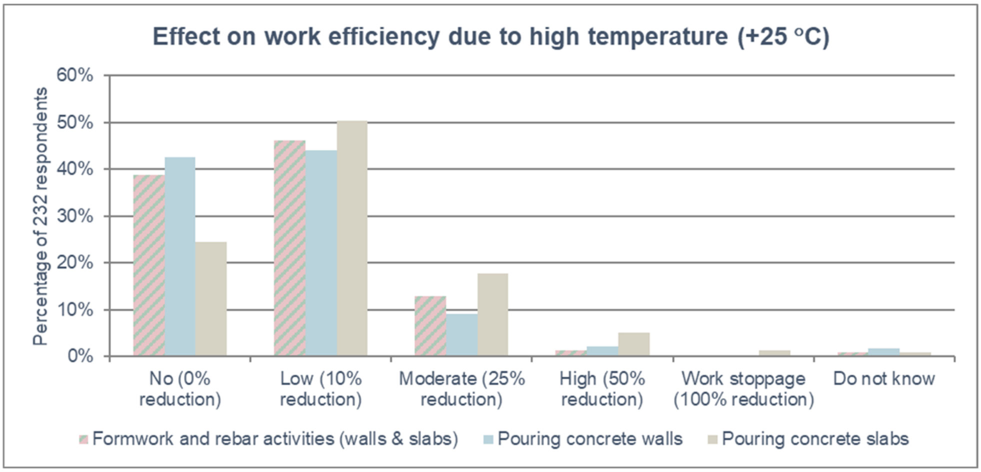

Figure 40
Estimated loss in productivity for different work tasks due to high temperature (paper 4).

Again, pouring concrete slabs are estimated to suffer somewhat higher losses compared to other works, but the difference is not as clear as was the case with low temperature.

Referring to RQ4, the estimated effects of weather on work task's productivity is strongly dependent on type of weather parameter, the intensity of weather parameter, and the type of work considered. For instance, light rain (or snow) result in minor reductions (up to 10%) whereas heavy rain or snow may result in reduction in the range of 25-100%. Cold temperature (-10 °C) is estimated to suffer losses in the range 10-50% depending on type of work whereas reductions at a hot temperature (+25 °C) is generally estimated to be less than 10%. The estimated maximum wind speed for cancelling lifting operations are in the range of 13-19 m/s. The results reveal somewhat different threshold values depending on type of lifting operation.

The pairwise comparisons show that precipitation is generally ranked as most important and temperature as least important for both summer and winter conditions. Wind is ranked as slightly more important than temperature.

8 Contributions and future research

In this chapter, scientific and managerial contributions of the dissertation are described. Thereafter, research limitations are addressed. Finally, suggestions on future research are presented.

8.1 Scientific contributions

8.1.1 DES as a tool to analyse resource usage in on-site concrete production systems

Referring to the complexity of the on-site production process (factor 1), this research contributes with a simulation-based approach facilitating a systematic analysis of the workflow specifically addressing the use of shared resources.

To enable analysis of resource usage during erection of on-site concrete frameworks more realistically, the description of the workflow and the interaction with resources must be sufficiently detailed. Compared to previous attempts to model and simulate on-site concrete production methods (e.g. Huang et al., 2004; Wang et al., 2014), this research suggest that the process description underlying a simulation model must be made more comprehensive, but also more detailed.

For instance, at an overall level it must consider the division of workflow into pour units to reflect that work are being executed in parallel competing for the same type of scarce resources. At a more detailed level, the workflow description must consider primary works (e.g. rebar and concrete operations), but also temporary works such as handling of falsework and formwork. Temporary works are an integrated part of the production cycle consuming resources in terms of labor and crane resources. It is also important to explicitly describe all resources required by primary and temporary works to capture the dynamic interactions between tasks and resources.

In addition, since the production method is dependent on concrete strength development to enable removal of formwork, also material-related processes such as concrete curing must be included. The time needed for concrete to gain sufficient strength is important as it determines the speed of the production cycles but also since it defines the timing of allocation of labor and crane resources needed to transfer formwork from one work location to another.

Moreover, connecting works that forms a part of the production cycle of the concrete framework should also be considered, e.g. installing prefabricated components or placing technical installation systems. Neglecting the influence of connecting works may result in wrong conclusions regarding estimated production cycles or the need for common resources, e.g. crane assistance.

Indeed, a detailed description of the workflow enhances the possibilities to study the interactions between tasks and resources. In this way, a specific design of the workflow can be analyzed more realistically accounting for the availability of critical resources such as labor and cranes. This address the challenge of on-site concrete production as discussed in chapter 2 where allocation of a restricted number of workers and crane resources must be considered when planning production cycles. This is also applicable for many other construction-related production systems. In fact, the design of a production system is closely integrated with understanding of how to allocate available resources effectively. Referring to chapter 3 (table 1), the simulation-based approach as suggested in this research (paper 1) addresses many of the factors that are pointed out in previous research as important for on-site productivity. For instance, the workflow becomes dependent on status of connecting works and availability of labor and crane resources.

The suggested simulation-based approach can also be expanded to include other resources needed to perform a work task, e.g. availability of materials, instructions etc. In this way, discrete-event simulation could provide a systematic method to study the effects of the seven preconditions on on-site construction workflows as stated by Koskela (1999). Preconditions could be analyzed separately or combined to identify which factor that influence the overall production system the most.

Another contribution is the use of four different simulation metrics to analyze a specific setup of resources for a given production method. In this research, common indicators such as time and cost are combined with indicators as suggested by Sadeghi et al. (2015), namely waiting times and resource utilization. As described in chapter 4, there are not many examples where all these indicators are combined to analyze construction systems. Therefore, this research provides new insights aiming to fill existing gap. Waiting time statistics were found to be a valuable indicator to identify location of bottlenecks due to resource allocation conflicts. In addition, statistics on resource usage provided useful information to identify highly utilized resources that could explain the occurrence of bottlenecks. By combining data on waiting time and resource utilization, reasons for the existence of bottlenecks could be identified and possible solutions to resolve these could be formulated, tested, and evaluated. Waiting times and resource utilization are rarely used as performance indicators in the traditional construction industry. They can also be difficult to measure since it not always obvious why a work task is not initiated. Resources waiting for other resources (e.g. workers waiting for crane assistance) on the job site can be a symptom of a resource allocation conflict, and a practical way to measure waiting times. However, other factors may be responsible for the presence of waiting times. Consequently, both simulated waiting times and resource utilization factors should be considered as theoretical values and used as indicators of how well a production setup is designed to avoid allocation conflicts and maximize the use of resources. However, to avoid sub-optimizations, it is recommended to use all four indicators when evaluating a production setup since these indicators are to some extent interdependent. For example, waiting times can be eliminated by adding more of the limiting resources which may have a positive effect on project duration, but not necessarily on resource utilization and total cost.

This research also contributes with knowledge about how to use discrete event simulation to perform systematic analysis of different production configurations considering implications on time, cost, waiting times, and resource usage. In addition, this research also contributes with new knowledge to a frequently addressed problem in previous research (e.g. AbouRizk & Shi, 1994; Cheng et al., 2005), namely allocation of resources to work tasks to optimize performance of construction. The simulation-based approach enables systematic analysis of a large number of different resource allocation combinations. The simulation software's in-built capability enabled an automized procedure where more than 4 000 resource allocation combinations were simulated in less than one hour. As part of this, this research also highlights the positive benefits of increasing the flexibility in workforce by adopting multiskilled workers as suggested by Haas, Rodriguez, Glover and Goodrum (2001).

On a methodological level, this research contributes with insights regarding documentation and conceptual modelling of construction methods to enable implementation in a discrete-event simulation system. Any real-world system is characterized by complexity due to many parallel workflows, dynamic behavior, and sequencing of workflows based on current state of the system variables. In this research it was found that the IDEF3-method (Mayer et al., 1995) has capabilities to describe process complexity in a structured and consistent way. The method offers a set of construct elements to describe a workflow in terms of individual tasks and their dependencies, sequencing and timing of tasks, various types of constraints acting on tasks, branching and merging of sub-processes based on a logical operation or based on present state of system variable(s) etc.

This research also addresses methods to collect necessary process knowledge and required data to develop a simulation model. In this research multiple methods were combined, e.g. time studies, activity sampling, site observations, interviews of site personnel, and review of project documents. It was found that no single data collection method could provide all data required. Instead, multiple methods should be combined to obtain sufficient process knowledge and data needed for model development and validation to perform simulation experiments.

8.1.2 Modelling effects of weather in discrete-event simulation

This thesis contributes by proposing a simulation-based framework to study the effects of weather on concrete frameworks addressing influence factor 2 according to section 1.1. An initial version of the framework is presented in paper 2. This framework is then further developed into a more comprehensive version as presented in paper 3b and also illustrated in figure 22. In contrast to previous attempts (e.g. Ballesteros-Perez et al., 2015; Jung et al., 2016; Moselhi & Kahn, 2010) the simulation-based framework as described in paper 3b provides a more holistic approach by considering effects of weather on both work task productivity and concrete curing. This is achieved by combining existing knowledge from two separate research domains, namely construction management and material science.

As part of the framework, this research contributes with an overall procedure (figure 25) to account for weather in a discrete-event simulation by combing research ideas from different sources. For example, the concept of baseline productivity as proposed by Thomas and Završki (1999) described in chapter 3 is used in combination with a proposed weather factor (equation 3) that combines the individual effect of the most important weather parameters.

An important part of the procedure in figure 25, is the weather-productivity relationships describing the loss in productivity as a function of intensity of a weather parameter as described in paper 2. These relationships are based on documented findings of previous research, e.g. Koehn and Brown (1985), Hassi (2002), Moselhi and Kahn (2010). In general, these relationships are valid for describing the effect on general construction works. However, the survey results as presented in chapter 7.4 (paper 4) suggest that the effects of weather cannot be generalized but should be treated separately depending on type of work task and weather factor. The need to differentiate the effects of specific weather conditions and types of work was pointed out already by Smith and Hancher (1989), and later on by McDonald (2000) and Ngyen et al. (2010). The simulation-based approach presented in this research (papers 2 and 3b) enables to implement specific weather-productivity relationships adopted to different work tasks (or group of tasks). Different thresholds for maximum allowable wind adopted to different types of lifting operations can also be defined as described in paper 2.

Considering the survey results in paper 4, it seems reasonable to distinguish effects of precipitation between work tasks performed on vertical and horizontal areas, but also between concrete operations and other work tasks such as formwork or rebar. Employing separate relationships to describe effects of temperature on concrete operations and other work tasks could also be reasonable as shown in figure 41.

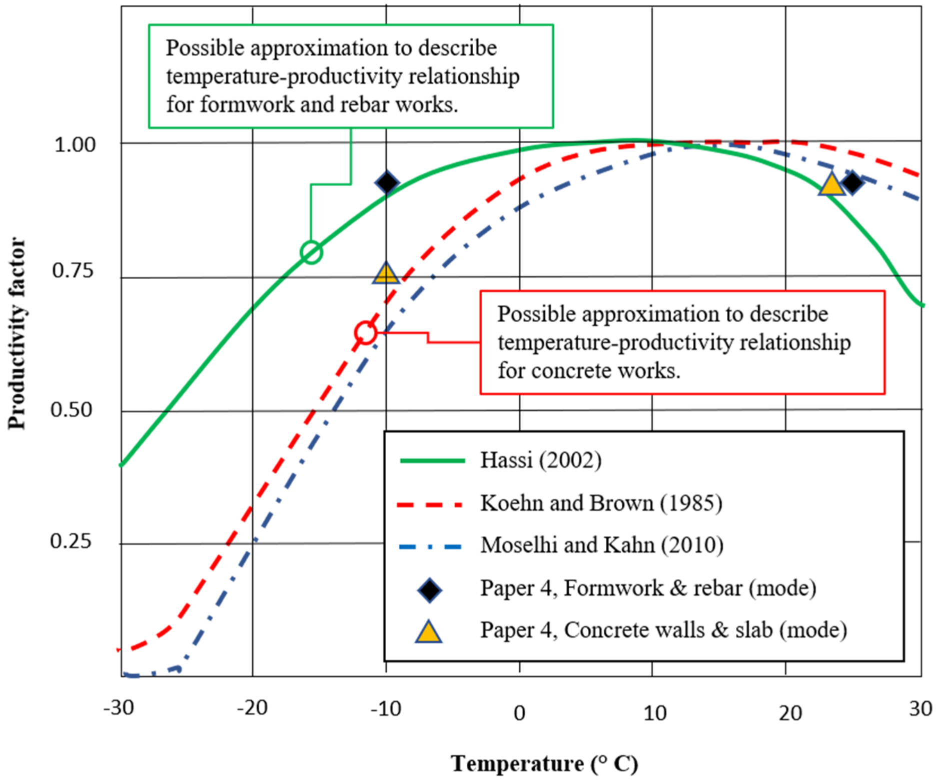

Figure 41
Effects of temperature on work task productivity based on previous studies described in paper 2, and survey results presented in paper 4.

The figure shows a comparison between effects reported in three previous studies and the most common estimations (mode) made by practitioners in the survey as described in paper 4.

Moreover, the results from the survey in paper 4 could also be used to refine the weather factor (*wf*) that determines the combined effect of temperature, wind, and precipitation according to equation 3. The proposed weather factor assumes that each weather parameter is of equal importance. This is a reasonable assumption given that the existing knowledge is limited to suggest a different priority of parameters. However, this could be adjusted by introducing a weight (*w*) to each weather parameter resulting in a modified equation 4.

$$wf = (p_{wind}(w) \times w_{wind}) \times \left(p_{temp}(t) \times w_{temp}\right) \times \left(p_{prec}(p) \times w_{prec}\right) \qquad (4)$$

Each weight could be determined by the priority vector derived from objective ranking methods such as pairwise comparisons as described in paper 4. For example, the pairwise comparisons of weather factors presented in table 11 suggest that precipitation (rain or snow) should be given the highest weight (priority), followed by wind and then temperature. However, since the rankings described in table 11 are based on a limited set of weather types, it is suggested to perform additional studies covering a broader set of weather conditions.

As a part of the simulation-based framework, this research also contributes with an algorithm to dynamically account for the effect of weather conditions on concrete curing in discrete-event simulation. More specifically, the algorithm determines when formwork can be removed for different combinations of concrete types and curing methods under varying weather. The algorithm responds to the need to consider effects of weather also on concrete curing as described in chapter 2.

In addition, the proposed simulation-based framework also dynamically accounts for the need of extra work associated with a certain curing method based on current weather conditions. In this way, the proposed simulation-based framework facilitates a more comprehensive analysis of the implications of weather on concrete production cycles by considering effects on formwork removal and additional works necessary to shield the concrete curing process.

In overall, it is believed that this research extend existing knowledge about how discrete-event modelling and simulation can facilitate a systematic analysis of weather conditions on concrete production methods. The model enables to improve the understanding of how weather conditions influence the overall production by considering the multiple effects related to physical work tasks, resources, and concrete curing.

8.1.3 Impact of weather on concrete construction productivity

This research also contributes with knowledge about how weather conditions affect a production method at different levels by employing different research methods. For instance, the simulation-based approach as described in papers 2, 3a, and 3b contributes with knowledge about how varying weather influence the workflow of concrete construction at a system level. As part of this, paper 3b also address implications of employing climate-improved concrete on construction time, cost, and CO_2-emissions. At a detailed level, paper 4 contributes with knowledge regarding how practitioners estimate the influence of weather on productivity for typical concrete-related work tasks. Again, this corresponds to influencing factor 2 and 3 (chapter 1.1) and the need to account for weather conditions and the use of climate-improved concrete when planning construction projects involving in-situ concrete methods.

8.1.3.1 Effects on system level (concrete framework)

By employing a simulation-based approach, this research contributes with new insights about how different weather conditions affect concrete framework construction. The simulations as described in paper 3b also provide implications on multiple indicators (time, cost, CO_2) when using different combinations of concrete types and curing methods. Compared to previous attempts (e.g. Jung et al., 2016; Shahin et al., 2011), this research contributes with simulated effects that accounts for weather in a more comprehensive way by considering effects on both working and material-related processes.

Considering the impact of weather on construction duration, the simulation results indicate that duration is extended by 8-42% depending on where and when construction takes place, but also due to the type of concrete and curing methods employed. In general, warmer weather conditions means a less impact on work task productivity and concrete curing. In contrast, colder weather means lower work task productivity, but also lower productivity due to effects on concrete curing. This means that construction duration is more affected during winter periods compared to other seasons. In addition, construction projects that takes place in the northern parts of Sweden (normally experiencing colder weather), are more affected compared to projects taken place in the southern areas. The simulated relative effects of weather during the winter period (up to 42%) are in accordance with previous experiences based on follow-ups of construction projects in the Nordic countries (Larsson & Söderlind, 2006). However, the results presented in this research are also in accordance with documented results from other geographical regions reporting a 35% increase in project duration due to winter conditions (Thomas et. al., 1999).

Employing a simulation approach also revealed interesting insights about the effects of weather on the modelled system. For instance, the need for extra works associated with a certain curing strategy can be an important reason for an extended duration during periods with colder weather (e.g. winter). However, this is dependent on how extra protective works are integrated in the primary production cycle and the inherent capacity of the workflow to avoid extended duration due to additional works.

Moreover, curing measures employed to avoid early freezing of concrete slabs resulted in rapid development of concrete strength and by that enabling for significant reductions of floor cycles. However, this assume that the rate of the overall working process is synchronized with the rate of the concrete curing process. Therefore, another contribution of this research is the idea of time buffers as a measure of how well certain concrete types and curing methods are adopted to meet the desired duration of floor (or wall) cycles.

The simulated results also highlight the need to adopt a certain degree of flexibility when designing an appropriate curing strategy. Since construction duration of a framework is ongoing for several months, the long-term changes in weather must also be accounted for. For example, starting construction in October means that the final works will be executed during the winter period, but also in more severe conditions due to the higher working altitude. Obviously, the cooling effect at elevated floor levels is higher compared with the ground level. In overall, this highlights the importance to explicitly consider implications of winter preparations associated with a particular curing method.

The simulations also contribute with important insights describing the possibilities to employ climate-improved concrete in different weather conditions. The simulation results indicate that the use of climate-improved concrete has a great potential to reduce CO_2-emissions. However, prevailing weather conditions given by the project location and season for construction may limit the possibilities to obtain desired reductions. In general, warmer weather conditions means that the use of climate-improved concrete can be used to a higher extent without the need for extensive curing measures. This is reflected in the simulations where the highest reduction (23%) was obtained for the most southern located site (Malmö) during the autumn season. In cold weather, the use of climate-improved requires more extensive curing methods to protect concrete curing against undesirable cooling effects. Curing methods also contribute to carbon emissions but the simulation results indicate that these are of minor importance compared to emissions related to the use of concrete. This means that employment of curing methods during periods with cold conditions are an effective way of reducing the total emissions of a concrete framework since they enable the use of concrete types with lower carbon footprint. However, bear in mind the implications on time and cost associated with extensive curing measures. As such, the results add new insights regarding possibilities to employ climate-improved concrete in different weather conditions and what curing methods that are needed. This knowledge is important for the industry's ambition to reduce overall carbon emissions of concrete structures as described in chapter 2.4 (figure 8).

The simulation-based approach also contributes with knowledge addressing implications of operational strategies by considering time, cost, and CO_2-emissions simultaneously. For instance, the simulations revealed that none of the tested combinations of concrete types and curing methods resulted in minimum values for all three indicators simultaneously. Obviously, there exists a contradiction between minimizing time, cost, and carbon emissions. Therefore, decisions on what operational strategy to employ under certain conditions must be based on company or project priorities, e.g. minimize time and cost, or minimize CO_2-emissions.

In overall, the simulation experiments support the idea of employing discrete-event simulation as a suitable method to study the impact of weather. Indeed, discrete-event modelling enables a systematic approach to describe and study the complexity associated with the dynamic behavior of both the modelled system and influencing weather parameters.

8.1.3.2 Effects on detail level (work task)

At a detailed level, this thesis contributes with new insights about how 232 practitioners estimate the influence of weather on typical concrete-related work tasks as described in paper 4 (figures 34-40). This responds to the general need to extend existing knowledge describing the relationship between weather parameters and work task productivity (McDonald, 2000; Nguyen et al., 2010). The findings reveal that weather have a significant effect at a work task level. However, the effects vary considerably depending on weather type, especially for more severe weather conditions. For example, heavy precipitation (rain or snow) reduce productivity in the range of 25-100% compared to when no effects of weather are considered. The survey results also reveal that different types of works are affected differently depending on type of weather factor. Work tasks performed on floor slabs are more sensitive to precipitation than work performed on concrete walls. Moreover, on-site handling of precast elements is generally also less sensitive to weather compared to other concrete-related tasks.

Figure 42 shows a comparison between results presented in figures 35-38 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 figures 35-38 are included.

The estimated effects in this study show both similarities and differences compared to previous research. For example, Noreng (2005), Thomas and Ellis (2009), and Moselhi and Kahn (2010), 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 paper 4 indicating only a 0-10% reduction for a light rain or a light snowfall. The effects of heavy precipitation have been reported in previous studied to be in the range 50-100%. In this study, the estimated 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 e.g. Noreng (2005).

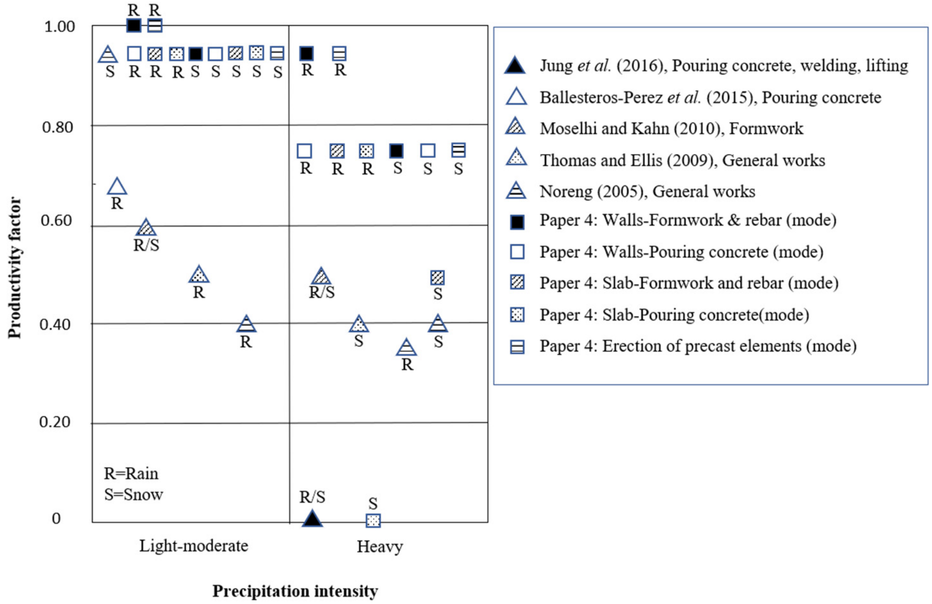

Figure 42
Effects of precipitation on productivity based on previous studies and present survey results (paper 4).

The estimated effects of high and low temperatures are partly in line with reported effects in previous research, e.g. Koehn and Brown (1985), Hassi (2002), Moselhi and Kahn (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 of type of work. Estimated losses reported in previous research are in the range 0-15% at the same temperature. The differences between the findings in paper 4 and previous studies can be explained by the fact that different work tasks have been considered. The findings in paper 4 have 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 adopt to the climatic conditions where they live. People living in the Nordic countries are obviously more adopted to cold weather compared to people living in, e.g., the south European countries. Moreover, construction methods and practices are continuously adopted to face the challenges of weather representative for a specific geographical region.

This research also contributes with knowledge about the effects of wind speed on lifting operations. As shown in figure 34, the estimated maximum wind speed for cancelling lifting operations are in the range of 13-19 m/s. The results indicate a lack of common knowledge regarding more precise threshold values for when lifting operations should be avoided. This is interesting since 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 light-weight objects (e.g. wall form panels) are estimated to be cancelled at lower wind speed compared to heavy objects such as precast elements. The results are interesting considering the effects on production cycles involving many lifting operations such as construction of concrete walls as studied in paper 2. Here, it was found that depending on the selection of threshold value for cancelling a lifting operation increases the duration of construction walls by 14% for a six-story building and by 32% for a 10-story building.

Considering both the simulation approach and the survey results (e.g. paper 2 versus paper 4), it can be concluded that both the unit of analysis and the time perspective matters when it comes to study the relative effects of weather. For example, the survey results indicate that heavy precipitation is estimated to result in highest impact on productivity at a work task level. However, simulations of concrete wall production considering long term effects of weather (paper 2), it was found that temperature was the single most important weather parameter for extended duration. This can be explained by that temperature varies continuously during simulation and more often affects productivity than precipitation which is a discrete variable characterized by an “on-off” kind of behavior. As a result, the effect of precipitation becomes more random. When simulating the effects of weather over longer time-periods, the overall effect of precipitation on project duration decreases. However, on a short term, the effects of heavy precipitation or strong winds may have a serious effect on work tasks. This is reflected in the survey results where higher losses are estimated for a heavy snowfall. However, the simulation approach also considers the timing aspect, i.e. how often a heavy snowfall may occur in connection to pouring a concrete slab. In contrast, temperature is always present explaining why it becomes more important when considering effects on long term perspective. Obviously, this reasoning is for and most valid for regions with similar climate conditions as Sweden. In other regions that have periods with constantly high precipitation, the single effect of this weather parameter may be most important.

8.2 Managerial contributions

8.2.1 Design and planning of concrete operations using discrete-event simulation

As a practical contribution, this section describes a novel approach of how discrete-event simulation can facilitate the design, analysis, and planning of concrete-related production systems. It concerns analysis of a specific production setup, weather conditions, and implications of employing climate-improved concrete types. Accordingly, this novel approach responds to influencing factors 1, 2 and 3 described in chapter 1.1.

The use of the model is discussed at a strategic level and an operational level as illustrated in figure 43. It is believed that the simulation modelling techniques can be a valuable tool in a construction company's toolbox to support their continuous improvement of different production methods. However, since discrete-event simulation is still relatively unknown in the construction industry, simulation specialists need to be involved to support building, validation, and operation of simulation models.

8.2.2 Strategic level

At a strategic level, construction companies can use discrete-event simulation to support design and analysis of concrete-related production systems. Simulation can facilitate systematic analysis of different operational configurations considering implications on time, cost, resource usage, and CO_2-emissions. Different models can be developed responding to typical construction methods such as in-situ concrete, prefabricated, or hybrid solutions.

The first step (in the strategic level in figure 43) involves description of the production system in a discrete-event simulation model. The inputs needed are process descriptions at a detailed level stating all essential work tasks and their dependencies as well as descriptions of how resources are used during production phase. The simulation model is validated by involving both simulation experts and experts on the production system. To facilitate validation process, simple graphical techniques are suggested in the early phase to discuss important aspect of the modelled system. Moreover, simulated input and output variables are also compared with data collected from the real system. In this research it was found that using lead times of production cycles at different levels are appropriate variables to use for validation purpose.

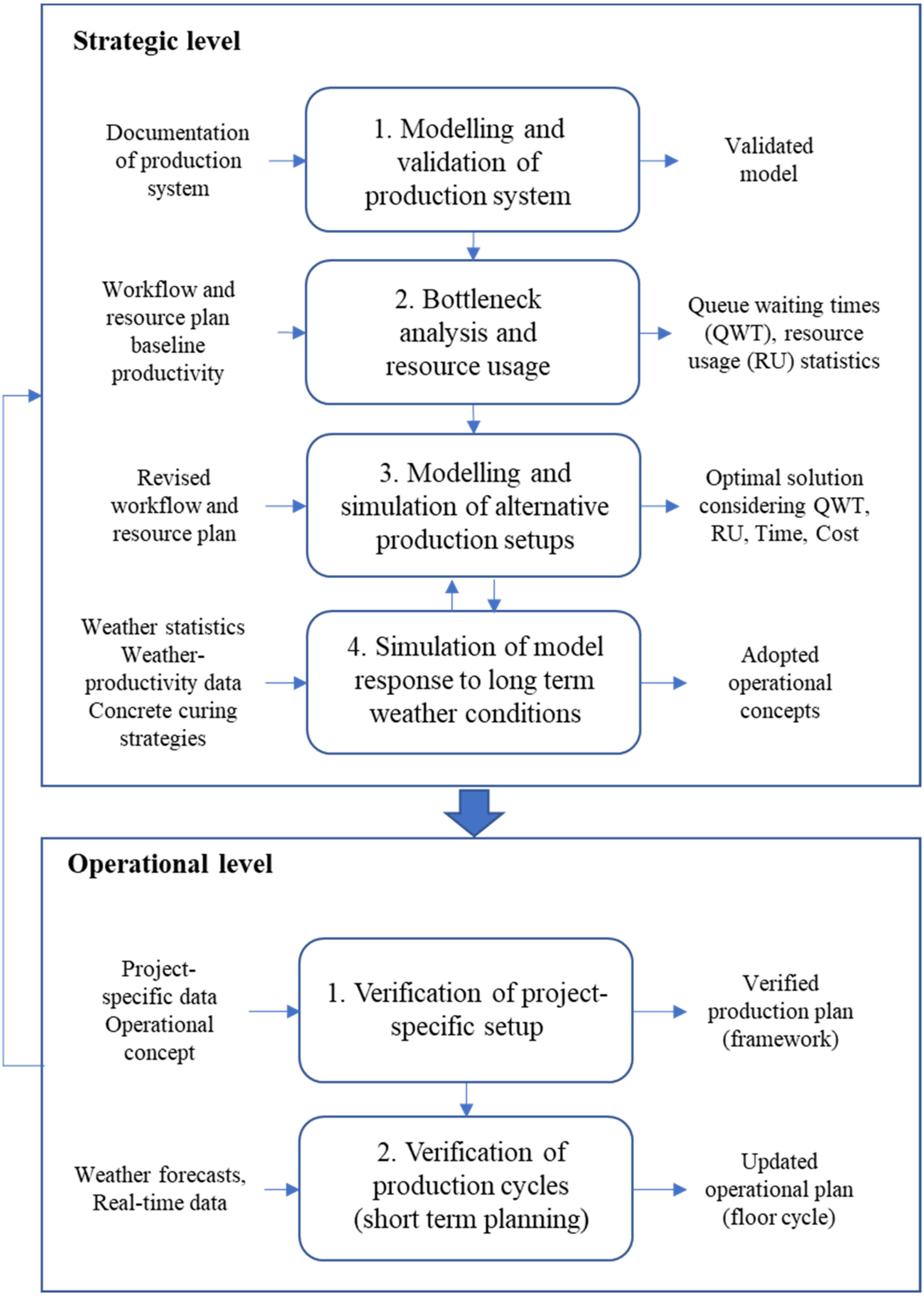

Figure 43
Novel framework for employing discrete-event simulation to analyze concrete-related production systems and factors that impact system performance.

In the next step (2), the workflow is configured so that no intermediate time buffers exist between tasks. Allocation of resources to work tasks are also implemented in the model according to a desired resource plan. At this stage, the idea is to design a workflow that reflects ideal conditions without any type of disturbances. To support this idea, it is also suggested to use baseline productivity data to reflect optimal performance of work tasks. Thereafter, the use of resources and the existence of bottlenecks due to resource allocation conflicts can be analyzed using model statistics on queue waiting time (QWT) and resource usage (RU). This information is then used to identify reasons for the existence of bottlenecks and alternative production setups are formulated to reduce or eliminate identified bottlenecks.

In step 3, formulated alternative production setups are simulated to identify the best possible option. To avoid risk of sub-optimization, multiple model output indicators can be used to facilitate evaluation, e.g. time, cost, QWT, and RU. Analysis of different configurations can be automated by enabling the simulation model to systematically alter model variables between each simulation run. For example, a large number of combinations of allocation of resources can be systematically studied in an effective way as described in paper 1.

So far, the design of the system reflects ideal conditions not affected by any external disturbances. Therefore, the next step (4) aims to study the response (or sensitivity) of the modelled system to different types of disturbances. Considering concrete-related production systems, weather is an important external factor that may significantly influence its performance. The influence of different weather conditions can be studied by using statistical weather data and weather-productivity relationships as described in paper 2. Moreover, strategies for the use of different concrete types and curing methods can also be tested as described in paper 3b. The simulation model enables to systematically study implications on time, cost and CO_2-emissions for different weather conditions, and combinations of different concrete types and curing methods. In this way, operational concepts can be studied involving the use of different levels of climate-improved concrete adopted to weather conditions typical for a certain geographic area and season. The operational concepts could contain different options depending on the priority in a project, e.g. minimize time, cost, or carbon-emission. If the modelled system involves the use of temporary formwork systems (e.g. table forms), time buffer statistics can be used to evaluate the synchronization between working process and concrete curing. The goal is to minimize time buffers as much as possible without affecting overall time or cost. This could be done by changing the overall working process or changing the combination of concrete and curing methods as indicated by the loopback to previous step in figure 43.

8.2.3 Operational level

The simulation model can also facilitate operational planning with a short-term perspective. However, it assumes that the actual production system is part of a company’s operational concept and already defined in a simulation model. In the first step (in the strategic level in figure 43), the simulation model may have to be adopted to project specific conditions. For instance, it could concern simulation of the production system with project-specific data regarding resources, productivity data, weather conditions reflecting the actual season and location of the project. The aim is to verify that the configuration of the production system is adopted to actual conditions and that project-specific requirements on time, cost, and carbon emissions are fulfilled.

During execution of construction (step 2), the model can be used to update production plans on a short term, e.g. by using weather forecasts for the next days or weeks. For example, the model can simulate the effects of weather on the duration of the next floor cycle. Real-time capturing of process data including the use of concrete sensor technology can also update the model status. However, the model needs to be more user-friendly, e.g. by enabling automatic import of input data, to be useful as an operational planning tool. Data captured at an operational level (e.g. by various sensors) can also be used as inputs at a strategic level to validate and refine model variables. This is indicated by the loopback arrow from operational to the strategic level.

8.3 Research limitations

8.3.1 Simulation model for systematic analysis of resource usage

The model is limited to include main activities for the concrete framework erection process. However, there are other operations that could influence the construction workflow of the concrete framework which are not included in the model. For instance, on-site logistic operations are not explicitly modelled, e.g. the handling of material from delivery to temporary storage areas and further on to final working areas. In the model, only lifting operations from storage area to final working area were modelled explicitly.

Another limitation is that the waiting times reported from queue blocks are only a result of workflow sequencing and the availability of workers and cranes. The availability of other resources (e.g. materials) is assumed not to influence the workflow in general and queue waiting times in particular. To further improve the model´s capability to reflect the behavior of a real production system, the availability of materials (and other resources) has to be described and implemented in the model.

Finally, only deterministic input variables have been used when running simulation experiments. To study the response of the system when exposed to uncertainty, stochastic data can be used as input variables. However, using stochastic data to describe variability requires a large amount of historical or real-time process data which is difficult and requires a lot of resources to obtain. However, automatized data capturing techniques as discussed in e.g. Taneja et al. (2011), could be a solution to overcome these problems.

8.3.2 Modelling and simulation of the impact of weather

The simulation model is valid to describe the effects of weather on the construction of on-site concrete frameworks. However, the model structure can be modified to describe other types of production methods. The model considers effects on work task productivity and concrete curing process. Other important aspects such as effects of weather and concrete types on drying-out of concrete floors to enable flooring activities has not been considered in the model.

The simulated effects of weather are based on data sets valid for Swedish climate conditions. However, using climatic data representative for other geographical regions, the effect of weather can be studied in similar way.

The results are also dependent on underlying relationships between weather parameters and work task productivity. If possible, these relationships should always be evaluated against own figures or personal experiences. The survey results presented in paper 4 could also support a review of existing relationships.

The formwork removal times used as input to the simulation model are only valid for a concrete wall and slab structure with specific geometry and dimensions. In addition, the simulated formwork removal times are valid for generic concrete types that are available in the PPB simulation tool. However, it is easy to feed the model with simulated formwork removal times valid for other concrete structures containing other concrete mixtures.

The simulated scenarios involving climate-improved concrete are based on a few combinations of generic concrete types with different carbon footprints. Indeed, it is possible to use concrete mixtures that contains even less Portland clinker enabling further reductions in carbon emissions. For this purpose, as also pointed out by Brooks, Schindler and Barnes (2007), having access to maturity properties for specific concrete mixtures may improve accuracy in predictions of formwork removal times and the risk of early freezing. Moreover, it is suggested to test more extensive curing measures as were studied here, to enable the use of climate-improved concrete mixtures also during colder periods and regardless of geographical location.

It should also be mentioned that the risk of freezing is based on simulations using the PPB tool. The PPB simulation tool reports problems due to early freezing even if it only concerns a very limited part of a concrete structure. No specific evaluation has been made concerning the extent of early freezing as it occurs in a PBB simulation prior to incorporating the result in the database connected to the DES-model. This approach may have resulted in rejection of a specific combination of concrete types and curing methods that in practice would have been considered as applicable.

Moreover, the use of wireless sensor systems to monitor concrete temperatures and strength development are important tools to enable an effective and safe removal of formwork (Alizadeh, 2019). In addition, sensor measurements can also be used to validate special-purpose simulation tools for making predictions of concrete strength, but also for validating temperature and strength development of new concrete mixtures. However, as pointed out in paper 3b, isolated sensor measurements are not enough for validation purpose. They should also be supplemented with additional information describing the contextual conditions of measurements, such as geometries of concrete structure, concrete mixture, type of curing measures, position of sensor nodes etc.

8.3.3 Estimation of the impact of weather on productivity

The estimated loss in work task productivity as well as rating of weather factors are 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 since 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.

8.4 Future research

In general, the simulation models and the results presented in this research need to be further validated by performing additional studies where simulation outputs are compared with reality, e.g. simulated time versus actual construction time. Future work should also focus on data capturing techniques to facilitate collection of model input and output variables. In future, simulation models should be continuously fed with real-time information to perform updated simulations of a production system's performance.

Considering the impact of weather, future work should be directed to increase the empirical base for establishing relationships between productivity and weather. Developing relationships (or thresholds) which are specific for a certain work task (or group of tasks) would make future estimations of weather even more precise. For this purpose, the concept of baseline theory can be employed. Indeed, this requires substantial amount of data to be collected, e.g. productivity data reflecting ideal conditions (baseline) combined with estimations of the single effect of weather on productivity. The latter can be collected by either performing structured survey studies as demonstrated in this research, or by repeated on-site measurements of productivity and corresponding weather parameters. The latter is time consuming and requires control of all factors that may influence productivity. Therefore, future research should also focus on how digital technologies (sensors, smartphones, AI-algorithms etc.) can automate collection and analysis of site information to enable establishment of specific productivity-weather relationships.

Considering the effects of weather on concrete curing, more research should be directed to verify the performance of climate-improved concrete types and curing methods exposed to different weather conditions.

Future research should also focus on how discrete-event simulation modelling could be integrated in strategic and operational planning of concrete-related production systems. The novel approach described in chapter 8.2 could be a starting point for developing capabilities in the industry to benefit of this type of advanced modelling and simulation techniques.

Finally, future work should also focus on enhancing the capabilities of the simulation approach to consider effects of other factors as highlighted by Koskela (1999). For instance, the model can be extended to also include deliveries of materials to site during erection of the concrete framework.

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