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Report TVBK-3074

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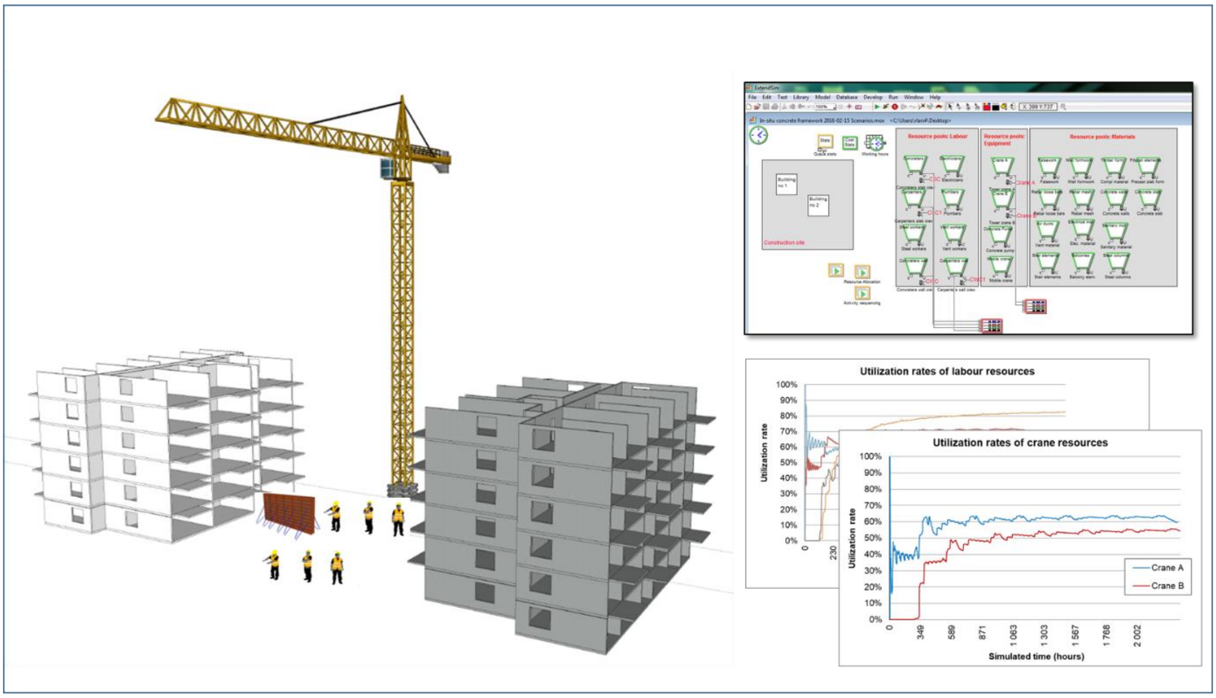

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Preface

The construction workflow of in-situ concrete frames in multi-storey residential buildings is highly complex and dynamic. Discrete-event simulation (DES) offers capabilities to model and analyse such complexity. Although DES has successfully been used by researchers in a wide range of construction-related applications there are not many examples demonstrating how different simulation outputs (time, cost, queue waiting time, resource usage) could be used in an integrated and systematic way to facilitate in-depth analysis of construction workflow.

This report presents a simulation model of concrete framework construction and demonstrates how it can be used for systematic analysis of a production setup using multiple performance indicators such as construction time, cost, resource utilization, and workflow waiting times. It was found that the proposed model can describe the complexity in construction workflow and support systematic analyses. Multiple simulation measures were also found valuable, e.g. in order to identify and remove bottlenecks.

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1. Introduction

The structural framework is an important sub-system in a multi-storey residential building since it provides fundamental properties such as load bearing capacity, fire resistance, and sound insulation. The most common way to build the structural framework is to use reinforced concrete. In Sweden for instance, almost 90% of all multi-storey residential buildings are built with a structural frame made of reinforced concrete (Andersson and Larsson 2014). An established and frequently used method involves the use of in-situ concrete in combination with temporary and permanent formwork systems, prefabricated concrete and steel components (Peterson 2008, Larsson 2010). This type of hybrid concrete construction has gained popularity due to advantages in its structural design such as flexibility and robustness. The disadvantages attributed to the construction method are for instance that it is labour-intensive, it requires temporary works (e.g. shoring), and additional time is required for development of concrete strength and for the drying out process (Illingworth 2000, Löfgren 2002, Peterson 2008).

The on-site production process is complex as it contains multiple activities and resources that interact in an unprotected and dynamic environment. In the pursuit of production time and cost optimization, work is often executed simultaneously at different work locations by sharing the same resources, e.g. labour and crane. This means not only that the execution of activities must be controlled but also the coordination and allocation of the resource flows. If the allocation 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 (Winch and Carr 2001, Josephson and Mao 2014).

Due to the production system's complexity and dynamic nature, it is difficult to understand how all the interrelations between activities and resources affect the production system as a whole in terms of time, cost, and resource usage. Discrete-event simulation (DES) has been proposed by researchers as suitable to analyse complex 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 understand (analyse) the system. DES has been used for decades by researchers to study construction-related systems (AbouRizk et al. 2011). Also, sub-processes related to construction of reinforced concrete structures have been analysed using simulation techniques, e.g. formwork (Huang et al. 2004), rebar (Polat et al. 2007), production, delivery and placement of ready-mix concrete (Zayed and Halpin 2001, Lu et al. 2003, Park et al. 2011). Although these projects have successfully demonstrated the use of DES, they were limited to studying isolated sub-processes to solve a specific problem. As a consequence, the description of the on-site construction workflow was either too narrow or incomplete. In addition, there are not many examples in previous research demonstrating how different simulation measures (time, cost, resource usage, waiting times) can be used in an integrated and systematic way to facilitate in-depth analysis of on-site construction workflow.

Therefore, this research aims to present a discrete-event simulation model of the on-site production process of in-situ concrete frameworks in multi-storey residential buildings, and to demonstrate how it can be used for systematic analysis using multiple performance indicators.

Based on the aim of this research, two research questions (RQ:s) were formulated;

- How can the on-site production process of in-situ concrete frameworks be described in a discrete event simulation model considering the interactions between activities and the use of resources?
- How can the discrete-event simulation model be used for systematic production analysis using multiple performance indicators?

After this introduction the report is structured as follows. First, a review of how DES has been applied in construction research is presented, positioning this study relative to previous research. The research process, which then is described, is developed to fill some of the identified gaps in previous research. A conceptual model is then presented which contains a detailed description of a typical production process of in-situ concrete frameworks. Thereafter, it is described how the conceptual model is implemented in a general-purpose simulation software. The procedures employed for validation of the simulation model are also described. Next, the use of the simulation model is demonstrated through a systematic production analysis, evaluating production performance by the means of multiple performance indicators. This is followed by a section devoted to discussing the characteristics of the simulation model, how DES can be used for analysing and improving operations, but also the benefits and limitations of the model as such. Finally, conclusions and recommendations for future research are provided.

2. Frame of reference

2.1 Discrete event simulation applied to analysis of construction systems

DES has been used to study a wide range of different construction applications, e.g. earth moving operations (Dong-Eun et al. 2010), tunnel projects (Alarcón et al. 2012), viaduct construction (Chan and Lu 2008), and highway reconstruction projects (Mohammed et al. 2015). Other research has focused on the integration of discrete-event simulation and building information models to enhance 4D planning, visualization, and scheduling (Kamat and Martinez 2002). In Kamat et al. (2011) different visualization concepts were described together with advances in techniques related to those concepts. Vidalakis et al. (2011) used simulation to perform a logistical analysis of construction supply chains. DES has also been used for project scheduling and productivity estimation (Song and AbouRizk, 2008), improving vertical transportation of manpower in high-rise building projects (Shin et al. 2011, Park et al. 2013), and implications of time-constraints on workflow (Zhang et al. 2008). Moreover, crane operations have been simulated in order to detect spatial conflicts on construction sites (Kim et al. 2006, Tantisevi and Akinci 2008). Baniassadi et al. (2018) proposed a discrete event simulation framework enabling to account for factors that influences both productivity and safety in construction operations. Discrete event simulation has also been used to simulate offsite construction systems. Mostafa et al. (2016) pointed out that the main applications focused on; simulation of supply chains; planning and scheduling of resources in offsite operations; and studying the relationships between operational variations and overall production efficiency.

On-site construction of reinforced concrete frames (RC frames), which is of primary interest of this report, 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 a RC structure were studied by Huang et al. (2004). In this report, the models used for simulation of different formwork reuse schemes were limited to consider sequencing and durations of formwork, rebar, and concrete operations carried out at one or multiple work locations. Furthermore, modelling the availability of resources was limited to only crane and form crew. As a result, the description of the overall on-site workflow is not complete neglecting the effects of other important operations (e.g. installing prefabricated elements) and the availability of additional resources such as steel and concrete crews. Wang et al. (2014) proposed an interface system that integrates a building information model (BIM) and a simulation model. 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). In addition, the use of cranes was limited to assisting the lifting of rebar assuming that other operations (e.g. formwork and concrete) could be executed without crane assistance. Simplifying the description of crane usage may lead to wrong conclusions since crane availability are crucial during construction of concrete frames in multi-storey buildings. Arashpour and Arashpour (2015) analysed workflow variability in multistorey buildings using discrete event simulation. The model focused on describing the effects of variability caused by rework and fluctuating work quantities. The authors clearly demonstrated the negative effects of variability on project productivity. Since the scope of the model was to demonstrate variability due to reworks, the description of the workflow was simplified. Consequently, the model lacks necessary details to facilitate analysis of internal workflow problems.

Looking at the supply of materials to the construction site, several research projects have addressed the production and supply of materials to RC frameworks. The focus in these projects was on studying the interactions between upstream processes and 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 analyse the relation between truck mixers' dispatching interval and resources' waiting time on site (Park et al. 2011). Lu et al. (2003) used simulation to study resource production planning 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.

2.2 Summary of previous research

Discrete-event simulation enables analysis of the dynamic and complex processes typically found in a wide range of construction projects. Previous studies have shown that it is possible to address very specific problems related to production and supply of rebar and concrete materials, but also to capture typical characteristics of on-site construction operations involved in the erection of RC frames. However, the models used for this purpose, e.g. in (Huang et al. 2004, Wang et al. 2014), were in some aspects simplified and incomplete in their description of the on-site workflow. Even though these simplifications could be reasonable and justified for specific purposes, it impairs the ability for detailed analysis of construction workflow. In order to fully reflect important characteristics of concrete construction, it is necessary to describe the workflow within and between work locations. Moreover, the construction workflow must be described at a work task level showing all relevant dependencies (technical and logical) between work tasks but also between work locations. Descriptions should also emphasize on highlighting process complexity such as parallel processing and process loop-backs. Furthermore, the availability of critical resources and how they are used dynamically by different work tasks during construction is essential in order to account for resource constraints on construction workflow. Therefore, the use of shared resources such as crane resources and multiple work crews must be explicitly described.

Using simulation for production analysis, the emphasis in previous studies has mainly been on analysing different resource setups using time and cost as the ultimate performance indicators (e.g. Huang et al. 2004, Chan 2008, Polat 2008). 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 analysing construction systems, such as queue waiting time and resource utilization. As pointed out by Sadeghi et al. (2015), queue performance measures (e.g. waiting time) are one of the most important simulation outputs in construction management for analysing interactions between resources and activities. 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. For instance, the use of queue waiting times as a measure to identify internal workflow problems is not sufficiently explored. Moreover, changing configuration of a given production setup in order to resolve a specific bottleneck problem may unintentionally lead to new problems, e.g. by moving the bottleneck to another part of the production system as a result of unsynchronized (unbalanced) processes. Therefore, it is necessary to employ a holistic approach when analysing construction systems in terms of internal workflow efficiency by simultaneously taking multiple indicators into consideration, e.g. queue waiting times, resource utilization, construction duration and costs. In order to make such analysis efficient and reliable, model variables must be systematically altered and corresponding model response closely examined in order to make decisions on further necessary actions. In general, previous studies lack a systematic approach when it comes to the use of multiple simulation outputs as a basis for production analysis. Therefore, more knowledge is needed when it comes to how DES can be used in order to support a systematic analysis of construction workflows using multiple simulation outputs. This also highlights the importance of describing on-site workflows at a detailed level including all relevant aspects regarding internal logical dependencies and resource constraints.

3. Research process

The research process used to address the two research questions is schematically presented in Fig. 1. The process consists of three phases, each comprising several steps. The results from each phase are used as inputs in the succeeding phase. The literature review is used in all three phases, both as background information and as a reference when analysing the results from this study. In the following, the three phases are described in more detail as well as their respective relation to the two research questions.

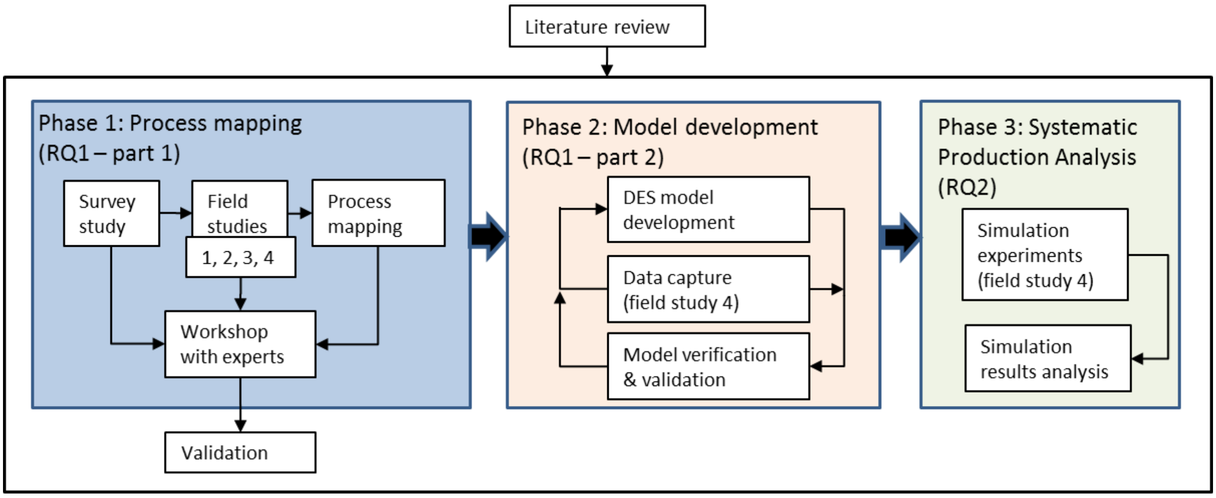


FIG. 1: Schematic description of the research process.

3.1 Phase 1: Process mapping

The first phase of the research focused on mapping a typical production process for erecting in-situ concrete frames for multi-storey residential buildings. First, a survey was carried out to investigate typical technical methods used for the production of in-situ concrete frameworks in multi-storey residential buildings on the Swedish market. The survey was conducted as structured telephone interviews with contractors in 38 projects where in-situ concrete frameworks were under construction (or recently completed), based on a stratified random selection process using a set of control variables (project size, geographic location, and type of contract form). Based on the knowledge gained from the survey and interview results, a total of four representative field study projects were chosen to study further. During the field studies (1 to 4) the production process of the concrete framework was documented, and activities, their interrelations, and the use of resources were described at a detailed level. For consistency the IDEF3-notation language (Mayer et al. 1995) was used for documenting the production processes. In field studies 3 and 4 it was possible to retrieve detailed process data such as lead times on both activity level and aggregate level using time studies and sampling methods (Jenkins and Orth 2003). Other data collected during the field studies were material quantities and cost of resources on activity levels. The descriptions from each field study were then combined into one generalized process description (conceptual model). The conceptual model contains a logical representation of the observed production process. The model contains a description of work locations which are defined by the division of the building into manageable working units, e.g. wall and slab units. It also contains a visual description of the workflow itself indicating dependencies between work tasks and interactions with resources. The model was verified and validated by the means of a workshop with 20 industry experts with special knowledge of the design and construction of in-situ concrete frameworks. The conceptual model, survey results and the data collected during the field studies were presented, discussed and validated during the workshop. As such, phase 1 provides the necessary input for developing the simulation model in phase 2 and for answering the first research question.

3.2 Phase 2: Model development

Using the conceptual model of the production process from phase 1 as input, a discrete-event simulation model was developed. 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 behaviour. During the simulation, items flowing through the system of modelled blocks resembling the workflow described by the conceptual model. Each block could also be modified in order to perform specific operations, e.g. changing the route of items or allocation of resources.

Parallel to the model development, real process data collected from field study 4 was structured according to the required input variables in the model. Since it was possible to collect the most detailed process data from field study four, including both task durations and costs at activity levels, it was used as the major reference for populating the simulation model with necessary input data. 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 behaviour with logical descriptions of the conceptual model. An ultimately goal of the verification process is to demonstrate that all parts of the model work, both independently and collectively, and use the right data at the right time. Integrated control functions of the software employed were used to verify the model's logical behaviour. For instance, the logical behaviour were visualised 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. The verification methods employed are further described in Shi (2002) and Sargent (2013).

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 4. The conceptual model together with the validated simulation model from phase 2 was used for answering the first research question.

3.3 Phase 3: Systematic production analysis

In phase 3, the validated simulation model was used for demonstrating if, and how, discrete-event simulation can support a systematic analysis of erection of in-situ concrete frames using multiple performance indicators. The performance indicators chosen were queue waiting times, resource utilization, total duration and cost. Queue waiting times were collected from queue blocks in where entities have to wait for resources to become available (or other triggers) in order to proceed. Consequently, waiting times are useful measures to reveal internal workflow bottlenecks. A complementary measure which could explain location of bottlenecks is utilization of resources. High utilization of resources is usually positive from an economical viewpoint. However, high utilized resources usually explain the existence of bottlenecks. However, an underutilized resource may temporarily also be responsible for bottlenecks. This motivates the use of both waiting times and resource utilization data in order to understand causes of internal problems. Of course, any modification of a production setup analysis should also consider effects on total duration and cost since these are the two dominant performance indicators in any type of construction project.

A systematic analysis of a given production setup using the simulation model was demonstrated. For this purpose, field study four was once again, used as a basis for comparisons of experiment results. First, the production setup according to field study four was simulated with no changes. Simulated waiting times and resource utilization provided detailed knowledge about both the occurrence and localization of workflow bottlenecks and critical resources. This information was then used in order to suggest and formulate scenarios containing operational changes in order to improve the workflow. The additional information needed to define each scenario was obtained primarily from discussions with industry experts. Each scenario was then simulated and evaluated using all four performance indicators. Selecting the most favourable scenario, the analysis continued with conducting a fine tuning of production setup by systematically altering the allocation of resources. This process was automatically simulated using a scenario-manager functionality provided by the simulation software. This function enabled to simulate a large number of resource allocation combinations in a controlled and efficient way. Based on all simulated combinations, the most favourable alternative considering all performance indicators was finally identified. The knowledge gained from conducting these experiments was thereafter evaluated considering both opportunities and limitations of the model as a tool for production system analysis. The findings from phase 3 were used for answering the second research question.

4. A typical production process of in-situ concrete frameworks

This section describes the results of the first research phase, which is a typical production process for the erection of in-situ concrete frameworks for multi-storey residential buildings. At first a conceptual description of the production process is provided and secondly a more detailed process description using the IDEF3-notaion language is outlined.

4.1 Conceptual description of the production process

The conceptual description of the identified typical production process of in-situ concrete frameworks is presented in Fig. 2. A building is divided into one or more work locations, exemplified with locations X and Y in Fig. 2. A work location is defined by the size of a pour unit of a floor slab. In addition, each floor slab also consists of one or more wall sections, defined by the size of a wall's pour unit. Each work location, e.g. X1, typically consists of multiple wall sections, and is composed of a number of activities arranged in a network to resemble the actual workflow. Activities A1-AN represent the workflow for work location X1. An activity represents a work task, such as erecting formwork or pouring concrete, and activities can be executed both sequentially and simultaneously depending on technical constraints. Arrows between activities indicate finish-to-start relations. For instance, A1 must finish before A2 can start. More complicated relations exist as well, e.g. the start of A5 depends of the finish of both A1 and A4.

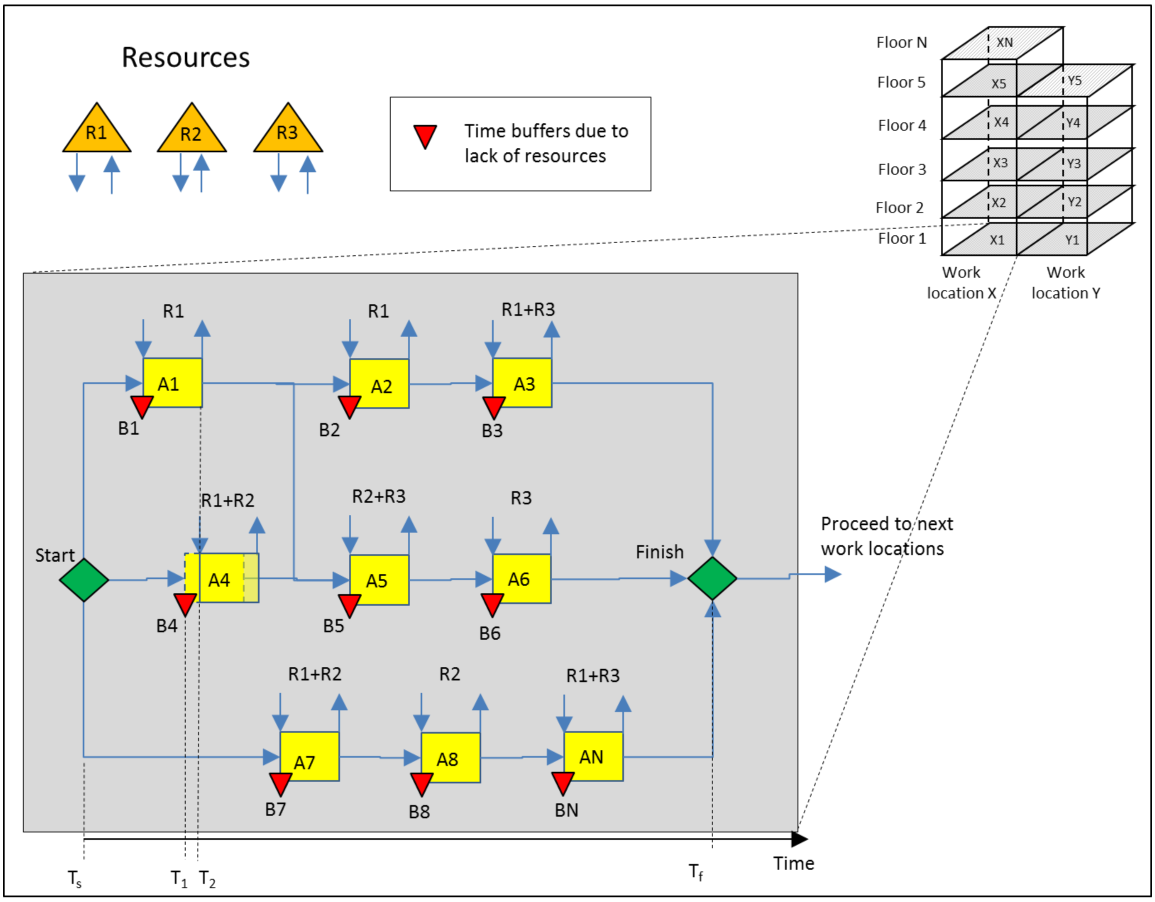


FIG. 2: A conceptualized description of the construction process of in-situ concrete frameworks.

Different types of resources are required to execute activities, e.g. labour, equipment, and material. These resources are denoted R1, R2 and R3 in Fig. 2. The interplay between resources and activities is illustrated by the incoming and outgoing arrows between activities A1-AN and resources R1-R3. When activity A1 is about to start, resource R1 is allocated to this activity during the processing time of A1. When A1 has been completed, R1 is released and becomes available for use by other activities. If several activities simultaneously request the same resource (and the resource has limited capacity), an allocation conflict occurs. The activities which cannot be assigned with required resources have to wait until the requested resources become available. The time an activity has to wait for resources is represented by the time buffers B1-BN in Fig. 2. For example, the start of activity A4 is delayed due to a resource allocation conflict with activity A1. Activity A4 has to wait until resource R1 becomes available, resulting in a waiting time equal to T2-T1 (see Fig. 2). Note that resources waiting for other resources (e.g. labour waiting for crane assistance) is a more practical interpretation of time buffers B1-BN, and a way to detect waiting time at a construction site is to observe resources currently waiting to get their job done.

Fig. 3 presents an example of an overall workflow sequence during the production of an in-situ concrete framework. In Fig. 3, $X1_{wall}$ represents all activities involved in producing the concrete wall sections at work location X1 (compare with Fig. 2). $X1_{slab}$ represents all activities involved in producing the floor slab between X1 and X2. As exemplified in Fig. 3, when the wall sections at X1 are finished the workflow proceeds with start-up of producing wall sections at work location Y1 ($Y1_{wall}$), and at the same time starting to erect the floor slab at X1 ($X1_{slab}$). This sequence repeats floor by floor, alternating between X and Y, until all work locations at all floors are finished. Note that arrows with solid lines indicate a technical constraint whereas arrows with dotted lines indicate a resource-based constraint. For instance, the dotted arrow between $Y1_{wall}$ and $X2_{wall}$ represents a resource-based constraint where formwork is moved between the two work locations.

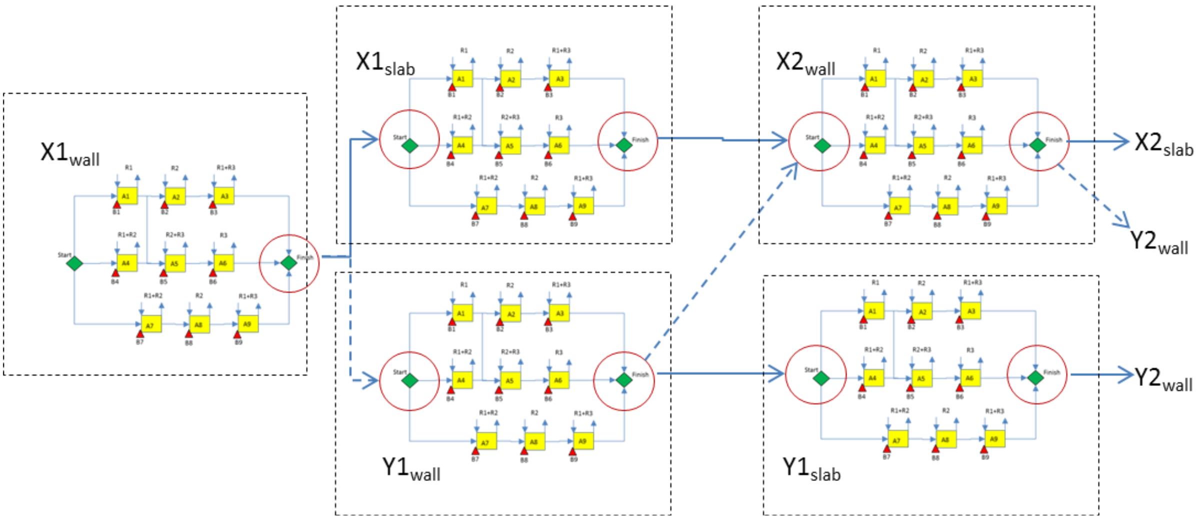


FIG. 3: A schematic view of the overall production sequence of in-situ concrete frameworks.

4.2 IDEF3 description of production process

Based on the conceptual description presented in Fig. 2 and 3, a detailed IDEF3-description of the production process has been developed using data from the field studies. The IDEF3 method is a scenario-driven process flow description capture method intended to capture the knowledge about how a particular system works (Mayer et al. 1995). Both the conceptual and the IDEF3 descriptions have been validated during the workshop with industry experts (cf. Fig. 1). The full IDEF3 process model is presented in Fig. A1 in Appendix A. The process description contains 29 activities in total, denoted UOB:s (Unit of Behaviour), representing the workflow of one work location (e.g. X1 Fig. 2). An UOB represents an activity such as erecting formwork or pouring concrete. However, it is also used to represent the curing-process of concrete. A brief overview of the UOB:s are presented in Appendix A.

Construct elements such as junctions and links are used to formally describe the internal logic of the workflow, e.g. process branching and relationships among activities. More details concerning IDEF3 notations are given in Mayer et al. (1995). The principal use of different resource types is presented in Table B1 in Appendix B.

5. Simulation model

This section describes the results of the second phase of the research process. It outlines the developed simulation model, and describes the model verification and validation. The production process outlined in Fig. A1 (Appendix A) is implemented in ExtendSim v.9 (http://www.extendsim.com). ExtendSim is a general-purpose simulation software for continuous and discrete-event simulation. Detailed descriptions of how the software works are given in Redman and Law (2002), Krahl (2003), and Schriber et al. (2013).

5.1 Overview of model structure

Fig. 4 provides schematic illustration of the model's structure, consisting of two sub-models denoted WLX and WLY, respectively. A sub-model is analogous to a work location according to the definition presented earlier. It contains a set of blocks arranged and interconnected in a very specific order to resemble the process description given in Appendix A. The arrow links between the sub-models WLX and WLY denote that the workflow described in each sub-model is interconnected to resemble the overall working process according to Fig. 3. For instance, when workers have finished the concrete walls in work location WLX, they move on to continue their work on the next work location WLY. At the same time, another work crew begins with erecting formwork for the next floor level in WLX. As given by Fig. 3, multiple activities are carried out simultaneously both within a specific work location, but also at different work locations.

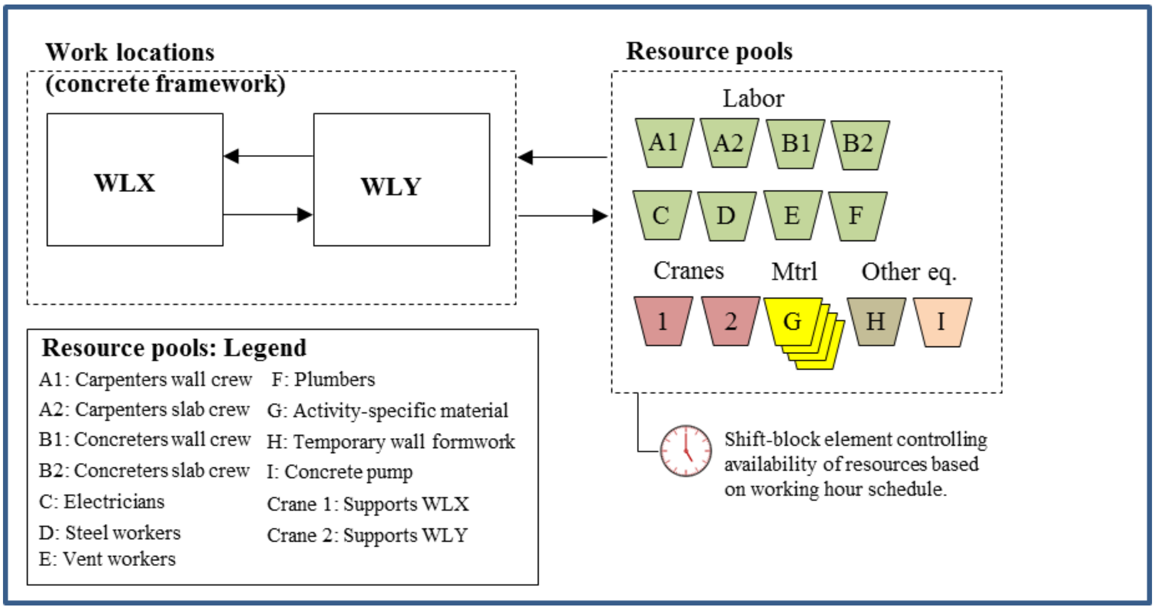


FIG. 4: Conceptual overview of the simulation model with two work locations (WLX and WLY).

Since resources are shared between activities, the representation of these resources and how they are used in each single activity is an important model characteristic. Resources are represented by multiple resource pool blocks. Each type of resource has its own unique resource pool block. A shift-block controls the availability of resources based on a working-hours schedule. This means that a resource is available for use during actual working hours. The arrows denote the allocation and release of resources to and from an activity and the actual resource pool. The release and allocation of resources are triggered by the start and finish of activities.

A simulation run is started by initiating the first modelled activity (UOB1 in Fig. A1) at floor level 1 in work location WLX. Activities UOB2 – UOB8 are repeated until all wall sections in WLX are finished. The workflow then continues with multiple activities UOB9 to UOB12. Activity UOB9 represents moving wall formwork and workers to the next work location

(WLY). While wall formwork is being moved to WLY, assembly of falsework to the next floor level at WLX is started (activity UOB12). The work sequence continues with UOB13 to UOB26 according to Fig. A1 (Appendix A). When activity UOB26 has been completed, the work sequence is repeated starting with UOB2 at a new floor level in WLX. At the same time, the work with the next floor level in WLY is initiated. The overall workflow follows the alternating sequence given by Fig. 3. The simulation is stopped when the run-end condition is met. That is when the last iteration of the last modelled activity has been completed.

5.2 Model variables

The input variables needed to run the model consists of both overall project information as well as activity-specific information. Examples of project-related information are the number of floor levels per work location and number of various types of resources available during project execution. Resources' cost data are also examples of project-related input variables. Examples of activity-specific information are productivity rates, number of resources needed for execution, and actual workloads. A complete set of input variables are presented in Tables C2 and C3 in Appendix C.

The model's output variables are:

1. Total simulated time defined as the time when the run-end condition is met. Normally this condition is set when the last modelled activity has been completed. In addition, statistics regarding lead times of wall or floor activities as well as floor cycle times can easily be obtained. Floor cycle time is defined as the difference between the start times of two consecutive floor levels.

2. Total simulated cost defined as the total cost of resources (material, equipment, and labour) during erection of the framework.

3. Resource utilization factor for each resource type. Resource utilization factor is defined as the relation between the total time a resource has been used and the total time the resource has been available during the project.

4. Queue waiting time defined as the total time items have to wait to receive requested resources.

5.3 Model verification and validation

Different methods for verification and validation of the simulation model were used at different stages of the development process. The methods used are described in (Banks et al. 1996, Shi 2002, Sargent 2013). A face validation technique was used for validation of the conceptual model. The computerized model was verified by using the simulation software's integrated functions to test the logical behavior and the management of resources. Finally, the model was validated by comparing the simulated output with data obtained from field study 4.

5.3.1 Conceptual model validation

According to Sargent (2013), conceptual model validation refers to ensuring that the model's representation of the real system is reasonable for the intended purpose. A face validation technique was chosen for validation of the conceptual model. The validation was carried out in two stages. Initially, during documentation of the production process in the field studies, flow charts were developed and discussed multiple times with site managers. The feedback from site managers was used to revise and refine the process descriptions. Secondly, the IDEF3 process scheme, according to figure A1, was discussed during a workshop with 20 participants. The participants were experts in engineering and construction of in-situ concrete structures. The discussion focused on the construction sequence given in figure 2 and figure A1, and at a macro-level as given in figure 3. Representation of activities and the logical dependencies between those were also discussed as well as the use of resources according to table B1. Based on the workshop discussion, it was concluded that the conceptual model was considered valid for the purpose of describing the production process of in-situ concrete frameworks.

5.3.2 Computerized model verification

Computerized model verification is used for assuring that the simulation model has been implemented according to the conceptual model description (Sargent 2013). Two tests were used to confirm the model's logical behaviour regarding sequencing of activities and management of resources. The simulation software's animation function was used to step-by-step display the routing of items through blocks in order to confirm the intended logical sequence of order. An important aspect of the model is the allocation and release of resources to an activity. Therefore, the second test focused on the transactions of resource entities between the modelled activities and resource pools. After the end of the simulation, trace reports were generated containing detailed information about resources' involvement in activities during a simulation run. These reports were analysed to understand how and when resources were used during a period of simulated time. This information was then compared with timing data related to the execution of activities. Based on the two tests, the computerized model was considered to be verified for its intended purpose.

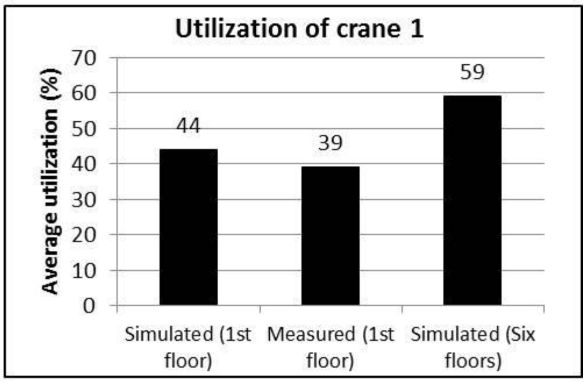
5.3.3 Operational model validation

Operational model validation refers to comparing simulated output with real process data. For this purpose, the project in field study 4 was used. The project consisted of two buildings with a framework made of in-situ concrete. The two frameworks were erected simultaneously following a 14 days construction cycle (table C1 in Appendix C). The work sequence was documented by daily on-site observations during a period of three weeks and reported in Lindén and Wahlström (2008). Information about activity durations were collected by time studies. Resource utilization was also measured for one of the two cranes during construction of the first floor. Since the site observations and measurements covered a limited period of the total construction time, the data was cross-checked with site managers and foremen. Cost data for resources as well as information about resource usage were also collected by reviewing project documentation and from discussions with site personnel. Data on productivity rates and costs were also compared with other sources Sveriges Byggindustrier (1999), Boverket (2007), Svensk Byggtjänst (2019) in order to ensure the quality of the data obtained. The operational validation consisted of reproducing the observed construction sequence using the input data obtained from the project, e.g. activities' workloads and durations, sequencing of activities, use of resources, and costs of resources. The input variables used is given in table C2 and C3 in Appendix C. Since the floor cycle time is an important and common performance indicator of the production process, it was used for comparison.

In figure 5 (left side), the simulated finish times of UOB26 and the corresponding floor cycle times are presented for building 1 and 2. The cycle times are given by the difference in time between the finish of two successive floor levels. All simulated floor cycle times were equal to 14 days which also were reported from the real project. The fact that the simulated floor cycle time is constant also shows a steady state behaviour. This is reasonable since no random input variables are used. Variable floor cycle times would have indicated that some internal problem in the model existed.

Floor number	Building 1		Building 2	
	Finish time (hrs)	Cycle time (days)	Finish time (hrs)	Cycle time (days)
1	345	14	512	14
2	681	14	848	14
3	1017	14	1184	14
4	1353	14	1520	14
5	1689	14	1856	14
6	2025	14	2192	14

a)



b)

FIG. 5. Left side (a): Simulated floor cycle time for building 1 and 2. Right side (b): Simulated and measured utilization of crane 1.

In figure 5 (right side), the simulated and measured utilization of crane 1 is shown. For practical reasons it was only possible to measure the usage of crane 1 during the construction of the first floor. The simulated crane utilization was somewhat higher which can be explained by the fact that the measurements did not include lifting of balconies and stairs. In that sense it seems that the simulated and measured utilization is relatively well correlated. The utilization of the crane increases when all six floors are simulated. This is explained by how utilization is calculated in the model. When only one floor is simulated, the time after building 1 is finished and crane 1 becomes idle is also included in calculation of the utilization factor. This is also true when all six floors are simulated but since the total time is much higher in this case, the influence of idle time on total utilization becomes more limited. In addition, increasing the number of floors also increases waiting times (due to allocations conflicts) which also are included when calculating the utilization factor. Therefore, crane utilization should be used carefully. However, it is still a useful indicator to identify resources that either are underutilized or are becoming a bottleneck resource.

The operational validation indicates that the model operates as intended. Given that the values obtained from project 4 are valid, the model is capable of reproducing the construction process as was observed and reported from the real project.

6. Systematic production analysis based on simulation

The results of the third research phase are described in the following section, focusing on how the simulation model can be used for systematic production analysis. The model could be used in many different ways to support a systematic analysis of a specific production setup, but here three ways of using the model are explored: bottleneck analysis, analysis of alternative production strategies/methods, and analysis of model variables. To demonstrate the use of the model, the concrete framework in field study 4 will be used as a reference case. Model input variables for the reference case are presented in Appendix C, Tables C2-C3.

6.1 Bottleneck-analysis of reference-case

In terms of bottleneck-analysis, the queue waiting time statistics could be used to detect workflow bottlenecks. Causes of these bottlenecks can be identified by combining waiting time data with statistics on resource utilization and detailed timing data of events, e.g. the start of an activity. In Fig. 6, waiting times from queue blocks located in each UOB are plotted against time during the simulated construction of building 1. A repeating pattern of waiting times is revealed by the diagram in Fig. 6 suggesting that bottlenecks occur systematically. Studying the timing when the waiting times are reported gives an overview of the bottlenecks in the workflow and also gives an idea of where they are located. In addition, statistics of average waiting times from each UOB can also be obtained from the model.

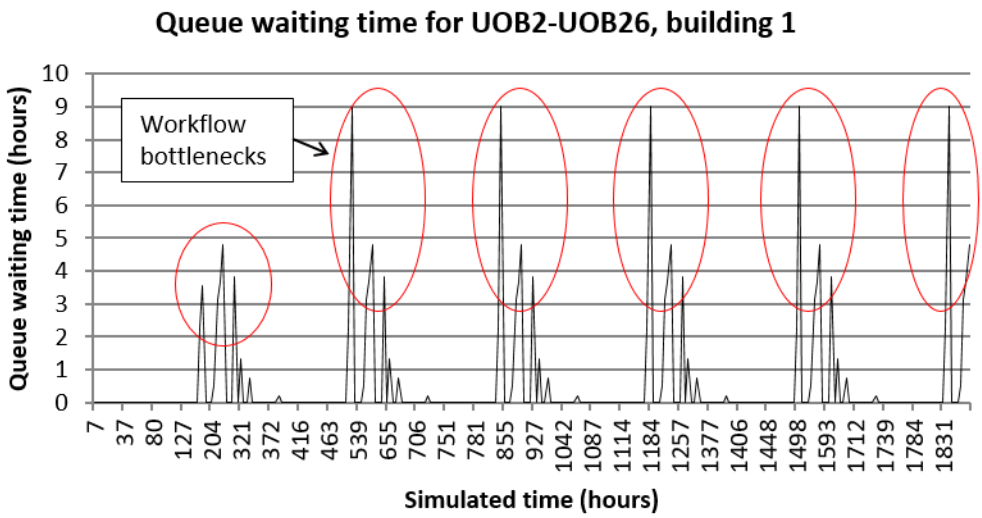


FIG. 6: Waiting times plotted against simulation time for UOB:s in building 1.

Fig. 7 presents the average waiting time reported for each UOB during the simulation of building 1, showing that UOB11, UOB16, UOB18, UOB19 and UOB23 reports high waiting times indicating possible bottlenecks. All these UOB:s require the use of both crane and concrete workers (slab crew) simultaneously which may lead to allocation conflicts and the occurrence of waiting times. Supplementary information regarding resource utilization (Fig. 8) reveals that crane resources are utilized 45-59% of total time (diagram a). Obviously, the unused capacity of crane resources are about 50%. However, even though cranes have a low utilization in average, they can temporary become a critical resource if several activities are requesting crane assistance simultaneously. The utilization of labours are in the range of 52-70% in average where concrete workers belonging to the slab crew have the highest average utilization and carpenters belonging to the slab crew are utilized the least during the construction phase.

By studying the sequencing of activities more closely using timing data, the occurrence of waiting time was explained by the fact that several activities (UOB16, 18, and 19) requested the crane and workers belonging to the concrete slab crew, simultaneously. Accordingly, measures to reduce waiting times should focus on the identified UOB:s and the resource types crane and concrete workers.

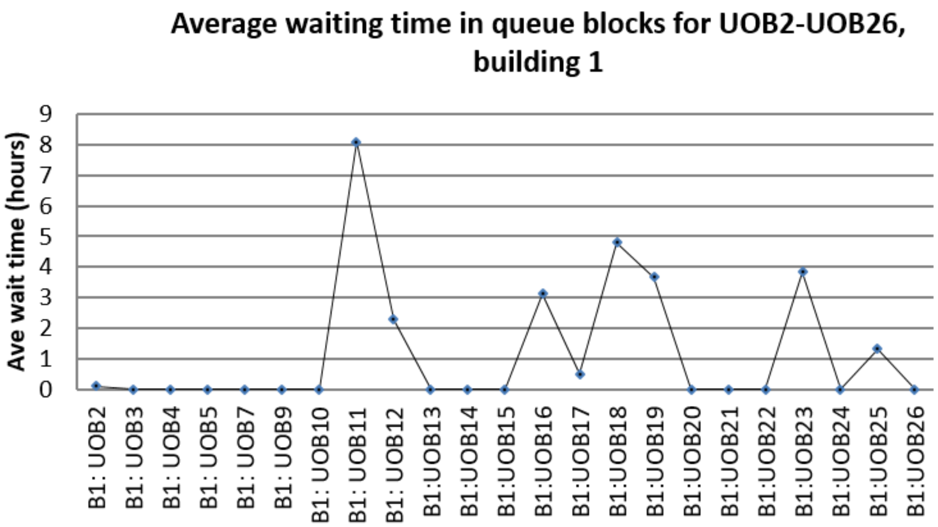


FIG. 7: Average waiting time for queue blocks located in UOB2 to UOB26 in building 1.

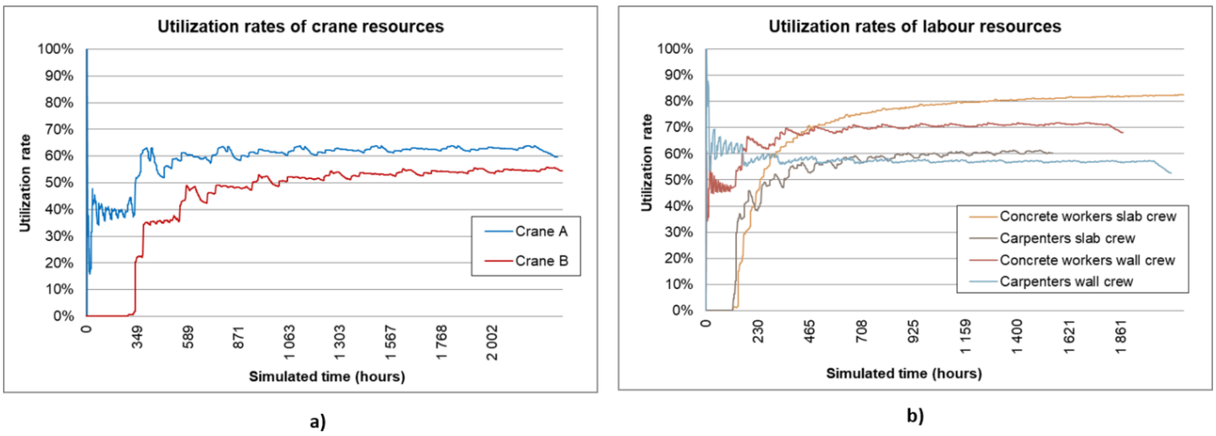


FIG. 8: Utilization rates for crane resources (diagram a) and labour resources (diagram b).

6.2 Analysis of alternative production scenarios

The simulation model supports implementation of various methodological and organizational changes. To analyse a new construction method, the model structure has to be adjusted and additional resources may also be required. Organizational changes are more easily implemented. For instance, changes in how workers are divided to perform specific tasks are done by configuration of settings in selected blocks. New resources could easily be added to the model structure and then configured to be integrated into the workflow. For the purpose of exemplifying this type of analysis, four different alternative production setups (scenarios A-D) were proposed and implemented in the model. The scenarios are grounded on knowledge gained from the simulation results of the bottleneck analysis. Each scenario is described in Table 1 together with assumptions specifically made for each case. The design of the scenarios also involved some general limitations. For instance, the proposed changes were assumed to be practically feasible with no implications on working conditions. However, such assumptions must be carefully analysed in advance if they were to be tested in reality. No alternative construction methods were tested since it would have required more efforts in data collection and validation. Moreover, the model didn't include all fixed costs related to the construction site (scaffolding, hoists, wheel loaders, etc.) since these are not only related to the concrete framework. The results for each simulated scenario were also based on steady-state conditions employing deterministic values. Employing randomness to the system would influence the result and different solutions may then be more suitable.

TABLE 1: Description of changes in scenario A-D, compared to reference-case.

Name	**Description**
Scenario A	Introduce a new resource (mobile crane) to temporary reduce workload for crane 1 and 2. A mobile crane was set to assist in lifting operations for activities UOB11, UOB18, and UOB19. The mobile crane was assumed to assist both building 1 and 2 covering the full height of the buildings. The cost of the mobile crane is calculated based on its actual use in the project.
Scenario B	Same settings as scenario A. In addition, a delay of starting up UOB16 was applied. The purpose of delaying the start of UOB16 was to eliminate a potential allocation conflict since the start of UOB16 could occur at the same time as UOB18 and UOB19.
Scenario C	Same settings as scenario B. In addition, two additional concrete workers were added to the concrete slab crew to make this resource type less critical. The project crew size was thereby increased by two additional labours. However, the allocation strategy as used in the reference case was kept the same. It was also assumed that these two additional workers were able to directly increase task productivity proportional to the additional number of heads. Obviously, this assumption is only valid for a limited number of workers. Too many workers may cause spatial conflicts and work congestions which may have a negative effect on productivity.
Scenario D	Same settings as scenario B. In addition, multi-skilled workers were used to replace the traditional division of different professional disciplines. In this case, multi-skilled workers were set to replace the division of concreters and carpenters as well as the division between wall and slab crews. One of the benefits of using multi-skilled workers is that the workforce becomes more flexible which can reduce the amount of waiting time. Multi-skilled workers are rarely used in practice but have been discussed and proposed by researchers as a possibility to improve construction workflow, e.g. in Haas et al. (2001). It was assumed that the productivity and labour cost is not affected by employing multi-skilled workers.

The results from the simulation of the four scenarios are presented in Table 2. In scenario A, the use of a mobile crane resulted in a 30% reduction in total queue waiting time (sum of building 1 and 2). Another effect is lower utilization of both cranes compared to the reference case. However, total time is not improved and the cost is increased due to costs of the mobile crane. For scenario B, total queue waiting time was reduced by 61%. Compared to scenario A, it appears that a delay in start time of UOB16 leads to a greater reduction in waiting time than the use of a mobile crane. However, the reduction of waiting time does not influence the total time. Also here, the total cost due to an extra mobile crane was increased. In scenario C, the queue waiting time was reduced by 80% compared to the reference. As expected, the resource utilization (RU) of the concrete slab crew drops as two additional workers were added without changing how they were used. However, keeping the same allocation setup only slightly improved construction time but resulted in higher total cost due to additional labourers. In scenario D, the queue waiting time was reduced by 94% when employing multi-skilled workers. However, the effect on total time and cost was still very limited. Nevertheless, alternative D was found to be more favourable compared to the other alternatives.

TABLE 2: Simulated results for the reference case and scenarios A-D.

	Unit	Reference	Scenario A	Scenario B	Scenario C	Scenario D
Total Queue Building 1	Hours	172	102	50	41	10
Total Queue Building 2	Hours	255	196	116	46	14
RU_crane 1	%	59	52	52,5	53	46
RU_crane 2	%	52	48	48	54.5	44
RU_carpenters wall	%	57.5	57.5	57.5	63	n/a
RU_carpenters slab	%	53.5	58	58	53,5	n/a
RU_concreters wall	%	66	66	66	66	n/a
RU_concreters slab	%	74	74	74	54.5	n/a
RU_multiskilled workers	%	n/a	n/a	n/a	n/a	64
Total Time	Hours	2 192	2 192	2 192	2 175	2 171
Total Cost	EUR	1,016,731	1,018,757	1,018,757	1,055,605	1,016,005

RU = Resource Utilization

Considerable reductions of queue waiting times were accomplished for all alternatives compared to the reference. However, the effect on total time and cost is very small. The reason for this is that most of the waiting time origins from queues in UOB:s that are not critical for the total project duration. For instance, UOB11, UOB16, UOB19 could be delayed due to waiting times without causing delays in successive activities. However, employing a different resource allocation strategy could influence time and cost. Considering scenario D, the use of multi-skilled workers (RU=64%) could still be improved. This is done by a systematic analysis of different resource allocation combinations which is described in next following section.

6.3 Analysis of resource allocation combinations

The selected production alternative can be fine-tuned by systematically altering input variables in order to improve time, cost, waiting time, and resource usage. For instance, a frequently addressed problem in previous research, e.g. in AbouRizk and Shi (1994), and Cheng et al. (2005) is the allocation of resources to activities. The simulation model enables systematic analysis of a large number of different resource allocation combinations. The tested combinations of different allocations of multi-skilled workers in each UOB are given in Table 3. A maximum and a minimum level of resource allocation were applied to those UOB:s where multi-skilled workers were used. Constant values were used for those UOB:s where sub-contractors were used. The creation and simulation of all possible combinations were divided in two steps to reduce the number of simulation runs required. At a first stage, all possible combinations for UOB:s 2-9 were simulated (shaded in Table). The resource combination that resulted in shortest time, lowest cost, and lowest waiting time were selected for the second stage in where all possible combinations for UOB:s 10-26 were simulated with constant values for UOB:s 2-9. In the first stage 64 (26) scenarios were simulated and 4096 (2^{12}) scenarios in the second stage.

Simulated total time and cost for each resource combinations are presented in Fig. 9. The best resource combination (id: 4026) resulted in a 15% reduction in total time compared to the reference. Total cost was reduced by 5%. The total queue waiting time for scenario 4026 was 69% lower compared to the reference and the RU of the multi-skilled workers was found to be 71%. Resource combination 0455 resulted in the highest time and cost compared to the reference. The allocation combination of workers for scenario 4026 is given in Table 4 with the reference values in brackets. Employing a new resource strategy (multi-skilled workers, delay of UOB16, and mobile crane) and improving the allocation of these resources resulted in improvements for all four indicators.

TABLE 3: Simulated results for scenario A-D.

UOB:s	Number of workers [Min/Max]	UOB:s	Number of workers [Min/Max]	UOB:s	Number of workers [Min/Max]	UOB:s	Number of workers [Min/Max]
UOB2	4/5	UOB9	4/5	UOB15	1/3	UOB21	2 (Const.)
UOB3	2/3	UOB10	1 (Const.)	UOB16	2/4	UOB22	1 (Const.)
UOB4	1 (Const.)	UOB11	2/4	UOB17	2 (Const.)	UOB23	2/4
UOB5	4/5	UOB12	2/4	UOB18	2/4	UOB24	2/4
UOB6	2/3	UOB13	2/4	UOB19	2/4	UOB25	3/5
UOB7*	4/5	UOB14	2/4	UOB20	1 (Const.)	UOB26	3/5
UOB8*	4/5						

* Modelled as one single activity.

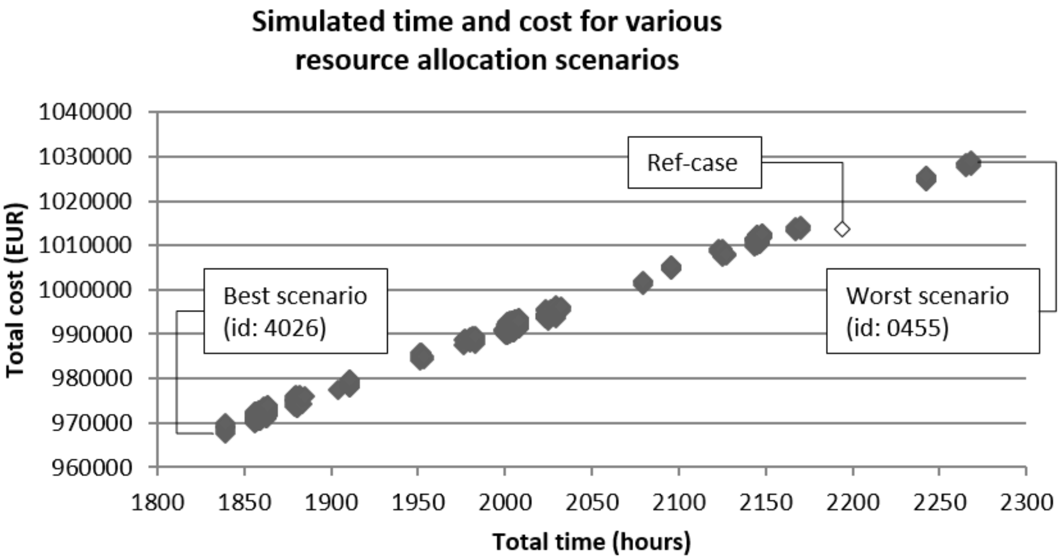


FIG. 9: Simulated time and cost for different resource allocation combinations.

TABLE 4: Suggested allocation combination for best-case scenario (id: 4026). Values in brackets refer to the resource allocation combination used in the reference-case.

UOB:s	Number of workers according to 4026 (reference)	UOB:s	Number of workers according to 4026 (reference)	UOB:s	Number of workers according to 4026 (reference)	UOB:s	Number of workers according to 4026 (reference)
UOB2	4 (4)	UOB9	5 (4)	UOB15	1 (1)	UOB21	2 (2)
UOB3	2 (2)	UOB10	1 (1)	UOB16	4 (2)	UOB22	1 (1)
UOB4	1 (1)	UOB11	4 (2)	UOB17	2 (2)	UOB23	4 (2)
UOB5	5 (4)	UOB12	4 (2)	UOB18	4 (2)	UOB24	2 (2)
UOB6	2 (2)	UOB13	4 (2)	UOB19	4 (2)	UOB25	3 (3)
UOB7*	5 (4)	UOB14	4 (2)	UOB20	1 (1)	UOB26	5 (3)
UOB8*	5 (4)						

*) Modelled as one single activity.

7. Discussion

7.1 General model characteristics

The model presented in this report has been developed to analyse the on-site construction process of in-situ concrete frameworks in multi-storey residential buildings. The model is capable of representing the characteristics of the specific construction method, i.e. cyclical work sequence, sub-division of work at multiple work locations, multiple operation tasks executed simultaneously, and the use of multiple resources at an operational level. The model is based on a detailed process description where activities and resources are modelled explicitly. In this way, the interaction between activities and resources can be studied, which enables to identify workflow bottlenecks and testing for alternative production setups. In contrast to previous research (Huang et al. 2004, Wang et al. 2014) where DES has been applied to study production process of concrete structures, this model is more detailed and complete in its representation of activities and resources involved in the production process. Accordingly, it enables to better account for resource allocation conflicts.

The model also provides an overview of the complex interrelations and the variables that influences the system's output. The model is built on pre-defined blocks which are interconnected and configured to create desired behaviour. The structure of the model is flexible and can relatively easily be adjusted to resemble the workflow of other construction methods. It is also relatively easy to add, remove, or modify resources.

Since the model has a relatively high level of detail more effort is required during the development and validation processes. As pointed out by Banks et al. (1996) large and complex models also increase the risk of errors. However, a systematic structure using hierarchical levels as discussed in Krahl (2003) and the use of in-built functionalities to facilitate verification and validation could overcome these issues. For instance, the use of special-purpose blocks to extract timing information from all modelled UOB:s was experienced to be very useful during the verification process. Also, in-built animation functionalities were found to be useful to visualize the workflow logic.

7.2 Usability for systematic production analysis

The model can be a valuable tool for a systematic analysis of construction-related production systems. The model outputs not only time and cost of the construction process, but also waiting times and resource utilization. The two latter variables were used to identify possible bottlenecks in the workflow due to resource allocation conflicts. Waiting time data was found to be a useful indicator in order to detect where in the workflow bottlenecks occurred. Statistics on resource usage were then useful to provide insights into which type of resources that were causing bottlenecks due to allocation conflicts. A highly utilized resource would more likely be responsible than an underutilized resource. However, the statistics on resource usage are measured on an average basis and it is therefore not possible to capture temporarily high loads. A resource that does not have relatively high resource utilization could occasionally still be a bottleneck. On the other hand, utilization is a useful indicator to see how much more a specific resource type could be utilized in order to increase production capacity.

Waiting times and resource utilization are rarely used as performance indicators in the traditional construction industry. They could be difficult to measure since it is not always obvious why a specific resource is idle. In addition, waiting time can be a result of multiple latent factors which might be even more difficult to measure. Consequently, both simulated queue 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.

Time and cost are the typical measures used to evaluate the success of a construction project. On the other hand, data such as waiting time and resource utilization provide a more thorough picture of the design of a construction-related production system in terms of internal efficiency. However, these measures cannot be used isolated but must be used in combination with time and cost indicators, wherefore the use of multiple performance indicators is preferable in a systematic production analysis.

The model also supports an automated design and simulation methodology of large number of production setups as demonstrated in this report. For instance, different resource allocation combinations could be simulated and their effect on performance indicators analysed.

7.3 Model limitations and future developments

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. In addition, lifting operations could be modelled more sophisticated in the model. For instance, lifting operations are assumed to be equal for all floor levels. A function could be implemented so that the duration of lifting operations is a function of the actual floor level.

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 behaviour of a real production system, the availability of materials (and other resources) has to be described and implemented in the model.

Additional improvements would also be to include external factors that affect the duration of modelled activities, e.g. material deliveries, weather conditions etc. However, such factors are usually uncertain regarding their occurrence and their effect on activities' durations. A common approach is to describe the effect on activities' duration using stochastic data. In this way, the effect of uncertainty due to external factors on system performance indicators could be analysed with the help of simulation. By adding stochastic data to model input variables (e.g. activities' durations), the model could also be used to analyse how variability affects the system's performance indicators. 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. Automatized data capturing techniques as discussed in Taneja et al. (2011) could be a solution to overcome these problems.

8. Conclusions

Referring to the first research question, it was found possible to describe the construction process of an in-situ concrete frame in a simulation model. The basic elements of the model are the work locations, the workflow containing all activities and their interrelations, and the resources involved. Activities (UOB:s) were explicitly represented using a set of pre-defined blocks which were interconnected in a specific order to resemble key characteristics, e.g. waiting for a resource to become available, processing time, release of resources. The overall workflow logic is established by using relational links between the modelled activities. Resource types are represented explicitly using a certain type of block elements. Typical indicators such as time and cost are model output variables. The model is also capable of delivering statistics on waiting time and resource usage. The model was validated against one of the projects in the field study. It was concluded that the model was capable of resembling the construction sequence found in this particular project given the same set of input data. However, the model should be tested in additional projects in order to confirm its validity. Suggestions on improvements of the model have also been discussed.

It was also demonstrated how the model can be used as a tool for systematic production analysis as was the focus in the second research question. Using one of the field study projects as a baseline, it was possible to achieve improvements for all indicators by changing production setup and allocation strategy. It was also found that statistics of queue waiting times combined with resource utilization provide valuable information in order to identify bottlenecks and to give insights on how to remove these. The model also supported the analysis of large number of production configurations in an automated and effective way where each scenario simulated was evaluated against the four performance indicators.

The model presented in this report contributes to the knowledge of how DES can be used for systematic analysis of complex construction-related production systems using general-purpose simulation software. The model is capable of providing new insights into how production systems can be improved. The use of queue waiting time statistics in different ways to identify and remove bottlenecks enables to more quickly review a production setup and propose measures to eliminate waiting time. The model also supports an automated approach for production analysis by systematically altering values of critical variables. This atomized approach was demonstrated for the well-known resource allocation problem. Even though the model is limited for the analysis of in-situ concrete frameworks, it could be modified and extended to cover a wider range of construction-related production systems. Ultimately, it can be a valuable tool for designing production systems where performance indicators such as time, cost, waiting time and resource utilization, are improved.

In the future, the model will be extended with additional operations and resources to capture the implications of material deliveries and on-site logistics. Additionally, the use of stochastic data will be used to study the effect of various external factors on production performance indicators.

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Appendix A

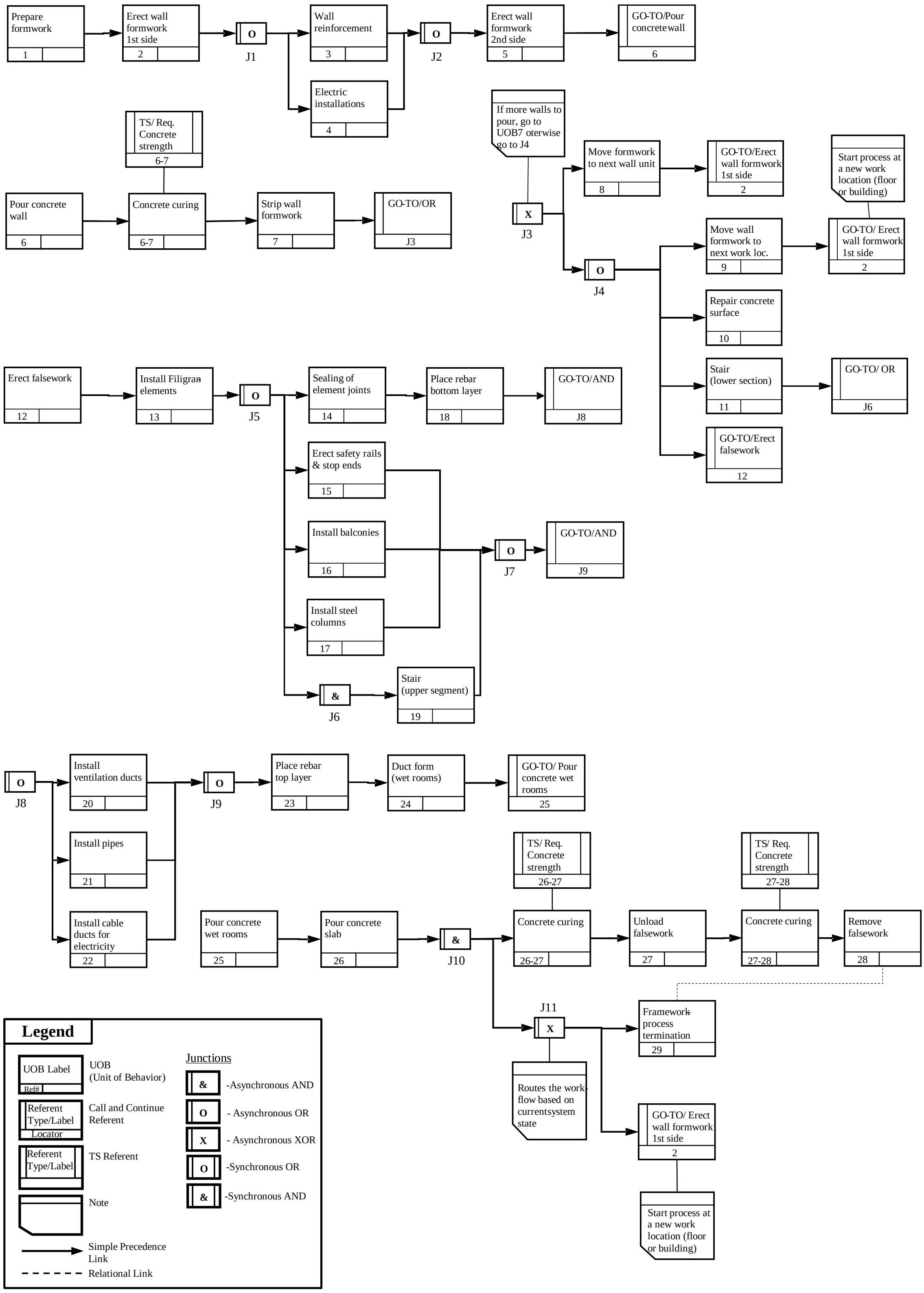

FIG. A1: IDEF3-description of a typical production sequence for an arbitrary work location.

Appendix A (cont´d)

UOB:s 1-8 in Fig. A1 represent activities involved in the construction of a concrete wall section. UOB 8 represents movement of formwork to next wall section to be constructed. The loop-back to resemble a new wall section is defined by the GO-TO Referent that succeeds UOB 8. UOB:s 11-28 represent the activities involved in erecting the concrete floor slab.

The production process starts with activity 1 (UOB 1) by preparing the formwork for concrete walls. However, this is only done once prior to start erecting the concrete framework. Consequently, this activity will only be executed once in the process model. The GO-TO Referents following UOB 9 and Junction J11 represent the proceeding of workflow to the next following work locations according to the sequence described in Fig. 3. The process ends when reaching UOB 29 at the final work location, e.g. YN in Fig. 2.

Appendix B

TABLE B1: Typical use of primary resources in field study projects 1-4.

Activity number (UOB)	Type of labour	Crane usage	Other resources	Activity number (UOB)	Type of labour	Crane usage	Other resources
1	A	Yes*	H	15	A	Yes*	G
2	A	Yes*	H	16	B	Yes	G
3	B	Yes*	G	17	D	Yes	G
4	C	No	G	18	B	Yes*	G
5	A	Yes*	H	19	B	Yes	G
6	B	Yes	G	20	E	No	G
7	A	Yes*	H	21	F	No	G
8	A	Yes	H	22	C	No	G
9	A	Yes	H	23	B	Yes*	G
10	B	No	G	24	A	No	G
11	B	Yes	G	25	B	No	I
12	A	Yes*	G	26	B	No	I
13	A, B	Yes	G	27	A	No	G
14	B	No	G	28	A	Yes*	G

A: Carpenter; B: Concreter; C: Electrician; D: Steel worker; E Vent worker; F: Plumber; G: Activity-specific material; H: Wall formwork; I: Concrete Pump; * Crane used only part-time of an activity's duration

Appendix C

TABLE C1: Construction sequence for the first 14 days for the project in field study 4.

Work day	Framework construction sequence (field study 4)	
	Building 1	**Building 2**
1 to 6	Wall sections 1 to 6 at floor level 1 (UOB2 to UOB8). Equals to one section per day.	N/A
7	Move wall formwork to building 2 (UOB9). Start assembly falsework up to floor level 2 (UOB12). Also start activities UOB10 and UOB11.	Move wall formwork to building 2 (UOB9). Prepare wall formwork.
8 to 13	Falsework, formwork, rebar, installations, prefab components, pour wet rooms (UOB12 to UOB25).	Wall sections 1 to 6 at floor level 1 (UOB2 to UOB8). Equals to one section per day.
14	Pour concrete floor slab (UOB26). Move wall formwork to building 1 (UOB9). Prepare wall formwork.	Move wall formwork to building 1 (UOB9). Start assembly falsework up to floor level 2 (UOB12). Also start activities UOB10 and UOB11.
15	Repeat work cycle at floor level 2	Falsework (cont'nd), …

TABLE C2: General model input variables for simulation of a project resembling field study 4.

Input variable	Value	Remark
Number of floor levels	6	Per building
Number of slab sections per floor (work location)	1	Per building
Number of wall sections per floor	6	Per building
Total number of carpenters	6	Shared between two buildings
Total number of concrete workers	5	Shared between two buildings
Total number of electricians	2	Shared between two buildings
Total number of plumbers	2	Shared between two buildings
Total number of vent-workers	1	Shared between two buildings
Total number of steel workers	2	Shared between two buildings
Total number of cranes	2	One per building
Total number of concrete pumps	1	Only on site when pouring concrete slabs.
Available wall formwork (m^2)	180	Single form side
Work-hours per day	8	7:00 to 12:00 a.m., 1:00 to 4:00 p.m.
Total labour cost (€/hour)	480	Including 18 workers.
Total crane cost (€/hour)	133	Two tower cranes incl. operators
TCPS walls (hours)	15	Time between Concrete Placement and Striking of wall formwork.

Appendix C (cont'd)

TABLE C3: Activity-specific input variables for simulation of a project resembling field study 4.

UOB	Activity name	Unit	Quantity of work	Resource allocation		Predecessor (UOBs)	Dfactor[1]	Prate (man-hrs/unit)	Material unit cost (€/unit)
				Workers[2]	Cfactor[3]				
1	Prepare formwork (not included)	m^2 formwork	n/a	n/a	n/a	n/a	n/a	n/a	n/a
2	Erect wall form (1st side)	m^2 formwork	57	4A	0,15	1	1,0	0,15	4,0
3	Fix wall reinforcement	kg reinforcement	477	2B	0,08	2	0,5	0,01	1,0
4	Installation systems	meter of pipes	53	1C	0	2	0,5	0,03	2,0
5	Erect wall form (2nd side)	m^2 formwork	57	4A	0,15	3; 4	1,0;1,0	0,15	4,0
6	Pour concrete wall	m^3 concrete	10	2B	1,0	5	1,0	0,4	90
7	Strip formwork (both sides)	m^2 formwork	114	4A	1,0	6	1,0	0,01	n/a
8	Move formwork to next wall sec.	m^2 formwork	114	4A	1,0	7	1,0	0,01	n/a
9	Move formwork to next work loc.	m^2 formwork	114	4A	1,0	8	1,0	0,08	n/a
10	Surface repair	m^2 treated wall area	114	1B	0	8	1,0	0,1	0,1
11	Stair lower section	number of segments	2	2B	1,0	8	1,0	2,28	2160
12	Erect falsework	m^2 supported area	515	2A	0,1	8	1,0	0,05	2,8
13	Install Filigran-elements	m^2 elements	463	2B	1,0	12	1,0	0,02	24
14	Sealing element joints	m^2 sealed element	463	2B	0	13	1,0	0,02	0,9
15	Erect stop ends and safety rails	meter formwork/rails	99	1A	0,07	13	1,1	0,14	2,9
16	Install balconies	m^2 balcony area	52	2B	1,0	13	1,5	0,11	166
17	Install steel columns	Number of columns	4	2D	1,0	13	1,2	2,0	330
18	Place rebar bottom layer	kg reinforcement	385	2B	0,02	14	1,0	0,05	0,7
19	Stair upper section	number of segments	1	2B	1,0	8;13	1,0;2,0	2,28	2160
20	Install ventilation ducts	meter of ducts	13	1E	0	18	0,5	0,15	7,0
21	Install pipes for water and sewage	meter of pipes	462	2F	0	18	0,5	0,09	7,6
22	Install cable ducts for electricity	meter of cable ducts	225	1C	0	18	0,5	0,06	4,1
23	Place rebar top layer	kg reinforcement	1900	2B	0,06	15;16;17;19 20;21;22	0,5	0,02	0,7
24	Duct forms (wet rooms)	meter formwork	58	2A	0	23	0,9	0,02	0,25
25	Pour concrete wet rooms (pump)	m^3 concrete	6	3B	0	24	1,0	0,2	105
26	Pour concrete slab (pump)	m^3 concrete	110	3B	0	25	1,0	0,2	105
27	Unload falsework (not incl.)	m^2 supported area	n/a	n/a	n/a	26	n/a	n/a	n/a
28	Remove falsework (not incl.)	m^2 supported area	n/a	n/a	n/a	27	n/a	n/a	n/a

[1] Dfactor which determines start-to-finish relation between activity and its predecessor(s).
[2] A=Carpenter, B=Concreter, C=Electrician, D=Steel worker, E=Vent worker, F=Plumber
[3] Crane usage factor which determines the use of crane in an activity ranging from 0-1, where 0 indicate no use and 1 indicate 100% use in activity