SIMULATION OF CONSTRUCTION OPERATIONS APPLIED TO IN SITU CONCRETE FRAMEWORKS

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ABSTRACT

The erection process of in situ cast concrete frameworks in multi-storey housing consists of multiple on site activities in which labour, equipment and materials are interacting in a complex system. Studies have shown that the current process involves a wide range of non-value adding activities, resulting in poor process efficiency.

This paper presents a model developed for discrete-event simulation of activities and resource use involved in the construction of in situ cast concrete frameworks in multi-storey housing. The model simulates the work flow which is subject to multiple work locations and resource availability constraints. The model has been developed and validated by studying four ongoing projects. The model functionality and simulation approach are described. The validation of the model is also described and finally a parametric study is conducted to demonstrate the use of the model.

It is shown that the model can reproduce the dynamic behaviour in a work flow constrained by resource availability. The model can be used to analyze how different production strategies involving resource allocation influence total construction time and cost.

KEY WORDS

discrete-event simulation, in-situ concrete framework, construction activities, work flow

INTRODUCTION

An established and commonly used method for construction of the structural frame in multi-storey housing is the use of concrete in combination with temporary or permanent formwork systems. In Sweden, this is the most commonly used method today. The construction method consists of several on site activities carried out sequentially or in parallel where materials, equipment and workers are interacting in a complex way, influencing the total work flow. Poor planning and control are important reasons for process variability, low resource utilization and a high level of non-value adding activities (waste). Studies have shown that the cost of waste in construction projects represents 30-50% of the total production cost (Josephson and Saukkoriipi 2005). Established organizational structures and traditional contractual and union-related agreements also contribute to waste creation. Exploration of the full

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potential of the construction process requires an approach which is not restricted by existing process obstacles and current practice.

Discrete-event simulation is a widely accepted research method for studying complex processes. It provides a realistic approach to analysis since it enables consideration of randomness in activity duration and the influence of resource availability as a constraint to construction work flow.

Discrete-event simulation has been used for several decades within research for studying construction processes. Simulation was used for the design and optimization of the concrete delivery process (Zayed and Halpin 2000; Wang and Halpin 2004). Huang et al. (2004) simulated different ways to use gang forming systems in building construction. Discrete-event simulation was also used for re-designing existing processes based on Lean-principles (Tommelein 1997; Halpin and Keuckmann 2002). In Maturana et al. (2003), a Monte-Carlo simulation was used to study possible improvements of the construction process by introducing multi-skilled workers and increasing the frequency of concrete placement operations. Different aspects of buffers in the value chain of HVAC ductwork using simulation were explored in Alves and Tommelein (2004) and Alves et al. (2006). Simulation of different approaches to lead-time buffering in construction processes were studied by González et al. (2006) and Srisuwanrat and Ioannou (2007).

The main application of discrete-event simulation in previous research has tended to be on solving specific issues, focusing on a particular part of the process at a work task level. However, in order to describe the on site work flow, a broader approach is necessary where all activities and resources involved in the construction process are considered. The interplay between multiple activities carried out at different work locations sharing the same resources must be considered in order to describe the dynamic behaviour of the total work flow. Use of discrete-event simulation to study multiple work flows in a concrete framework erection influenced by resource constraints has not been fully addressed in previous research.

This paper presents a model for discrete-event simulation of activities and resources involved in the construction process of in situ cast concrete frameworks in multi-storey housing. The model simulates the work flows subject to different work locations and constrained by resource availability. The model can be used for studying how different construction alternatives involving resources influence construction time, cost and resource utilization. This in turn could give new insights into improvement of the efficiency of a specific construction method.

DESCRIPTION OF THE PROCESS BASED ON FOUR CASE STUDIES

To obtain insights into current practice in the construction of in-situ cast concrete frameworks, a two-stage study of such a construction process was carried out for four ongoing multi-storey housing projects. In the first stage, two case-studies, denoted A and B, were carried out using data collected from on-site visits where the process work flow was mapped by interviewing responsible site mangers and supervisors. In addition, the site visits also involved documentation of resource usage practice, construction methods used and activity durations. The knowledge obtained was used to develop a conceptual model of the construction process. It also gave insights into requirements for implementation of the conceptual model in simulation software. Additionally, the case-studies were also used for validation of the conceptual model during development and subsequent parametric studies. In the second stage, the same procedure was then repeated for two more projects, C and D, resulting in additional knowledge, which was used to further refine the model. To obtain real process data, extensive measurements of on site activities were carried out in projects C and D (Lundström and Runquist 2008, Lindén and Wahlström 2008). In project D, associated construction costs were documented and used to analyze definition and management of costs in the simulation model (Lindén and Wahlström 2008).

The work sequence used to erect the concrete framework was found to be similar for all projects studied. The process starts with erection of temporary wall formworks and proceeds with placement of reinforcement and electric cables, followed by erection of the second side of the formwork. The work sequence ends by pouring concrete into the formwork using a tower crane and a skip. The following day, the formwork is stripped and prepared for the next wall section. When all walls are finished, the formwork is moved to the next work location, allowing space to enable erection of props and stringers supporting the slab formwork system and the prefabricated balconies. The work sequence then continues with the placing of prefabricated lattice girder elements onto the stringers. This is then followed by several activities carried out in parallel, such as sealing the formwork, placing reinforcements over joints between the lattice girder elements and installing prefabricated balconies, stairs and steel columns. After that, the work of placing HVAC ductwork is carried out. The placement of top reinforcement is carried out after placement of the installation systems together with a finalizing sealing of the formwork making the slab section ready for concreting. Finally, the work cycle ends with the pumping of concrete onto the slab. The procedure is then repeated for each slab section (pour unit). One work crew (mix of carpenters and concreters) is assigned to carry out wall operations, with another crew responsible for slab operations. Sub-contractors are employed to carry out placement of installation systems and steel columns. When a crew has finished its work at a slab section, it moves on to perform the same activities at a new slab section. The main layout of the different slab sections for projects A-D is illustrated in figure 1. The number of each section represents the order in which the slab sections were processed by the work crews.

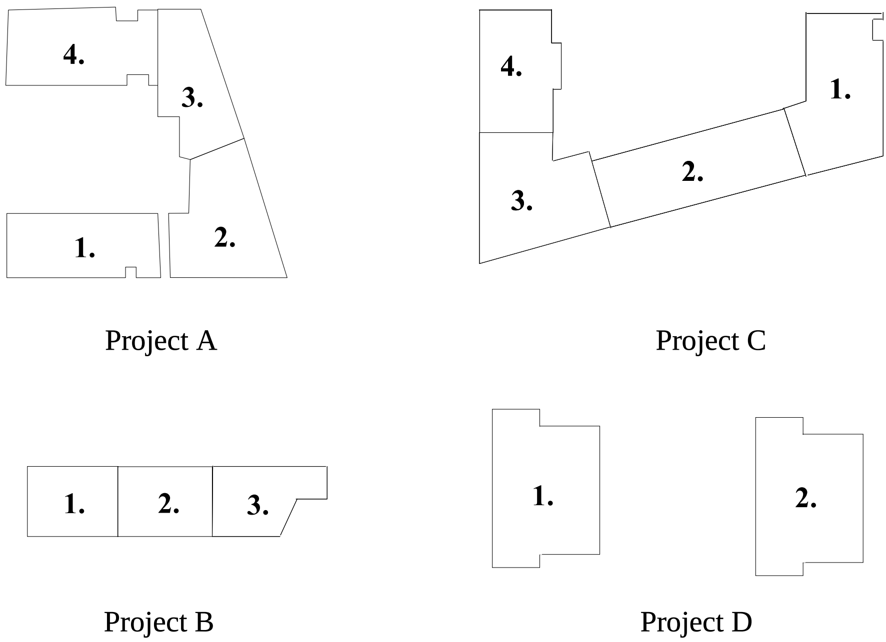

Figure 1: Schematic layout of slab sections in projects A-D.

MODEL DEVELOPMENT

CONCEPTUAL MODEL OF CONSTRUCTION WORK FLOW AND RESOURCE USAGE

A model was then developed to describe the logical dependencies of activity work flow and the use of resources in the construction processes observed, see figure 2. An activity was defined as one or more work operations carried out over a continuous and clearly defined period of time using the same setup of resources. The model covers a complete set of activities (numbered 1-23) connected to a work location which represents a slab section (pour unit). Each slab section could consist of several wall units (wall cycles). Activities 1 to 7 represent one single wall cycle.

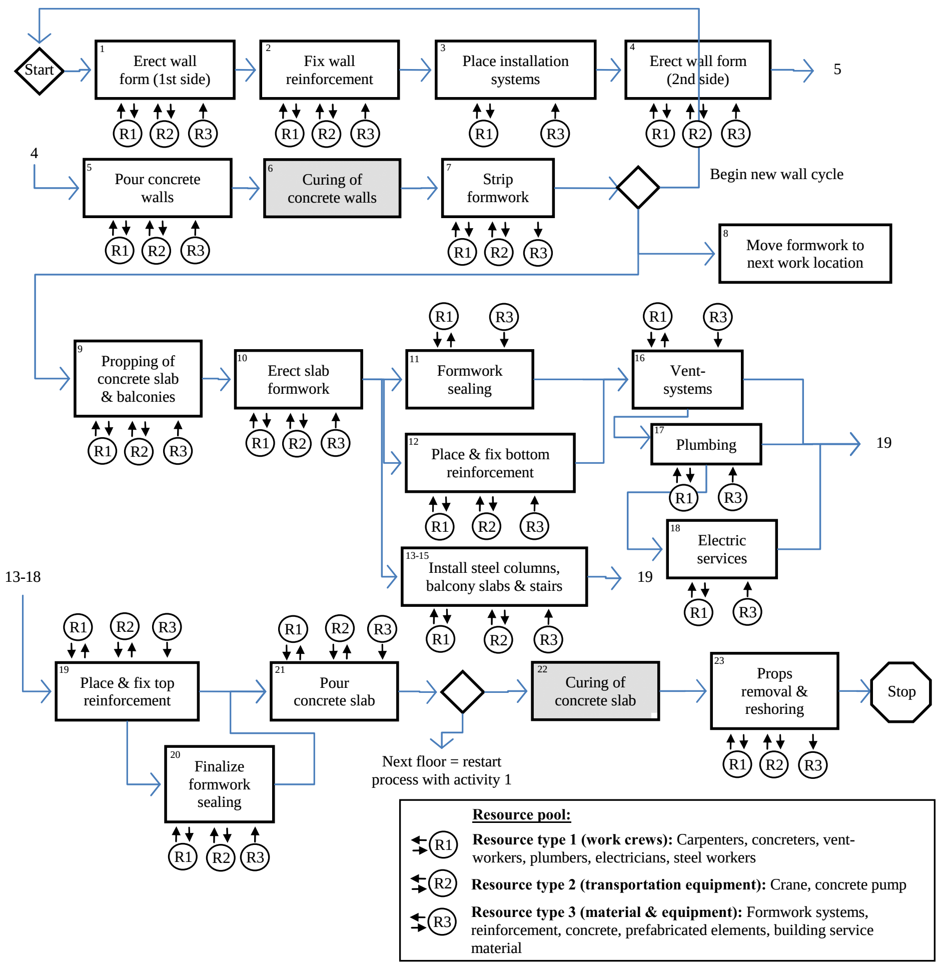

Figure 2: Process scheme for in situ concrete framework construction

The process starts with erection of the first side of the wall formwork (activity 1). All wall units belonging to the same slab section are processed during activities 1-7 until all walls are poured. When activity 7 is finished and all wall units have been poured, the process continues with the erection of props and stringers (activity 9) and the temporary formwork is moved to the next work location (activity 8). The simulation stops when activity 23 is finished at the top floor. If the floor slab is divided into several sections (work locations), each section is described according to the process scheme in figure 2. There exists only one resource pool for each resource type controlling the transactions of resources between the different work locations. This approach could also be used to model projects consisting of several buildings which are erected simultaneously sharing the same resources.

DESCRIPTION OF SIMULATION SOFTWARE USED

The conceptual model was implemented in the commercial simulation software Extend^{TM}, which is general-purpose software for continuous and discrete-event simulation. Extend^{TM} uses a graphical user interface which facilitates understanding and communication. A model is created by selecting blocks which are added to the model window and then connected. The connected blocks represent the system of interest. Extend^{TM} provides many types of blocks which all are pre-programmed to perform a specific task.

ExtendTM uses an event scheduling approach which is somewhat different from the established systems used for simulation of construction processes, such as CYCLONE (Halpin, 1977) and STROBOSCOPE (Martinez, 1996). These systems are based on a modified activity scanning strategy which is more suitable for model work flows in cyclic form (Lu and Wong, 2007). However, since the research focused on studying the erection process of the concrete framework which could be seen as being processed by a sequence of activities performed in a linear work flow repeated at different work locations and constrained by resource availability, the event scheduling strategy was considered to be applicable.

IMPLEMENTATION IN THE SIMULATION SOFTWARE

The conceptual model described in figure 2 was implemented in Extend. The modelling and simulation approach used to describe the work flow and the use of resources is illustrated in figure 3. An item arrives at event time T_1 initiating activity number 1. In the model, the item is viewed as a “work order” flowing through the system initiating activities.

During the simulation run, events changing the state of the system are scheduled. Events represent, for instance, start and finish time of activities 1 to n (T1-Tn) as illustrated in figure 3.

All activities are modelled in Extend using existing pre-programmed blocks which are arranged in similar way, as illustrated by the lower part of figure 3. Simulation of one activity consists of five steps:

1. *Preparation:* The item arrives and is assigned a priority describing the importance of the activity when requesting resources. It is also possible to define a delayed start for the activity. For instance, activity 3 is scheduled to start with a delay in relation to activity 2, as illustrated in figure 3.

2. *Allocate resources:* The item enters a multi-resource queue where a request to allocate a specific quantity of different resources is sent to the global resource pool. Several types of resources could be specified in the request, such as carpenters, concreters, crane, materials etc. If the requested quantity of the different resources types is available at current time, these are allocated to the multi-resource queue, enabling the item to continue. If the resources in the resource pool are busy, supporting other activities, the item has to wait until the resources requested become available. If several

activities request the same type of resources simultaneously, the activity with the highest priority will receive the requested resources first.

3. *Calculate serving time:* In this step, the activity duration is calculated based on actual quantity of work, production rate and number of resources allocated in step 2.
4. *Processing activity:* The item is held while being processed according to the calculated time in step 3.
5. *Release resources:* The allocated resources are released and sent back to the resource pool where they then become available for use in other activities. Resources such as materials are permanently consumed by the activity and not released back to the resource pool.

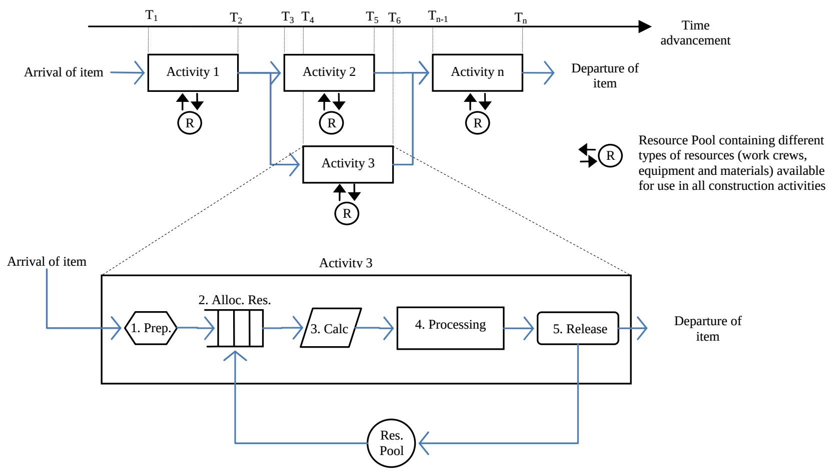

Figure 3: Modelling approach used to describe work sequencing and use of resources

When the simulation has completed step 5, the activity is finished and the item is routed to initializing the following activities defined by the model order. The time it takes for the item to be processed by steps 1 to 5 is recorded by the simulation clock which is used to calculate total time and resource utilization factor.

Additional blocks describing the logic of work flow between different work locations have been added to the model in order to enable simulation of a complete erection process of one or more multi-storey frameworks.

REQUIRED INPUT INFORMATION

The input information necessary to run a simulation consists of general information and activity-specific information. The general information consists of; Number of floors and wall units per floor or slab section; Number of available resources (work crews, temporary formwork systems, cranes); Work-hours schedules which apply to each work crew; Curing time before stripping of temporary formwork; Resource costs (workers, material and equipment).

The activity-specific information needed consist of; Quantity of work defined as unit per activity; Number and type of resources needed per activity; Production rate defined as man-hours per unit. The production rate can be either a constant value or variable according to a specific statistical distribution.

A more detailed example of general and activity-specific information required by the model is presented in appendix A.

MODEL VERIFICATION

The measurements in projects C and D were used to verify the model. The measurements and a detailed description of the project and the construction process are presented in Lundström and Runquist (2008) and Lindén and Wahlström (2008). Detailed information for each activity was inserted into the model and simulated floor cycle time was compared to measured floor cycle time as given in table 1. The measured construction cycle for each floor was 18 days for project C and 14 days for project D. The simulated floor cycle time for project C was almost constant at 19 days. Simulated floor cycle time in project D was more close to actual floor cycle time but also had a higher variability between floor cycles.

Table 1: Simulated floor cycle time for projects C and D.

	Measured floor cycle time (days)	Simulated floor cycle time (days)		No. of floor cycles simulated
		Mean	Std dev	
Project C	18	19.0	0.04	20[1]
Project D	14	14.3	0.6	10[2]

The deviation between simulated and measured values could be explained by the modelling assumption that an allocated resource is locked during the whole activity duration. In reality, it is possible to have a more flexible use of resources. Nevertheless, the results clearly indicate that it is possible to reproduce complex work flows which are subject to resource constraints. In addition, simulated start and finish times for activities were analyzed to verify that activities were executed in the right order. The validation also included discussion with site personnel and people responsible for on site measurements in projects C and D.

PARAMETRIC STUDIES

To demonstrate the use of the model for simulation of alternative design of the construction process, three alternative production strategies, P1, P2, and P3, were tested in comparison to P0 which was actually used in project D. In P1, the number of wall cycles was reduced from six to four. Two additional workers were allocated to wall operations to compensate for the increased work load per wall cycle. In P2 three additional workers were allocated to some of the slab activities besides the changes implemented in P1. The only difference between P3 and P0 was that only one larger crane was used in P3 instead of two in P0. In

[1] Each slab section included
[2] Two buildings

table 2, the results from the simulation experiments are shown. Total time and cost for P0 are normalized. The data used for the parametric studies are presented in appendix A.

Table 2: A simplified comparison between four construction alternatives.

	P0	P1	P2	P3
Total time (normalized)	1.0	0.96	0.86	1.15
Total cost (normalized)	1.0	1.065	1.068	1.13

As expected, the results indicate that P1 and P2 decrease the total construction time but at the expense of increased cost due to higher labour costs. The effect of applying additional resources in P1 does not result in any significant reduction of time due to bad synchronization between wall and slab operations causing stagnation in work flow. When additional resources are added to slab operations, the total times are further reduced but still at a higher cost compared with P0. The simulation also reveals that removal of one of the cranes, as given by P3, results in increased time and cost. The crane becomes the critical resource delaying the total work flow.

POSSIBILITIES TO SIMULATE LEAN CONSTRUCTION CONCEPTS

The model enables to study the influence on process productivity by applying concepts based on Lean-construction. For example, the model enables simulation of different ways to level out the work load and to improve synchronization between wall and slab activities in order to minimise work flow stagnation and process variability. Another possible application is to simulate alternative work-hour schedules (for example work in two-shifts) to improve the utilization of resources during the total available construction time. The effect on process work flow by introducing multi-skilled workers could also be implemented and simulated. Furthermore, alternative construction methods, such as prefabricated permanent wall form systems enabling a reduced amount of on-site work and trade-offs, could be modelled and simulated.

CONCLUSIONS

Simulation offers new possibilities for analyzing the dynamic behaviour of processes influenced by several resource constraints. A new process model and simulation approach has been proposed to study the total work flow of the erection process of in situ cast concrete frameworks. Based on experience from the verification, it has been concluded that the model is capable of simulating the construction work flow, considering the influence of resource availability. The use of the model was demonstrated by simulation of three alternative construction strategies. It has been shown that the model can analyze how different production strategies involving resource allocation influence total time and cost. This can improve the understanding of improvement of construction work flow in terms of increased efficiency and reduced costs.

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APPENDIX A

Table A1: General information required for simulation of project D.

General layout and production-related information (P0\P1\P2\P3)		Resources available for framework erection (P0\P1\P2\P3)			
		Resource type	No. of resources	Resource type	No. of resources
Number of floors	6\6\6\6	Carpenters	6\7\7\6	Crane	2\2\2\1
Number of slab sections per floor[1]	1\1\1\1	Concreters	4\5\6\4	Concrete pump	1\1\1\1
Number of wall units per floor slab (section)	6\4\4\6	Electricians	2\2\3\2	Wall formwork (m^2)	180\270\270\180
TCPS[2] walls (hours)	16\16\16\16	Steel workers	2\2\2\2	Cost information:	EUR/hour:
TCPS slab (hours)	720\720\720\720	Vent workers	1\1\1\1	Total labour cost	480\544\640\480
Work-hours schedule	8-12 a.m.,13-16 p.m.	Plumbers	2\2\3\2	Total crane cost	133\133\133\120

Table A2: Activity-specific information required for simulation of project D. Information is defined per wall unit and slab section.

Activity per pour unit (numbering according to fig. 2)	Amount of work per activity		Resource allocation[3]		Material cost (EUR/unit)	Production unit rate (hour/unit)
	Unit	Quantity P0\P1\P2\P3	Workers P0\P1\P2\P3	Transport-equipment		
1. Erect wall form (1st side)	m^2 formwork	57\85\85\57	2A\3A\3A\2A	G	1.6(2.3[4])	0.17
2. Fix wall reinforcement	kg reinforcement	477\716\716\477	1B\2B\2B\1B	G*	1.0	0.01
3. Installation systems (elec.)	metre of elec.pipes	53\80\80\80\53	1C\1C\1C\1C	-	0.5	0.03
4. Erect wall form (2nd side)	m^2 formwork	57\85\85\57	2A\3A\3A\2A	G	1.6(2.3)	0.11
5. Pour concrete wall	m^3 concrete	10\15\1510	1B\2B\2B\1B	G	103	0.19
6. Strip formwork (both sides)	m^2 formwork	114\170\170\114	2A\3A\3A\2A	G	n/a	0.04
8. Move formwork	m^2 formwork	114\170\170\114	2A\3A\3A\2A	G	n/a	0.07
9. Propping slab & balconies	m^2 supported	515\515\515\515	2A\2A\2A\2A	G*	2.8	0.05
10. Erect lattice girder elements	m^2 lattice girder elem.	463\463\463\463	2B\2B\2B\2B	G	24	0.02
11. Sealing lattice girder elem.	m^2 sealed area	463\463\463\463	2B\2B\2B\2B	-	0.9	0.02
12. Place btm reinforcement.	kg reinforcement	385\385\385\385	2B\2B\3B\2B	G*	0.7	0.05
13. Install steel columns	number of columns	4\4\4\4	2D\2D\2D\2D	G	330	2
14. Install balconies	m^2 balcony area	52\52\52\52	2B\2B\2B\2B	G	166	0.11
15. Install stairs	number of stairs	1\1\1\1	2B\2B\2B\2B	G	5106	2
16. Install ventilation system	metre of vent. duct	13\13\13\13	1E\1E\1E\1E	-	7	0.15
17. Plumbing	metre of pipes	462\462\462\462	2F\2F\3F\2F	-	6.2	0.14
18. Install electrical sys.	metre of elec. pipes	225\225\225\225	1C\1C\2C\1C	-	1.2	0.02
19. Place top reinforcement	kg reinforcement x1000	1.9\1.9\1.9\1.9	2B\2B\3B\2B	G*	0.7	0.02
20. Stop ends (shaft, slab edge)	metre of sealing	99\99\99\99	1A\1A\1A\1A	G*	2.9	0.14
21. Pour concrete slab	m^3 concrete	116\116\116\116	3B\3B\3B\3B	F	123	0.2
23. Props removal/re-shoring	m^2 propped area	515\515\515\515	2A\2A\2A\2A	G*	n/a	0.03

[1] Two buildings with one slab section per floor.
[2] TCPS: Time between Concrete Placement and Striking of formwork
[3] A=Carpenter, B=Concreter, C=Electrician, D=Steel worker, E=Vent worker, F=Plumber, G=Crane, G*=Crane used for lifting material to work location, F=Concrete Pump
[4] Valid for P1 and P2 due to the extra quantity of formwork needed