

# Discrete-Event Simulations of Construction Related Production Systems



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# **Discrete-Event Simulations of Construction Related Production Systems**

Diskret händelsestyrd simulering av byggrelaterade  
produktionssystem

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2009

## **Abstract**

The construction industry both in Sweden and abroad suffers from low productivity and quality related issues. This work investigates how discrete-event simulation can be used in planning of construction related productions systems. The purpose of this work is to develop a model which simulates on-site construction activities in terms of time, cost and resource usage. A model was developed which simulates on-site construction activities considering uncertainty factors such as prevailing weather conditions. The model was tested in a real project with promising results. Five different scenarios were simulated to demonstrate the possibilities of the model.

## **Keywords**

Construction, Concrete frameworks, Discrete-Event Simulation, Efficiency, Resource utilization.

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## **Forewords**

This report is written as a master thesis in Civil Engineering at the Faculty of Engineering at Lund University.

I would like to begin by thanking my supervisor Robert Larsson for all the help he has provided and I would also like to thank my father Birgir Karlsson for all his help. It was great to have people who were interested in my work and were always ready to help.

I hope this work may provide the reader with some insight into simulation modeling and how it can be used in the construction industry and hopefully encourage others in further studies.

This work corresponds to 30 credits at the University, it started in May 2009 and was finished in November 2009.

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Karl Raymond Birgisson



## Summary

The construction industry both in Sweden and abroad suffers from low productivity and quality related issues. According to Josephson and Saukkoriippi (2005), the amount of non-value added work at a construction site was measured to be 33% of a workday. Consequently, it is important to introduce new ideas and methods which aim to increase the process efficiency in terms of shorter construction time, reduced costs and higher quality. A major reason for low productivity is lack of planning. Today's methods and tools for planning do not fully support the planner's needs to see the complex relationships in how resources are used in the construction site and also to take uncertainties into account, e.g. in the form of various weather conditions.

Discrete-event simulation is a method well suited to describe and simulate complex systems. It is especially appropriate for dealing with complex relationships between components, resources and how they are used in the process. The method is now a standard tool in manufacturing industries but it is so far limited to individual research projects in the construction industry. However, the recent developments in computer software, that support this technology, open for an introduction of discrete-event simulation as an alternative planning method in construction projects.

This work is about how simulation can be used as an alternative method in project planning.

The purpose of this work is to develop a model which simulates on-site construction activities in terms of time, cost and resource usage. Another purpose is to demonstrate the use of the model by simulating various scenarios, e.g. random phenomena caused by variable weather conditions, scenarios involving assessment of the effect of workers' experience or by introducing an alternative construction method.

The goal is that the model should enable the user to analyze how different construction scenarios will affect the construction project and use that information to increase the efficiency in work procedures in the project. Another goal is that the model should be easy to use for people involved in planning construction projects.

The work has consisted of three parts. The first part consisted of literature studies where most emphasis was laid on studying the theories of discrete event simulation, studying unit times and unit costs of construction activities and how Access databases work. The second part consisted of among other things of data gathering, developing of a simulation model that simulates the time, cost and resource use, creating a user interface and to demonstrate how the model can be used to plan and evaluate a building project by comparing the simulated results with a real project and by testing the model in five different simulated scenarios. The third part consisted of writing the report.

The results from the five different simulated scenarios are as follows:

Scenario 1: The total cost of the building project increased by 8,3% if the work was carried out over the winter months compared with summer months. The duration of the construction time increases by 18%.

Scenario 2: The total cost did reduce by 4,8% if the experience gained from repetitive work was taken into account compared with the reference case where experience was not taken into account. The duration of the construction time did decrease by 12%.

Scenario 3: The total cost did reduce by 0,6% if both the influence of weather (winter months) and the experience effects were taken into consideration and the duration of the construction time decreases by 1% compared with the reference case.

Scenario 4: The total cost increases by 6% if precast twin walls were used instead of walls casted on-site (which was used in the reference case), but the duration of the construction time reduces by 19%.

Scenario 5: The total cost did reduce by 3,1% compared with scenario 4 if the precast twin walls were used while some other changes were made, for example the use of an additional crane and an additional workgroup. Compared with the walls casted on-site (reference case), the total cost was still 3% higher but the duration of the construction time has been reduced by 43%.

This work has clearly demonstrated the potential of simulation technology. By using simulation in project planning, a whole new window of opportunities opens. Simulations allow exploring different ideas and methods without committing resources to acquisition. Using simulation models in project planning definitely has its advantages but the best solution is to combine the strengths from both the traditional methods and simulations.

## Sammanfattning

Byggbranschen både i Sverige och utomlands lider av låg produktivitet utveckling och bristande kvalitet. Enligt Josephson och Saukkoriipi (2005), är andelen icke-värdeskapande arbete på en byggarbetsplats cirka en tredjedel av en arbetsdag. Det är därför viktigt att införa nya idéer och metoder som syftar till att öka processens effektivitet i form av kortare byggtid, minskade kostnader och en hög och jämn kvalitet. En viktig orsak till låg produktivitet är brister i planeringsskedet. Dagens metoder och verktyg för planering stödjer inte planerarens behov av att se komplexa samband gällande hur resurser används på arbetsplatsen eller att hänsyn tas till osäkerheter i form av olika väderförhållanden etc.

Diskret-händelsestyrd simulering är en metod som väl lämpar sig för att beskriva och simulera komplexa system. Det är speciellt lämpligt för att hantera komplexa samband mellan komponenter, resurser och hur de används i processen. Metoden är idag ett vanligt hjälpmedel i den fasta industrin men inom byggbranschen används det hittills begränsat till enstaka forskningsprojekt. I takt med att datorverktygen som stödjer tekniken förbättras ökar möjligheterna för att introducera metoden som ett alternativt planeringsstöd även i byggprojekt.

Detta examensarbete handlar om hur simulering kan användas som en alternativ metod i planeringen av byggprojekt.

Syftet med arbetet är att utveckla en modell som simulerar aktiviteter i form av tid, kostnad och resursanvändning. Ett annat syfte är att demonstrera användningen av modellen genom att simulera olika scenarier, t.ex. osäkerheter orsakade av varierande väderförhållanden men även hur upprepade arbetsmoment påverkar produktiviteten eller vilken effekt som fås av att införa en alternativ byggmetod.

Målet är att modellen ska ge användaren möjlighet att analysera hur olika produktionsscenarier påverkar byggprojektet och att använda denna information för att öka effektiviteten i projektet. Ett annat mål är att modellen ska vara enkel att använda för dem som deltar i planeringen av byggprojekt.

Arbetet har bestått av tre delar. Den första delen bestod av litteraturstudier, störst tonvikt lades på att studera teorier om händelsestyrd simulering, studera enhetstider och enhetskostnader av aktiviteter i byggbranschen och hur Access-databaser fungerar. Den andra delen bestod bland annat av informations samling, att utveckla en simuleringsmodell som simulerar tid, kostnad och resursutnyttjande, att skapa ett användargränssnitt och att visa hur modellen kan användas för att planera och utvärdera ett byggprojekt genom att jämföra simulerade resultat med ett verkligt projekt och genom att testa modellen i fem olika simulerade scenarier. Den tredje delen bestod av att skriva rapporten.

Resultaten från de fem olika simulerade scenarier var följande:

Scenario 1: Kostnaden för ett byggprojekt ökade med 8,3% om arbetet genomfördes under vintermånaderna jämfört med sommarmånaderna. Den totala byggtiden ökade med 18%.

Scenario 2: Om hänsyn tas till upprepning i arbetsmoment minskar kostnaden med 4,8% jämfört med om det inte beaktas. Den totala byggtiden minskar med 12%.

Scenario 3: Om både inverkan av väder (vinterfall) och upprepningseffekter beaktas samtidigt minskar kostnaden med 0,6% och den totala byggtiden med 1% jämfört med om inget av detta beaktas.

Scenario 4: Om skalväggar används istället för platsgjutna väggar (vilket användes i referensfallet) ökar kostnaden med 6% men den totala byggtiden minskar med 19%.

Scenario 5: Om skalväggar används samtidigt som vissa andra förändringar görs, tex användning av ytterligare en kran och ett arbetslag minskar kostnaden med 3,1% jämfört med scenario 4. Jämfört med platsgjutna väggar (referensfallet) är kostnaden fortfarande 3% högre men den totala byggtiden har minskat med 43%.

Arbetet har tydligt visat på potentialen med simuleringsteknik. Genom att använda simulering i projektplanering öppnas nya möjligheter. Simuleringar gör det möjligt att utforska olika idéer och metoder på ett kontrollerat och kostnadseffektivt sätt. Simuleringsmodeller i projektplanering har definitivt sina fördelar, men den bästa lösningen är att kombinera simulering med traditionella planeringsverktyg.

## **Definitions**

Activity – A construction task

Attribute – An inherent characteristic, which provide information about the item

Block – A block represents a portion of the process or system that is being modeled

Continuous models – The system changes state at a fixed time step

Database – A large collection of data organized especially for rapid search and retrieval

Discrete models – The system changes state only as events occur

Entities – Items which move from block to block as events occur during the simulation run

Filigran element – A prefabricated reinforced concrete slab

Level – A project can be broken down into different levels, e.g. floor 2

Model – A representation containing the essential structure of some objects or events of a system at one point in time

Precast twin walls – Consists of two prefabricated concrete plates which form a single unit. The cavity between the plates is filled with concrete on site after the panel has been erected to complete the composite wall

Predecessor – If activity A is a predecessor to activity B then has the activity A to be finished in order for activity B to start

Simulation – The imitative representation of how a system or process functions by means of the functioning of another

Stage – A level can be broken down into different stages, e.g. walls, north wing

System – A group of interaction entities forming a complex whole based on the rules or operation policies of the system

Unit time – The normal time which it takes to perform a curtain amount of work

User interface – a computer program designed to allow the user to interact easily with the another program

Workgroup - Workgroup is a group of workers who work together on the same activity at the same time. Workgroups are created to get higher performance and for safety issues

# Table of Contents

1. Introduction.....	1
1.1 Background.....	1
1.2 Purpose and goals .....	2
1.3 Limitations.....	2
2. Method .....	3
2.1 Literature studies .....	3
2.2 Main phase.....	3
2.3 Report phase .....	4
3. Theory .....	7
3.1 Discrete-event simulation (DES).....	7
3.2 Construction process planning.....	13
4. Uncertainties in construction projects .....	25
4.1 Data collection by questionnaire .....	25
4.2 Results from the questionnaire .....	27
5. Description of simulation model.....	39
5.1 General.....	39
5.2 User interface.....	40
5.3 ExtendSim - model structure and components .....	48
5.4 Model results .....	50
6. Testing the model on a real project.....	55
6.1 Description of the real project used in the simulation .....	55
6.2 The input data .....	57
7. Verification of simulation model .....	61
7.1 Time plans .....	61
7.2 Utilization of workers.....	66
7.3 Costs .....	70
7.4 Work Breakdown Structure .....	74
8. Simulations of five scenarios .....	75
8.1 Case 1 – Effect of different weather conditions .....	75
8.2 Case 2 – How experience affects productivity .....	77
8.3 Case 3 – Combinations of cases 1 and 2.....	78

8.4 Case 4 – Precast twin walls .....	79
8.5 Case 5 – Use the model to increase efficiency .....	85
9. Discussion .....	87
10. Conclusions.....	91
11. References.....	93
11.1 Printed books and articles.....	93
11.2 Digital material .....	93
11.3 Interviews .....	94
Appendix A - Description of activities .....	95
Appendix B - Example of weather data used in case 1 and 3 .....	101

## **1. Introduction**

### **1.1 Background**

The construction industry both in Sweden and abroad suffers from low productivity and quality related issues. According to Josephson and Saukkoriippi (2005), the amount of non-value added work at a construction site was measured to be 33% of a workday. Consequently, it is important to introduce new ideas and methods which aim to increase the process efficiency in terms of higher quality and reducing the construction time and costs.

There are several reasons for why the construction industry suffers from low productivity. For instance, the construction process is highly fragmented where many actors with different disciplines are involved. Each actor is responsible for a specific part of the project and they tend to focus on their own interest instead of to make the final product as good as possible.

Another important reason for poor productivity is that a construction site has so many influencing variables, e.g. different weather conditions, different site locations, different delivery times of material, various stock sizes, different designs and different working conditions. These variables make planning of a construction project much more complicated than planning for example an assembly line in a car factory where every day is the same.

So what can be done to make the construction industry more effective? It is generally accepted that the lack of proper planning is a major reason for poor project performance. It is both complicated and time consuming in many planning programs today to take into account all the uncertainties or disturbances that occur during a construction project. Traditional planning methods and tools do not fully support the planning engineer to deal with these complexities. It is therefore a need for better tools for project planning which makes it easier for the user to create better plans with higher accuracy.

Discrete event simulation is a powerful tool to analyze and design complex systems. It enables to explore alternative methods or testing new ideas in advance at a fraction of the cost compared to test the ideas in reality. A simulation model may contain complex relationships between activities which specifically consider resource usage and uncertainties such as variable weather conditions or randomly machine failure. Today, discrete-event simulation is a common tool supporting decision-making in manufacturing industries. In the construction industry, the use of discrete-event simulation has been limited to research projects even though it has been shown that the technique can shorten design cycles, reduce costs, and enhance knowledge in the construction industry. However, to introduce the technique in practice, the tools must be user-friendly.

## **1.2 Purpose and goals**

The purpose of this work is to develop a model which simulates on-site construction activities in terms of time, cost and resource usage. Another purpose is to demonstrate the use of the model by simulating various scenarios, e.g. random phenomena caused by variable weather conditions, scenarios involving assessment of the effect of workers experience or by introducing an alternative construction method.

The goal is that the model should enable the user to analyze how different construction scenarios will affect the construction project and use that information to increase the efficiency in work procedures in the project. Another goal is that the model should be easy to use for people involved in planning construction projects.

## **1.3 Limitations**

The possibilities to model and simulate processes are almost endless. It is therefore important to set limitations. The model is generic to its structure but is tested on activities involved in the erection of a concrete framework casted on-site. The activities concerned are; assemble and disassemble of temporary formwork, tying reinforcement of walls and plates, placing of electrical and water installations, erection of false work, placement of precast concrete elements (e.g. formwork, balconies and stairs), and pouring of concrete walls and slabs.

The model has been built in ExtendSim v7.2 which is commercial software for discrete-event simulation.

## 2. Method

The work consists of three major phases, literature studies, main phase and finally report phase, see figure 2.1.

### 2.1 Literature studies

Literature studies have been carried out continuously during the project. In the beginning of the work, most emphasis was laid on learning how the simulation software ExtendSim works. Then as the project evolved, more emphasis was laid on studying unit times and unit costs of construction activities and how these are influenced by various aspects. In the last part of the project, emphasis was laid on learning Access databases and how Access can be used to create a user interface for data management.

### 2.2 Main phase

#### 2.2.1 Data gathering

To develop the model, two types of data were necessary to collect. The first type concerned unit times and unit costs data for the activities that the model was going to simulate. It is important to know what type of work and the quantity of work which is included in the unit times. The main source of information about unit times in Sweden was obtained from Nybyggnadslistan (Sveriges Byggindustri 1999). In addition, three other international sources were used for comparison reasons:

- RSMeans, *Metric Construction Cost Data, 66<sup>th</sup> Annual edition*, 2008 (North-America)
- Institution of Civil Engineering, *CESMM3 Price database*, 2009 (Britain)
- Mannvit, *Building Cost database*, 2009 (Iceland)

To gain better understanding of how Nybyggnadslistan is structured and how the data has been collected, a person with knowledge in this matter was interviewed (Wallander, 2009). He described how the unit times in nybyggnadslistan have been measured and what are included in those unit times.

The second type of data concerned how e.g. different weather conditions affect various construction activities in terms of work performance. To gather that information, a questionnaire was created and distributed to people with knowledge and experience of planning and leading construction operations.

### **2.2.2 Model building**

Firstly, a simple model was created. A real project was used as a basis for creating the model. It is important to start with a simple model which just covers the basics of the system. Then a simple verification is made and the model is tested to see if it works. If the results are in harmony with the real system, then the model is on the right tracks. The model is then continuously further developed by adding more details and functionality in order to fulfill the goals and purpose of the project.

### **2.2.3 Creating databases**

The simulation model needs a lot of input data and produces even more result data. Microsoft Access 2007 was used to maintain both the input data and the result data using databases.

### **2.2.4 Creating user interface**

It is important that the user can enter data easily and sufficiently into the model. That is why a user interface was created.

### **2.2.5 Verifying the model**

After the model was finished the results were compared with a real project to see how well the model could simulate the behavior of a real construction process.

### **2.2.6 Simulation scenarios**

The next step was to create different simulations scenarios and analyze how these affect the results. Five different scenarios were simulated.

- Case 1 – The weather effects
- Case 2 – How experience effect the productivity
- Case 3 – Combinations of cases 1 and 2
- Case 4 – Precast twin walls
- Case 5 – Use the model to increase efficiency

These cases were selected in consultation with the instructor. Case 1-3 involve random events and Cases 4 and 5 are a change of method.

## **2.3 Report phase**

The last part of the project was to put everything together in a report. The goal for the report was to describe how the model works and show the results.

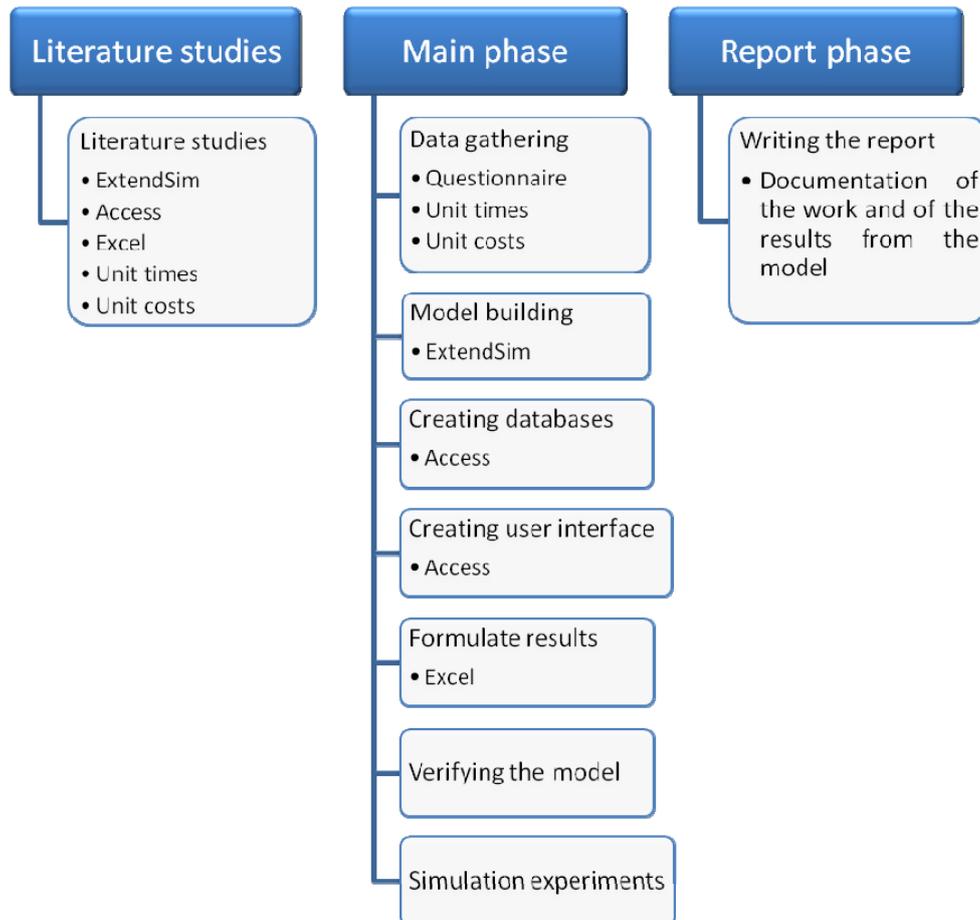


Figure 2.1 - The work consisted of three major phases, namely literature studies, main phase and report phase



### **3. Theory**

#### **3.1 Discrete-event simulation (DES)**

##### **3.1.1 Definition of simulation**

The Merriam-Webster Online Dictionary defines simulation as “the imitative representation of the functioning of one system or process by the functioning of another”. This means that to determine how an actual system functions, you would build a model of the system and see how the model functions (Imagine That Inc., 2007).

Simulation is an indispensable problem solving methodology for the solution of many real-world problems. Simulation is used to describe and analyze the behavior of a system. It is especially useful to perform “what-if-scenarios”. Both existing and conceptual systems can be modeled with simulations (Banks, 2000).

Advanced computer programs can simulate weather conditions, assembly lines and even war strategies. In theory, any phenomena that can be reduced to a model can be simulated on a computer. In addition, simulation is used to study how a system behaves under different conditions and for evaluating new ideas.

Simulations run in simulation time, an abstraction of real time. As the simulation clock advances, the model determines if there have been changes, recalculates its values, and outputs the results. If the model is valid, the outputs of the simulation will be reflective of the performance or behavior of the real system (Imagine That Inc., 2007).

##### **3.1.2 Modeling concepts**

There are several concepts underlying simulation. These include system, model, methodologies, system state variables, entities and attributes.

###### **Systems**

In the real world are systems all around us, e.g. natural systems or the economical systems. A system is a group of interacting, interrelated, or interdependent entities forming a complex whole based on the rules or operating policies of the system.

An entity represents an object that requires explicit definition. An entity can be dynamic in that it “moves” through the system, or it can be static in that it serves other entities (Banks, 2000).

Operating policies, the types of controls and availability of resources, are the external inputs to the system. They govern how the system operates and thus how the entities interact (Imagine That Inc., 2007).

The changes in the system over time are called system behavior or dynamics. The changes are caused by the activities and interactions of entities. You can find both very simple systems like a man walking from point A to point B and complex systems such as supply chain operations composed of planning, producing and distributing of products (Imagine That Inc., 2007).

### **Models**

A model is a representation containing the essential structure of some objects or events of a system at one point in time. Because it is a representation, no model includes every aspect of the system. If it did, it would no longer be a model. In a model, simplifications are made to increase efficiency, reliability and to make analysis easier. A model should capture only the most important aspects of the real system. In general, there are at least four basic types of models:

- A scaled representation of a physical object, such as a scaled model of a boat or a scale model of the solar system.
- A graphical or symbolic visualization, such as a flow chart of a process or an architect's plans for a building.
- An analytical or mathematical formula that yields a static, quantitative solution. They represent a system at a fixed point in time. Consider the annual budget of a firm. This budget resides in a spreadsheet. Changes can be made in the budget and the spreadsheet can be recalculated, but the passage of time is usually not a critical issue.
- A mathematical description that incorporates data and assumptions to logically describe the behavior of a system. This type of model is typically dynamic it has a time component and shows how the system evolves over time (Imagine That Inc., 2007).

### **3.1.3 Modeling methodologies**

The two main modeling methodologies are: Continuous and Discrete-event. Continuous modeling is used to describe a flow of values. Discrete-event models track unique entities.

The two main modeling methodologies are: Continuous and Discrete event. In addition to these main modeling methodologies, other modeling approaches are useful and usually based on one of the two main methods: Monte Carlo, Agent-based and State/Action (Imagine That Inc., 2007).

To model different aspects of the real system it is possible to use different methods. However, it should be understood that there is no such thing as "the" model of a system. A system can be modeled in a number of different ways depending on what it is one want to accomplish. How the system is modeled depends on the purpose of the model and what kind of information is needed (Imagine That Inc., 2007).

### Continuous Models

In continuous models, the time step is fixed at the beginning of the simulation. Time advances in equal increments and values change based directly on changes in time. In this type of model, values reflect the state of the modeled system at any particular time and simulated time advances evenly from one time step to the next, see figure 3.1. Continuous simulations are comparable to a constant stream of fluid passing through a pipe. The volume may increase or decrease at each time step, but the flow is continuous (Imagine That Inc., 2007).

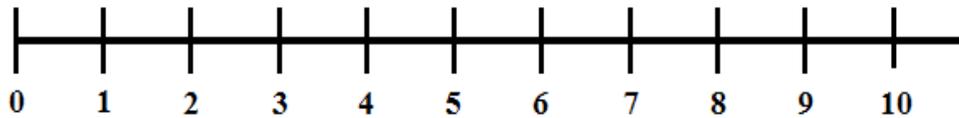


Figure 3.1 - Shows fixed time steps in continuous models

### Discrete event

In discrete-event models, the system changes state as events occur and only when those events occur. The mere passing of time has no direct effect on the model. Unlike a continuous model, simulated time advances from one event to the next and it is unlikely that the time between events will be equal, see figure 3.2. A factory that assembles parts is a good example of a discrete event system. The individual entities (parts) are assembled based on events (Imagine That Inc., 2007).



Figure 3.2 - Shows time steps in discrete events models

#### 3.1.4 System state variables

The system state variables are the collection of all information needed to define what is happening within the system to a sufficient level at a given point in time. The determination of system state variables is a function of the purposes of the investigation. So what may be the system state variables in one case may not be the same in another case even though the physical system is the same. Determining the system state variables is as much an art as a science (Banks, 2000).

Having defined system state variables, a contrast can be made between discrete-event models and continuous models based on the variables needed to track the system state. The system state variables in a discrete-event model remain constant over intervals of time and change value only at certain well-defined points called event times. Continuous models have system state variables defined by differential or

difference equations giving rise to variables that may change continuously over time (Banks, 2000).

Some models are mixed discrete-event and continuous. There are also continuous models that are treated as discrete-event models after some reinterpretation of system state variables, and vice versa (Banks, 2000).

### **3.1.5 Entities and attributes**

Discrete event models pass entities (called items in ExtendSim) from block to block as events occur during the simulation run. The items in the simulation are usually generated as a random distribution within specific parameters, or as a scheduled list of when events will occur. These items can have properties, such as attributes and priorities, which help them correspond more closely to real world products, customers, or jobs. Items are processed by activities, and the time and extent of processing is often dependent on the availability of resources (Imagine That Inc., 2007).

Attributes are an important part of a discrete-event simulation because they provide information about items. Each attribute consists of a name that characterizes the item and a value that indicates some dimension of the named characteristic. For example, an item's attribute name might be "Carpenters" and its value could be "4" representing four workers. The attribute name might also be "Quantity of work" and its value "20" m<sup>3</sup> (Imagine That Inc., 2007).

### **3.1.6 Activities and delays**

An activity is duration of time whose duration is known prior to the beginning of the activity. Thus, when the activity begins, its end can be scheduled. The duration can be constant, a random value, a result of an equation, or based on the event state. For example it can take the workgroup 1 hour to pour 14,25 m<sup>3</sup> of concrete (Banks, 2000).

A delay is an indefinite duration that is caused by some combination of system conditions. A delay is not defined by the user in advance but rather happens as a result of the system state, for example different weather conditions or if there are no resources available.

### **3.1.7 Advantages and disadvantages**

Simulation is an advanced technology based on a complex theory. Before start using the technique it is important to be aware of its advantages and disadvantages.

The most important advantage is that simulation enables to test every aspect of a planned change without committing resources to their acquisition. This is critical, because when the construction has begun, changes and corrections can be very

expensive. Simulations allow testing specific designs or changes without committing expensive resources to acquisition (Banks, 2000).

In simulations it is possible to manipulate time. By compressing and/or expanding time, simulations allow one to speed up or slow down phenomenon so that one can thoroughly investigate them. It is possible to examine an entire shift in a matter of minutes or spend two hours examining all the events that occurred during one minute of a simulated activity (Banks, 2000).

It is very important to understand why certain phenomena occur in a real system. With simulations, one can determine the answer to the “why” questions by reconstruction and examine the scene thoroughly to determine why the phenomenon occur. Also when you have created a valid model, you can explore new policies, operating procedures or methods without the expense and disruption of experimenting with the real system (Banks, 2000).

Simulations can also answer “what-if” questions. That can be useful for both designing new systems and redesigning existing systems. Example, what will be the consequence if the price of material or labor increases by 15% over the next 5 years due to an overheated market? Or what happens if the weather condition over the winter months will be especially unfavorable? (Banks, 2000).

The disadvantages with discrete-event simulation are that creating a model requires special knowledge in simulation concepts and can be time-consuming. The possibilities are endless so even if two models of the same system are built by two competent individuals they may have similarities but it is unlikely that they will be the same (Banks, 2000).

Furthermore, most simulation output are essentially random variables (they are usually based on random inputs). Consequently it may be hard to determine whether a simulation output is a result of system interrelationships or a result of randomness. (Banks, 2000).

### **3.1.8 Steps in a simulation study**

There are nine important steps to follow when creating a simulation model according to Banks (2000).

#### **Problem Formulation**

Every simulation study begins with a statement of the problem. The statement of the problem must be well defined, preferably directly in the beginning of the study. It is important that both the simulation analyst and the client understand the problem in the same way.

### **Setting of objectives and overall project plan**

The objectives indicate the questions that are to be answered by the simulation study. The project plan should indicate a statement of the various scenarios that will be investigated.

### **Model building**

It is recommended to begin simple and then to continuously develop the model and add complexity. Construction of a too complex model at once will add to the cost and the time without increasing the quality of the output.

### **Data collection**

The results can never be more accurate than the input data. Therefore the collection of data is important. Often can the client provide the necessary data, but if not, it has to be taken into consideration that data collection can be very time consuming. Model building and data collection are often carried out in parallel.

### **Verification**

The results from the model can be verified by comparing them with experiments or observations of the real system. Because of the simplification of the model-building process, no model can ever be in perfect agreement with the real system. In all cases, the important question is not whether the model is true, but whether the model was adequate for the purpose at hand. Model-building is a continuing process and with new and more powerful models, the results become a closer and closer approximation of the real system.

### **Experimental Design**

For each scenario that is to be simulated, decisions need to be made concerning the length of the simulation run, the number of runs and how to assign the initial input values.

### **Production Runs and Analysis**

Production runs and their subsequent analysis are used to estimate measures of performance for the scenarios that are being simulated.

### **More runs?**

Based on the analysis of runs that have been completed, the simulation analyst determines if additional runs are needed and if any additional scenarios need to be simulated.

### **Documentation and reporting**

Documentation is necessary if the simulation model is going to be used again by the same or by another person. It may be necessary to understand how the simulation model operates. Also if the model is being modified then documentation can prevent misunderstanding. The results need to be presented in a readable and clear way so the client can review the final formulation.

## **3.2 Construction process planning**

### **3.2.1 Introduction**

There exist today many different methods and tools for planning a project. Good preparation, understanding the project objectives and utilize effective planning techniques, is what makes the project to be successful (Kerzner, 2006).

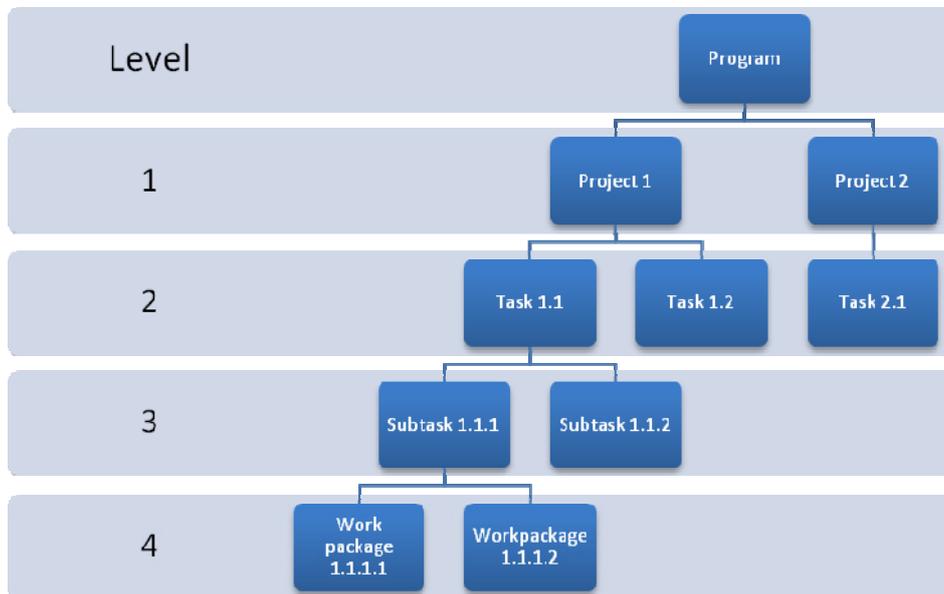
There are four basic reasons for project planning (Kerzner, 2006):

- To eliminate or reduce uncertainty
- To improve efficiency of the operation
- To obtain a better understanding of the objectives
- To provide a basis for monitoring and controlling

### **3.2.2 Work Breakdown Structure**

The Work Breakdown Structure (WBS) shows the work breakdown of a project in a graphic presentation and is the foundation in project planning because it breaks the project down into manageable pieces. The WBS can be used to identify the tasks in the Critical Path Method (CPM) and Program Evaluation and Review Technique (PERT) project planning models (Chase, Jacobs and Aquilano, 2006).

WBS defines the hierarchy of project tasks, subtasks and work packages. A task is a further subdivision of a project. It is usually not longer than several months in duration and is performed by one group or organization. A subtask may be used if needed to further subdivide the project into more meaningful pieces. A work package is a group of activities combined to be assignable to a single subtask. The package provides a description of what to be done and a rough estimate of start time, duration and budget. A representation of this structure is shown in figure 3.3.



*Figure 3.3 - Example of a Work Breakdown Structure*

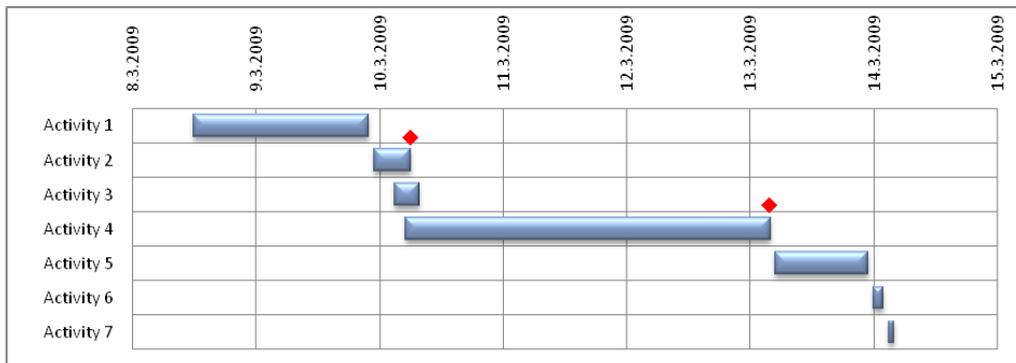
How much detail and the number of levels will vary depending on the project. There is not a single correct WBS for any project. Two different project teams might develop different WBS for the same project. It is important to remember when working with WBS that a Work Breakdown Structure is not a complete list of work. It is instead a comprehensive classification of project scope and that a WBS is neither a project plan nor a schedule. It is considered poor practice to construct a project schedule (e.g. using project management software) before designing a proper WBS. This would be similar to scheduling the activities of a project before completing the designs (Chase, Jacobs and Aquilano, 2006).

### 3.2.3 Traditional planning

According to the traditional planning method the result (the time plan) are shown in Gantt chart. Gantt charts have become a common technique for representing the phases and activities of WBS. The graphical display of a gantt chart is easier to read and gives a better overview of the project. The precise start date, duration and the finish date is decided for each activity. Gantt charts might also show the critical path which indicates which activities that are not allowed to be delayed (Chase, Jacobs and Aquilano, 2006).

The horizontal axes in Gantt charts shows the duration of time which it takes to perform a specific activity and the vertical axes shows the list of activities, see figure 3.4.

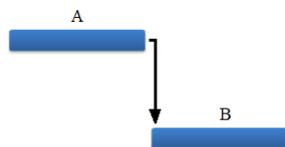
## Discrete Event Simulations of Construction Related Production Systems



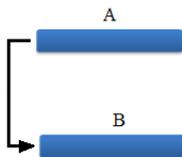
*Figure 3.4 - Example of a Gantt chart*

Specific events are called project milestones marked as red triangles in figure 3.4. Examples of milestones might be completion of design specifications or when all casting of concrete has been finished (Chase, Jacobs and Aquilano, 2006).

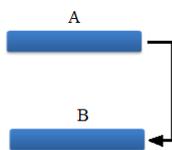
A Gantt chart also shows the predecessors for the activities. That means the activities which have to be finished or started in order to allow for a specific activity to start. There are four different types of relations between the activities, figure 3.5 (Chase, Jacobs and Aquilano, 2006).



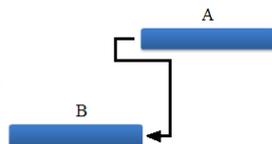
**Finish to Start:** The work of activity B can start only after all the work of activity A is finished.



**Start to Start:** The work of activity B cannot start until the work of activity A starts.



**Finish to Finish:** The work of activity B cannot finish until the work of activity A finishes.



**Start to Finish:** The work of activity B cannot finish until the work of activity A starts.

*Figure 3.5 – Shows different types of relations between activities*

### 3.2.4 Critical Path Method

The Critical Path Method (CPM) is an important tool for planning complex projects. The basic concept of the method is that it is possible to calculate the total duration of the project with some precision and different start dates for different activities on the path. The method is only used if there are available data to show fairly precise duration of the activity. The method can be applied to all forms of projects, such as construction, software development, research, engineering operations, maintenance activities and etc. (Chase, Jacobs and Aquilano, 2006).

To take advantage of this approach the user needs to:

Identify each activity and estimate how long it will take to complete each activity: The project is broken down into activities. A list is created for all the activities and the time it takes to complete each task involved is determined. People who have experience can evaluate the durations of the activities. The CPM model is not designed for variable activity durations and only uses one expected duration for each activity (Chase, Jacobs and Aquilano, 2006). Example: A (1), B (2), C (1) and D (1), see figure 3.6.

Determine the required sequence of the activities and construct a network reflecting the precedence relationship: Some activities are dependent on others and therefore have predecessors. For instance, A, in figure 6, is a predecessor for B and C. It is important to identify all the predecessors before making a CPM network. Figure 6 shows a CPM network that takes into account the predecessors and the duration of the activities (Chase, Jacobs and Aquilano, 2006).

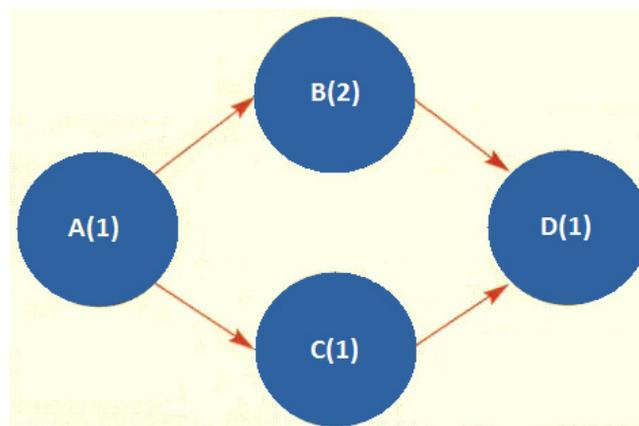


Figure 3.6 - Shows a CPM network

Determine the critical path, the longest path through the project: The critical path means that the activities that lie on this path are not possible to delay without delaying the whole project. The duration of the activities which lie on the critical path must be reduced to decrease the total duration of the project. In the example there are two

paths through the project; 1) A-B-D which takes 4 weeks and 2) A-C-D which take 3 weeks, see figure 3.6. Then the critical path is A-B-D because the total time is longer (Chase, Jacobs and Aquilano, 2006).

Determine the early start/finish and late start/finish schedule. When scheduling a project it is needed to find when each activity needs to start and when it needs to finish. For some activities in a project there may be some flexibility in when an activity can start and finish. The flexibility is called slack. Four points in time are calculated for each activity in the project, the early start (ES), early finish (EF), late start (LS) and late finish (LF) (Chase, Jacobs and Aquilano, 2006). See figure 3.7.



Figure 3.7 - Shows the position of the ES, EF, LS and LF

The difference between the early start and the late start is the slack. There is no slack on the critical path, i.e.  $ES = LS$  and  $EF = LF$  for every activity which lies on the path (Chase, Jacobs and Aquilano, 2006).

To calculate the ES and EF you start at the beginning of the project and work your way to the project end. ES for activity B is the time of the EF of activity A, or week one. The same can be said for the activity C. EF for activity B is week three but EF for activity the C is week two. Activity D can not start until both B and C are finished. Consequently, ES for activity D is week three, see figure 3.8 (Chase, Jacobs and Aquilano, 2006).

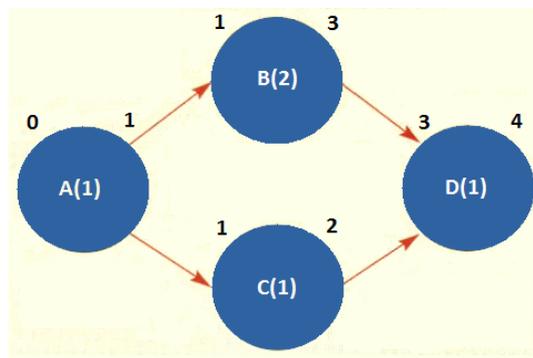


Figure 3.8 - Shows the ES and EF for the project

When LS and LF is calculated it is best to start at the end of the project and work towards the beginning. For the activity D, which is the last activity, is the LS the same as ES if the project is on time. Activity B is on the critical path and therefore is LS = ES. Activity C has to be done in week three. It has the duration of one week, that is why LS = week 2 and LF = week 3, see figure 3.9 (Chase, Jacobs and Aquilano, 2006).

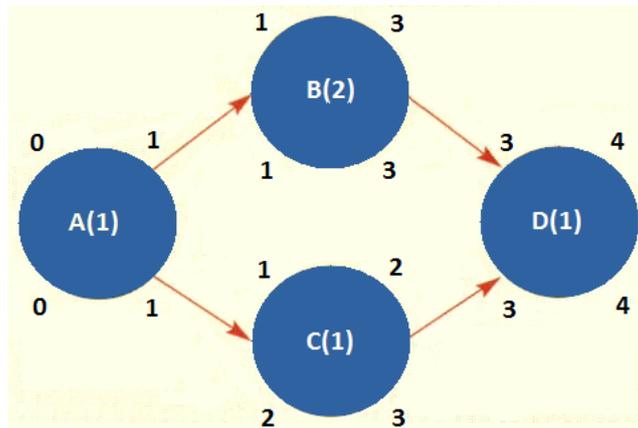


Figure 3.9 - Shows the LS and LF for the project

Update the CPM network: As the project develops and the durations of the activities can be estimated with more accuracy it is possible to update the information in the network. It is important to pay attention to that if changes are made to the durations of the activities, then it is possible that a new critical path can be created (Chase, Jacobs and Aquilano, 2006).

### 3.2.5 Line of Balance

Line of Balance method (LoB) has greatly grown in popularity the past years. In the LoB method is the repetitive work shown as a single line on a graph rather than a series of individual activities on a Gantt chart. The slope of the lines shows the rate of work, the x-axis shows time and the y-axis shows the number of units, see figure 3.10. It is important that the lines do not overlap each other because if they do it usually means that the activities are in space conflict. The LoB-method aims to obtain the same slope of all lines (activities) that is why it is called the “line-of-balance” (Planning engineers, 2009).

A typical project where this may exist is a housing project consisting of several houses where the same type of work such as foundations, brickwork, roof construction, and internal trades are undertaken on each house, see figure 3.10 (Planning engineers, 2009).

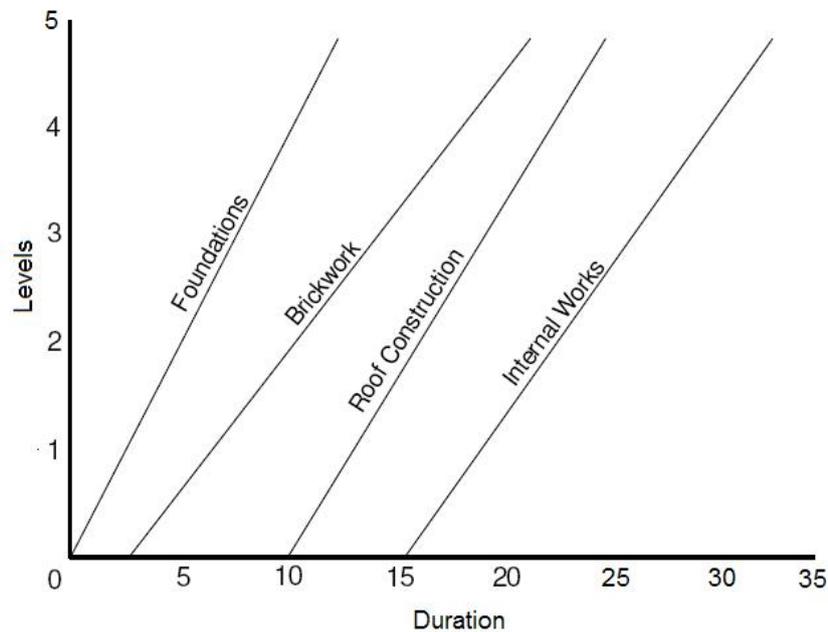


Figure 3.10 - An example of a Line of Balance graph

### 3.2.6 DES compared with current planning methods

Using discrete event simulation in project planning has its advantages and disadvantages compared with current methods. One of the biggest advantages is that in simulation it is possible to try out different scenarios and see directly how they affect the project's time and cost plan. That is a very useful feature for making the project more effective. It is also possible to run the simulation for example 1000 times in just seconds and use the results in risk analysis.

In many of the current methods which are used today, e.g. in Microsoft Project it is not possible to describe the complex relationships between resources and activities, for example when specific resources are needed to be available to allow for an activity to start. Therefore using traditional planning methods increases the risk of using the same resource twice at the same time. But when using simulation models it is easy to define which resources are needed so a specific activity can start and the model controls that the same resources are not used twice at the same time.

The ability to describe random events is also much more sophisticated in DES. DES is also dynamic which means that the system changes over time, based on current conditions. Traditional planning methods have limited ability to describe dynamic processes.

The disadvantages are that it can be hard to simulate the construction process because a construction site has so many variables. If one desires to consider all these

variables, the model will become very complex and the risk of failure will be impending.

It is also important to remember that a simulation never gives the exact “truth” but should be used to see how different events or new technology affect the results of the project.

To get the best results it is best to combine the strengths from both sides and use DES as complementary to traditional planning methods.

### 3.2.7 Measurement of work performance

Construction projects can be very different from each other and the level of complexity can vary considerable between projects. All construction projects need planning and to plan a complex project requires a great amount of data and information. The key for gathering the data and information is communication between those who are involved in the project e.g. between the designer and the engineer. It is also very important that everybody “speaks” the same language to reduce the risk of misunderstanding (Byggeförbundet, 1973).

Time and capacity are often used, in planning of a construction project, as planning units. Time data indicates the normal time which it takes to perform a certain amount of work, e.g. 2 man-hours/m<sup>2</sup>. Such time data is called unit times and is calculated according to equation (1):

$$\text{Unit time} = \frac{\text{Total man hours to perform an activity}}{\text{Amount of work}} \quad (1)$$

Capacity data concentrates on the amount of work performed per hour, e.g. 10 m<sup>2</sup>/hour. Capacity is calculated according to equation (2):

$$\text{Capacity} = \frac{\text{Amount of work}}{\text{Total man hours to perform an activity}} \quad (2)$$

Workgroup is a group of workers who work together on the same activity at the same time. Workgroups are created to get higher performance and for safety issues. The workgroup can consist of several types of workers, e.g. concrete worker, laborer and equipment operator. The total performance of the workgroup can be calculated both from using the unit time or the capacity, see equations (3) and (4):

$$\text{Total performance} = \frac{\text{Quantity of workers}}{\text{Unit time}} \quad (3)$$

$$\text{Total performance} = \text{Quantity of workers} * \text{Capacity} \quad (4)$$

### 3.2.8 Definition of unit times

It is very important, when planning a construction project, to know what includes in the unit time which is being used because the time to perform a specific amount of work can be expressed in different ways. There are different definitions used to distinguish between different concepts of time, figure 3.11.

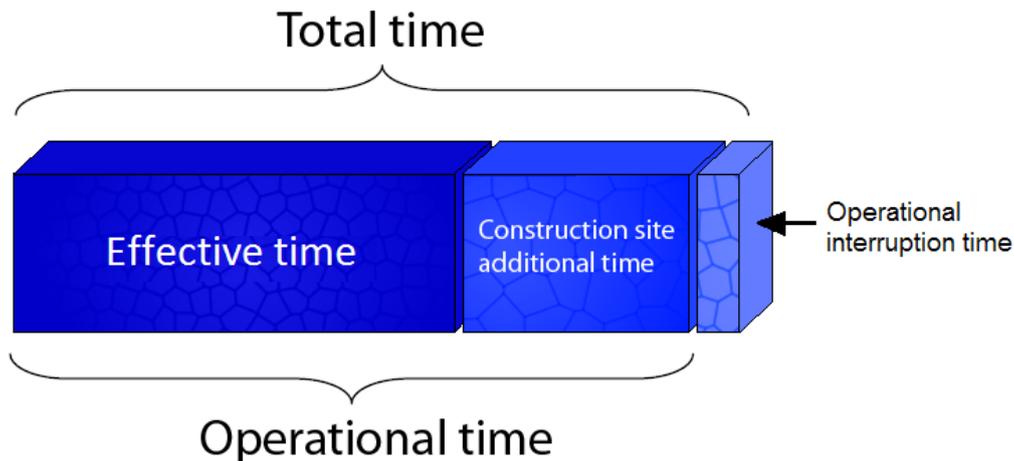


Figure 3.11 - Shows how the unit time can be divided into smaller parts

The broadest concept is the **total time**. That is the time from when the activity starts to when the activity is finished. The total time includes everything that happens, even longer interruptions (Byggeförbundet, 1973).

**Operational time** is the time from when the activity starts to when the activity is finished but it does only include interruptions which are shorter or equal to one hour. Operational time can be divided into effective time and construction site additional time (Byggeförbundet, 1973).

**Effective time** is the exact time that it takes to complete an activity without any interruptions (Byggeförbundet, 1973).

**Construction site additional time** is the accumulated time for all the interruptions which last less than one hour. For example the time it takes to read the drawings, look for the right material and tools, personal pauses, waiting time, rework and other factors which affect the performance. The construction site additional time is about 30% of the operational time, but that can vary between projects (Byggeförbundet, 1973).

Interruptions that last over an hour are called **operational interruption time**. If an interruption occurs that last 100 minutes, 40 minutes should be looked at as

operational interruption time and 60 minutes as construction site additional time (Byggförbundet, 1973).

### 3.2.9 Factors that cause disturbance in the production

“Production disturbance is a deviation from the planned production process that leads to consequences in terms of additional costs, delay or irritation in the workplace” Martvall and Wirdenius, Byggeforskningens report 1969:36.

An activity is usually an assembly operation. If an assembly operation involves multiple purchased parts, the reliability of deliveries is extremely important. The preconditions for the execution of an activity, like assembling of formwork, are shown in figure 3.12.

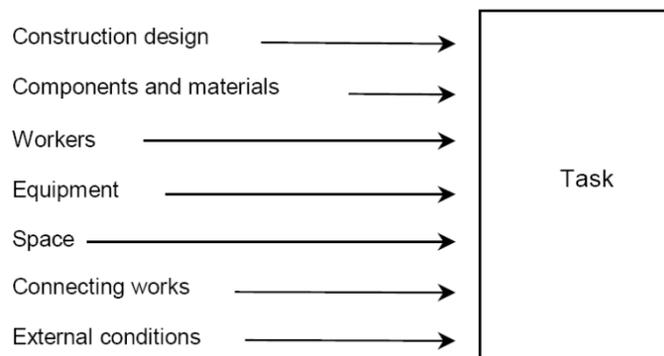


Figure 3.12 - Shows the preconditions for the execution of an activity

There are at least seven resource flows that unite to generate the activity result, usually even more if there is more than one material used. Many of these resource flows have high uncertainty factors due to uncertainties in construction. Therefore, the probability of a missing input is considerable. For example, it is not uncommon that detailed drawings are still lacking at the intended start date or deliveries of prefabricated material are delayed. External conditions e.g. weather, can also cause increased variability. The productivity of manual labor and equipments can also vary and therefore cause uncertainty (Koskela, 1999).

Let's assume that the probability of a deviation in any of the resource flows to a construction task over one week (5 workdays) is 5%. The probability that there is no deviation in any input flow is thus, according to equation (5):

$$Prob\{no\ deviation\ in\ any\ input\ flow\} = (0,95)^7 = 0,70 \quad (5)$$

This is in harmony with the construction site additional time talked about in the last chapter. Planning and controlling production so that the workstations do not starve

due to lack of inputs is a very difficult task. That is why activities and flows have to be considered paralleled in production management (Koskela, 1999).

According to Lean theories it is common to refer to waste as those activities that do not add any value for the end customers. Eight different types of waste can be distinguished (Blücher & Öjmertz, 2007).

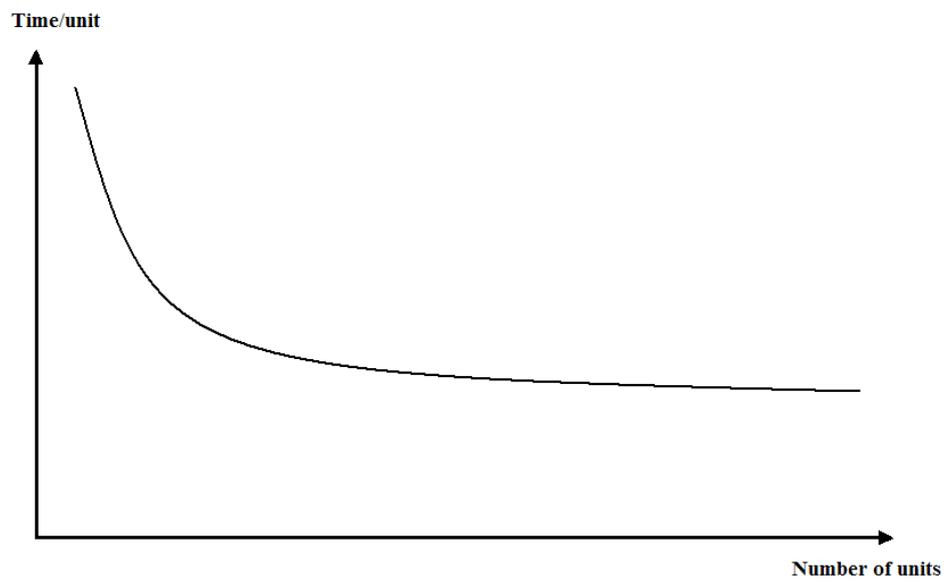
- Overproduction – to perform more work or to perform the work earlier than needed.
- Waiting - for something to happen, for example, the materials deliveries to arrive or for other workgroups to be ready.
- Storage - to store more than what is necessary, e.g. to store materials on the building site.
- Motion - unnecessary movement when employees are performing their jobs, such as movements to retrieve the materials and tools.
- Rework - rework, adjustments and repairs that do not add any value to the customer.
- Over work - to do more work than what the customer requires. The customer expects a certain level of quality, but more is not needed.
- Transport - unnecessary transport, such as relocating of materials and equipment.
- Unused employee creativity - not to use the employee's full skill.

### **3.2.10 Experience effect**

It is known from experience that the more often the same work is performed, the faster it will go. It is also known that it usually takes longer time for a less experienced worker to perform a task compared to a more experienced worker.

So when the same project part is performed a few times of the same workgroup the work time decreases every time the project part is repeated, assuming that the external effects are the same, until the work time reaches a specific low point. The project part can for example be one floor in a building which is repeated over and over. The first floor is probably going to take longer time compared to the second floor because the workgroup gets more experience. They can use that experience to learn from their mistakes and develop more effective working methods. For instance, an experienced worker does not have to read the drawings as often as a less experienced worker (Byggeförbundet, 1973).

How big the improvement is, depends on the complexity of the work. More complex activities have bigger possibilities to be improved. At the same time, there exists always a point where the maximum improvement has been found. The improvement typically follows a non-linear curve, figure 3.13 (Byggeförbundet, 1973).



*Figure 3.13 - Schematic plot of how the time per unit decreases with increased number of units produced*

## 4. Uncertainties in construction projects

### 4.1 Data collection by questionnaire

What makes a model function right is the quality in its input data. A model will never be more accurate than its input data. That is why the main purpose of the questionnaire and interviews was to gain data concerning how much different weather conditions effects the workers performance. Another purpose was to collect data concerning interruption in material deliveries and site equipment and how workers' experience influence the work performance.

The goal was then to use the results to show that the model can take different weather conditions into consideration and therefore produce better results.

The activities of interest were all related to casting concrete on the construction site. The activities of interest were:

- Assemble and disassemble of formwork (walls)
- Reinforcement of walls and plates
- Casting concrete walls and plates

The weather conditions which were asked about were:

- Wind speed
- Precipitation, both rain and snow
- Temperature
- Combinations of different weather conditions

The respondent was asked to answer how much those weather conditions effected work performance in terms of percent according to his/hers experience. The level of influence was in the range from 100% to 0%.

- If the weather had no effect on the work performance the answer should be 100%.
- If the weather had some effect on the performance against normal the answer should be from 99% and down to 1% depending on how great the effects are.
- If the weather would totally stop the work, should the answer be 0%.

Five persons from five different companies answered the questionnaire, two from Sweden and three from Iceland:

Company name: Peab (Sweden)  
Company's field: Contractors  
Interviewee's field: Project Manager

Company name: Midroc (Sweden)  
Company's field: Consulting firm  
Interviewee's field: Project Manager

## Discrete Event Simulations of Construction Related Production Systems

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Company name: VSÓ Ráðgjöf (Iceland)  
Company's field: Engineering consulting firm  
Interviewee's field: Project and construction management

Company name: Mannvit (Iceland)  
Company's field: Engineering consulting firm  
Interviewee's field: Project Manager

Company name: Ístak (Iceland)  
Company's field: Contractors  
Interviewee's field: Foreman

The standard deviation of the results was calculated according to equation (6).

$$\text{Standard deviation} = \sum \frac{(x - m)^2}{n - 1} \quad (6)$$

Where:

$x$  = the answer in the set

$m$  = mean value of the answers

$n$  = the number of answers in the set

The standard deviation was calculated separately for every answer according to equation (6). Then the average value for all the standard deviations was calculated and the result became 14%. By taking into consideration that the responders' answered the questions based on their experience and how many variables could affect their answers, is an average standard deviations of 14% sufficient accuracy.

The answerers were compiled in accordance with both the actual answers and the comments from the respondents. It should be noticed that the final value presented in the following figures are not necessary an average value. For instance, if a respondent did have strong arguments for his/her answers it would result in a higher impact on the final value.

Since the numbers of respondents were rather limited, it was considered to be more important to collect qualified assumptions rather than statistical data with somewhat uncertain quality.

## 4.2 Results from the questionnaire

### 4.2.1 Effect of wind speed

The effect of wind speed on work performance for various activities is shown in figure 4.1.

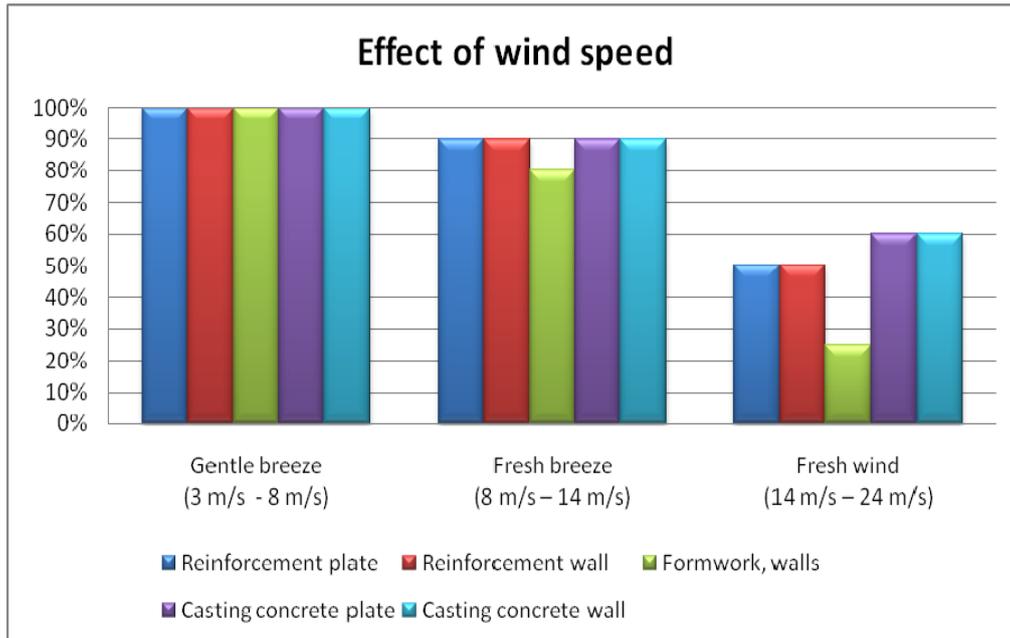


Figure 4.1 - The effect of wind speed on work performance

#### Reinforcement of plates

The crane is a large factor in the work regarding reinforcement of plates because reinforcement steel bars are mainly lifted by crane to its correct position. The wind has large effect on the crane and as the wind speed increases the performance of the crane decreases. That has negative effect on the work performance of the reinforcement workgroup. But even though the crane plays a big role is there still work, that needs to be done, which does not depend on the crane. For example, the workgroup can continue with preparing and finishing work even if the crane is idle due to high wind speed.

#### Reinforcement of walls

The wind speed has the same effect on reinforcement of walls as it has on the reinforcement of plates because the crane is needed in both activities.

**Formwork, walls**

The crane is also an important factor in assembling formwork. The formwork can begin to swing a lot in the air when the wind is blowing and it is much more difficult to heave large form panels compared to if there were no wind. That has negative effect on the work performance of the workgroup. It is very important, when the wind speed increases, to increase all safety issues. The workers can do some preparing and assembling work on the ground, if the crane is stopped, but it is rather limited.

**Casting concrete plates**

It does matter if a pump or a crane is being used during casting of concrete plates and the floor level (height) at which the casting occurs also matters. The wind has larger effect on the crane than it has on the pump. It is also important to increase all safety issues if workers are working on scaffolds in great wind.

**Casting concrete walls**

The wind speed has the same effect on casting concrete of walls as it has on the casting of the concrete plates because the crane is needed in both activities.

All the activities are effected of wind speed when the wind is fresh breeze or fresh wind. The main reason is the effect that the wind has on the crane. It is clear that the wind has the biggest effect on assembling formwork but the reason for that is that the forms have a large area which can sometimes acted as a sail in the wind.

### 4.2.2 Effect of precipitation

The effect of precipitation on work performance for various activities is shown in figure 4.2.

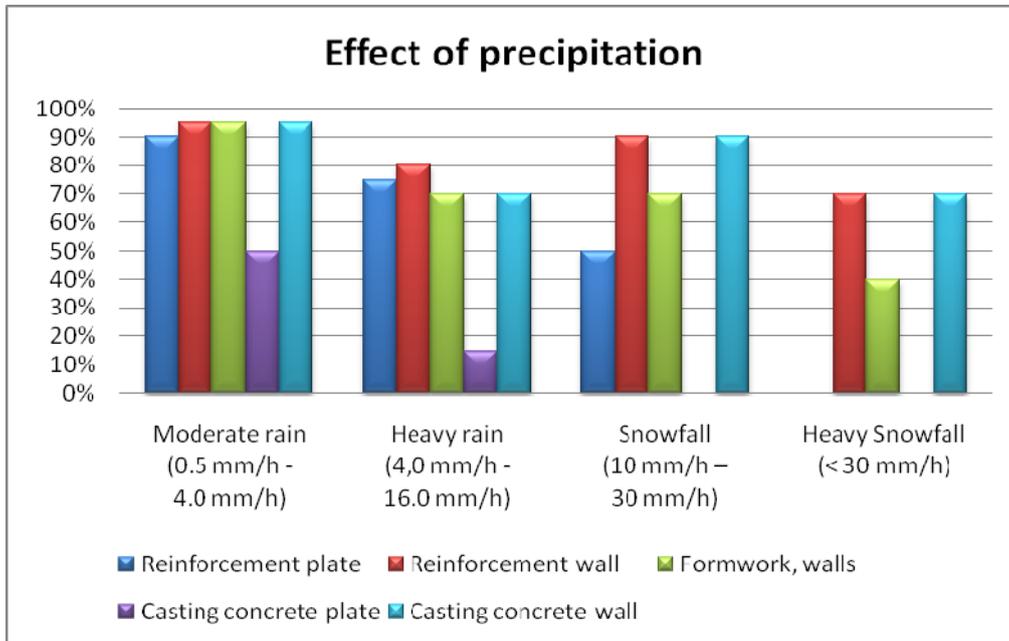


Figure 4.2 -The effect of precipitation on work performance

#### Reinforcement of plates

The workers do need to put on waterproof clothes, when it rains, which both takes time and makes it a little bit harder to work. Heavy rain can create puddles which can make the work, during reinforcement of plates, harder. Snowfall also makes the work harder and reduces the performance and under normal circumstances would heavy snowfall totally stop the work.

#### Reinforcement of walls

Puddles and snow do not have as much effect, during reinforcement of walls, as during reinforcement of plates. Therefore, precipitation has less effect on the activity.

#### Formwork, walls

Precipitation does not have an effect on the crane but it slows down the workers. Extra work is needed to shovel or melt snow which is in the way of the wall spot. Snow and puddles can also make it harder to see the markings which indicate the right locations of the walls.

**Casting concrete plates**

Concrete plates are very sensitive to precipitation. The precipitation can ruin the texture of the surface and damage the concrete. It is possible to cast concrete plates during heavy precipitation if a weather protection system is used to protect the area. But with that follows extra costs. The temperature must also be above 0°C to avoid frost damage.

**Casting concrete walls**

Precipitation should not have large effect on casting concrete walls. Snow and rain can make the scaffolds slippery so it is important to increase all safety measures during heavy precipitation.

It is clear that the precipitation has a large effect on the work performance, especially during casting of concrete plates. Snow layers on the ground and puddles make the work harder and it is essential that things are done properly under these conditions to avoid errors.

### 4.2.3 Effect of temperature

The effect of temperature on work performance for various activities is shown in figure 4.3.

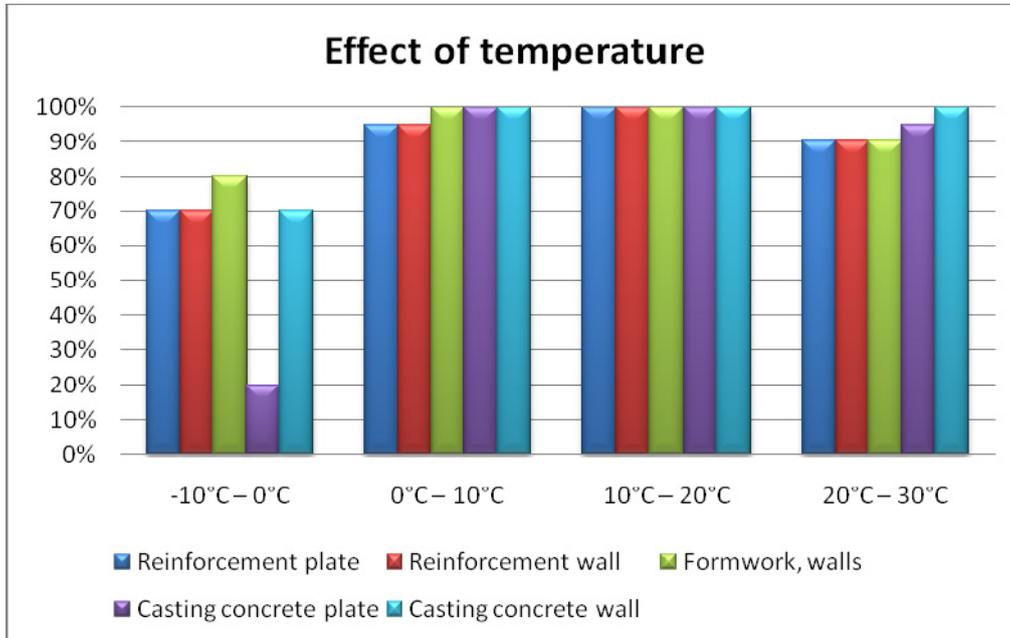


Figure 4.3 - Shows the effect of temperature on work performance

#### Reinforcement of plates

Temperature does not have a large effect on reinforcement of plates. However, it is not possible to bend reinforcement bars in very cold weather, because the bars may damage. The temperature can affect the workers too. They need to have more cloths on in cold weather which can slow them down and very hot weather can also have a negative effect on their performance. High temperature can make the workers get tired faster.

#### Reinforcement of walls

Temperature does have the same effect on reinforcement of walls, as it has on the reinforcement of plates.

#### Formwork, walls

Temperature does not have a large effect on assembling formwork but the temperature does affect the workers.

#### Casting concrete plates

Casting a concrete plate in cold weather can only been done if the plate is protected with a cover and heated up. These measures result in additional material costs.

Thickness of the plate and the cement type does also matter. It is important to make sure that the concrete does not harden too fast and is protected from evaporation, when the temperature is high, in order to avoid cracks.

**Casting concrete walls**

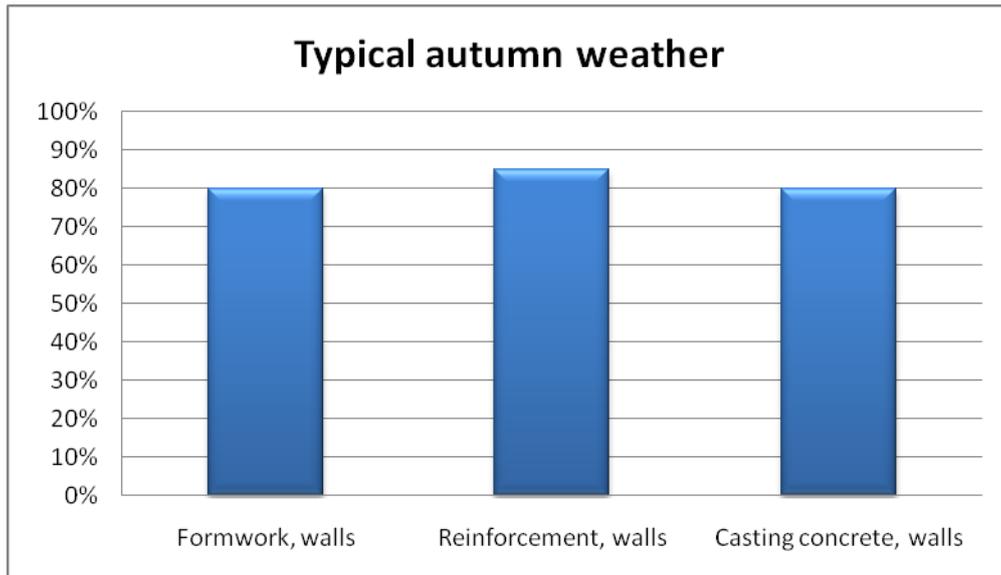
The temperature does not matter as much during casting concrete wall. It is easy to use extra isolated formwork to protect against low temperatures.

Low temperatures (below zero Celsius degree) have the largest negative effect on the work performance. The activity of casting concrete plates is most sensitive for low temperatures and appropriate precautions should be made. The temperature from 0°C to 20°C does not affect the work performance but as it gets warmer can the workers become tired more quickly.

#### 4.2.4 Combinations of weather conditions

In addition, the respondents were asked to provide their opinion about how two typical weather conditions effected wall activities. The first combination was a typical autumn weather and the results are shown in figure 4.4.

**Heavy rain (4.0 mm/h – 16.0 mm/h) + Fresh breeze (8 m/s – 14 m/s)**



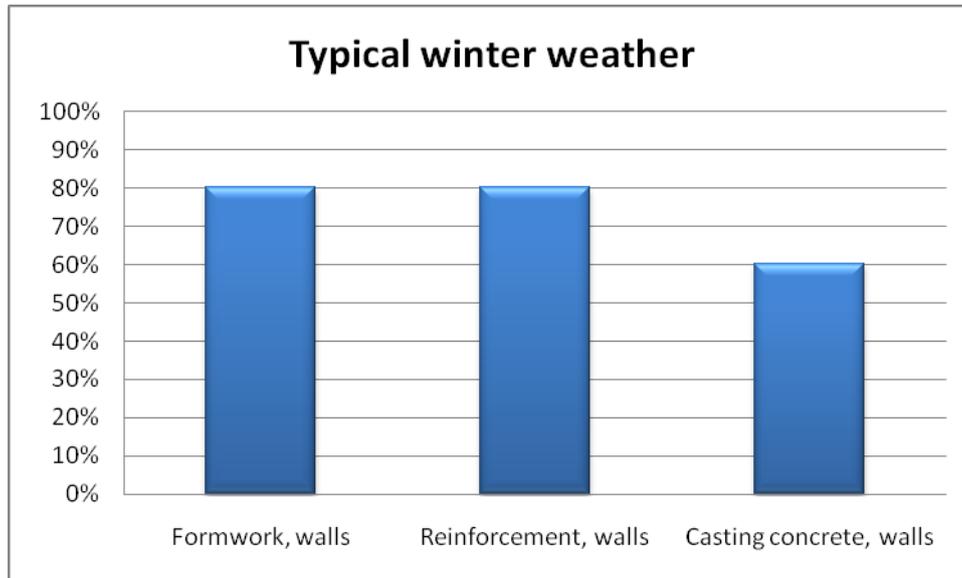
*Figure 4.4 - The effect of different weather combinations on work performance*

Figure 4.4 shows that the performance is 15-20% worse compared with ideal conditions.

The plates are much more vulnerable to different weather conditions than the walls. If the same question had concerned plates, the results had probably been considerable lower.

The second weather condition which was asked about was typical winter weather and the results are shown in figure 4.5.

**Frost (-10°C – 0°C) + Fresh breeze (8 m/s – 14 m/s) + Snowfall (10 mm/h – 30 mm/h)**



*Figure 4.5 - The effect of different weather combinations on work performance*

It is common that winter work is 20-30% more expensive than ideal circumstances. Results show that the weather has largest effect on the casting concrete walls.

#### 4.2.5 Darkness over the winter months

The darkness over the winter months does also affect the work performance. Therefore, the respondents were asked to provide how much darkness affects the work performance. In this respect, only the winter months ranging from November to February are considered. The results are shown in figure 4.6.

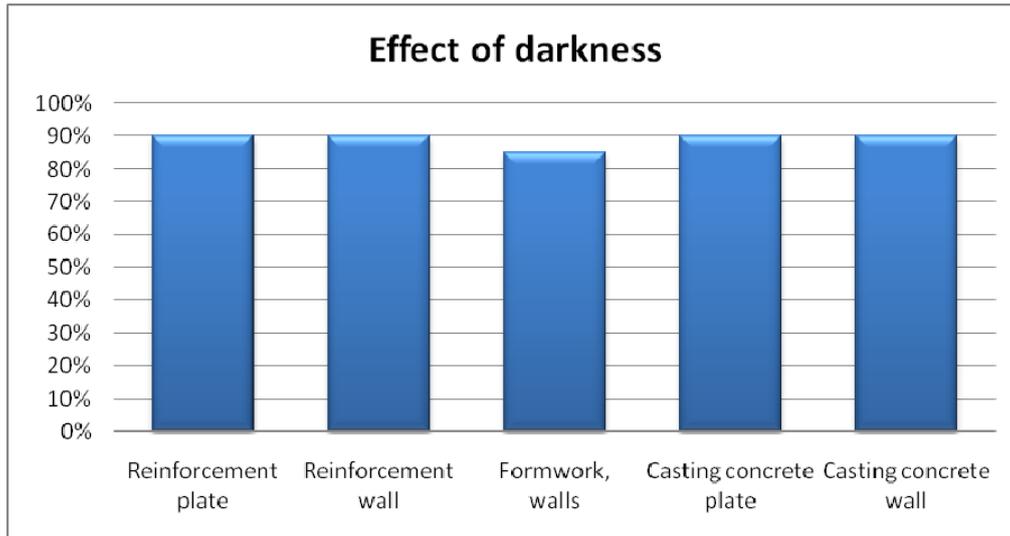


Figure 4.6 - The effect of darkness on work performance

How much darkness affects the work depends on the situation on the construction site. The risk of mistakes gets higher in the dark so the workers have to be more cautious. Furthermore, the risk of accidents increases and the need for measures for safety increases as well. However, modern light equipments make it possible to bring light to the whole site and the difference between day and night becomes very little. It is therefore possible, if good lighting conditions are provide, to bring the performance up to almost 100%. Of course, it will require additional costs.

#### 4.2.6 Delayed material deliveries

Two aspects regarding delayed material deliveries were investigated. The first aspect concerned how often (in average) deliveries of various material are not delivered on time. The second aspect concerned the duration of such delay. The results are displayed in table 4.1.

*Table 4.1 - Frequency of delayed deliveries and their durations*

Type of delivery	Percent of delayed deliveries	Normal duration of a delayed delivery
Delivery of reinforcement steel	5%	1 day
Delivery of precast plates	30%	0,5 days
Delivery of precast walls	30%	0,5 days
Delivery of concrete	10%	2 hours

#### 4.2.7 Disturbance related to crane.

As noted above is the crane a large factor in the building process. Therefore when a crane failure occurs, it affects the whole process. Two aspects were investigated related to crane failure. The first aspect concerned the frequency of crane failure and the second what a typical duration of such event. The results from the respondents are given in table 4.2.

*Table 4.2 - The frequency of crane failure and the duration of the failure*

	Frequency of a crane failure	Typical duration of a crane failure
Crane failure	1 failure per month	0,5 to 5 days

### 4.2.8 Experience effect

Finally, the respondents were asked to provide their opinion about how experience effects work performance related to formwork, rebar, and concrete operations. The results are shown in figure 4.7. The figure displays the improvement on work performance when the work is repeated a second and third time.

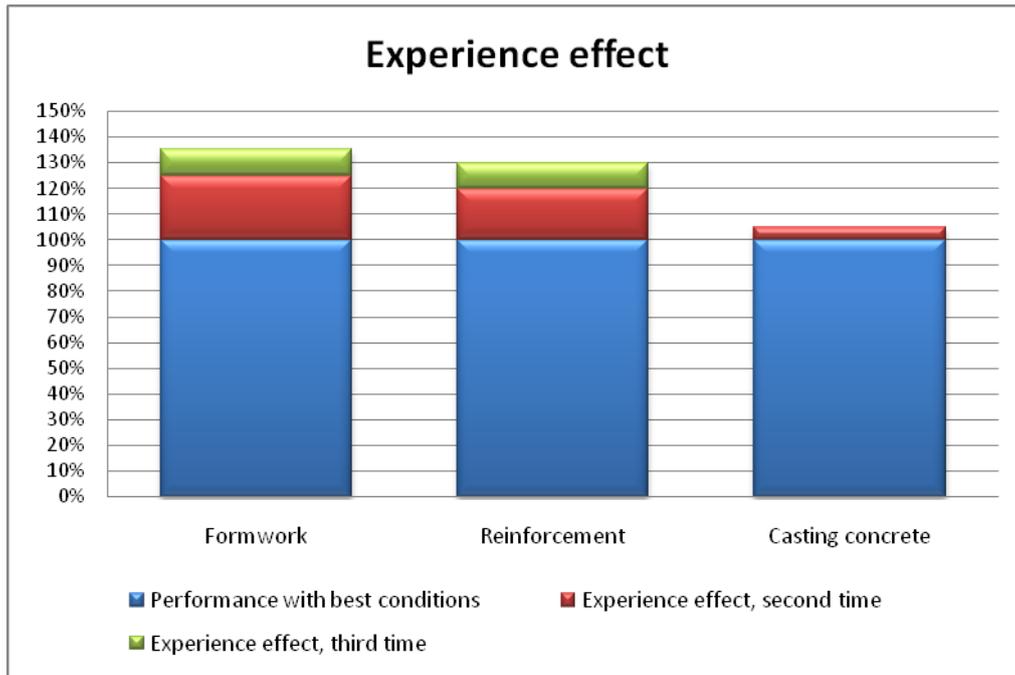


Figure 4.7 - The effect of work repetition on work performance

The improvement of the workers performance is of course depended on the circumstances on the construction site each time. For example, in an apartment building with 10 floors, the improvement applies maybe for the first three or four floors. At higher floor levels other factors has to been taken into consideration, e.g. the time it takes for the workers to travel up and down or to transport tools and materials.

The result indicate that the activity of casting concrete only experience a 5% improvement for both the second and third time related to when the first time the activity is performed. The reason for that can be that the complexity level of casting concrete is lower than formwork and reinforcement. In these activities, the workers need for example to study drawings before the formwork is assembled. The same applies for reinforcement the workers must study the drawing to know exactly how the rebars should be placed. On the other hand, pouring concrete is usually a similar procedure from pour to pour.



## 5. Description of simulation model

### 5.1 General

As stated in chapter one: “The purpose of this work is to develop a model which simulates on-site construction activities in terms of time, cost and resource usage. Another purpose is to demonstrate the use of the model by simulating various scenarios, e.g. random phenomena caused by variable weather conditions, scenarios involving assessment of the effect of workers experience or by introducing an alternative construction method.

As stated by the purpose, the work does not only deal with creating a simulation model but also to develop solutions for improving the flow of data to and from the simulation model. To accomplish this, three different programs were used. The simulation model was created in the program ExtendSim. The quantity of input data into the model is large and the output from the model is even larger. Maintaining a good control over the data is very important. Microsoft Access is great tool to store and manage databases and therefore was Access used to maintain the data. Access was also used to create a user interface where the user can enter data into the model. Then Excel was used to formulate the results stored in the databases in order to create graphs and charts. It was desirable to automate the flow of data as according to figure 5.1.



*Figure 5.1 - The data flow in the project.*

In project management it is common to divide the project into smaller units. In the model it is possible to define three different projects. Each project can consist of up to 10 floor levels and each floor level can consist of up to 10 different stages. Each stage can consist of up to 20 different activities. So the total capacity of the model is 6000 activities.

## 5.2 User interface

The purpose of the user interface is to create a platform which enables the user to enter data into the model in a simple and sufficient way. The interface enables the user to define a project in different levels, e.g. floor levels, stages, and activities, see figure 5.2.

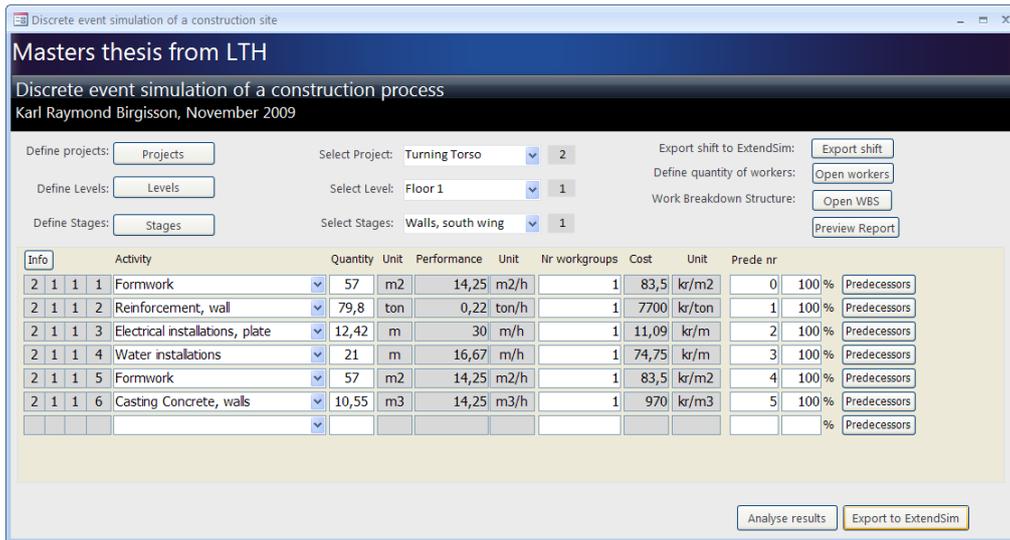


Figure 5.2 - The user interface where the user defines the project

### 5.2.1 Creating a project

The user can start by creating a new project to work on or select an existing project. To create a new project, the user can press the “Projects” button and a new window opens. The interface can manage three different projects, see figure 5.3.

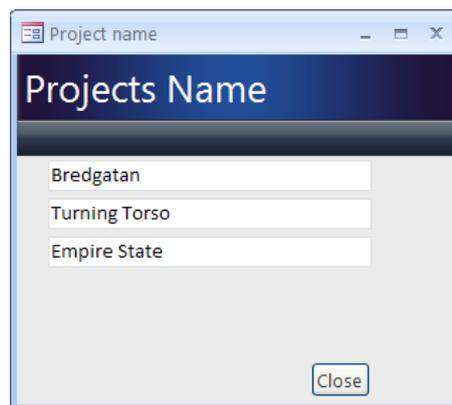


Figure 5.3 - The user can define his projects in the project name window

In figure 5.3 can the user define the projects name, for example Turning Torso.

When the project has been assigned with a name it becomes available in the “Select Project” combo-box, figure 5.4.

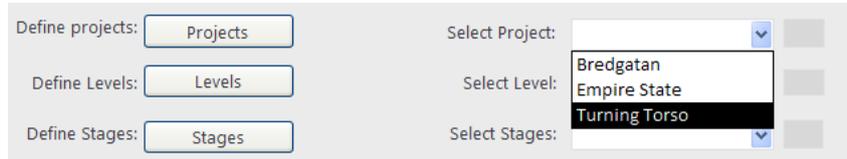


Figure 5.4 - Example of interface for selecting a specific project

### 5.2.2 Creating levels

The next step is to define different levels in the project. To create a new levels, the user can press the “Levels” button and a new window opens, see figure 5.5. It is possible to define maximum of 10 different levels for each project.

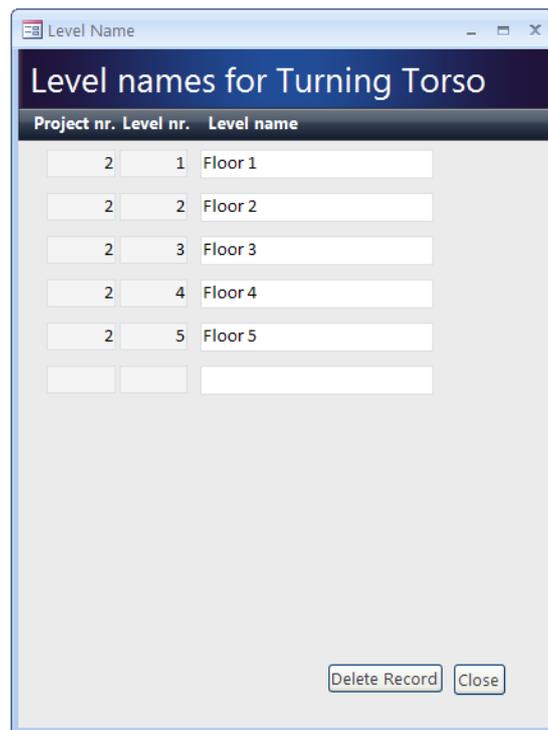


Figure 5.5 - The user can define the levels in the level name window

When all levels have been defined the levels become visible in the “Select levels” combo-box, figure 5.6.

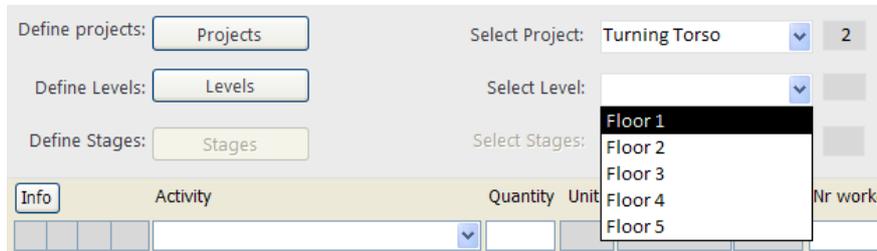


Figure 5.6 - Example of user interface for selecting a specific level

### 5.2.3 Creating stages

Each level can then be broken down into stages. To create a new stage, the user can press the “Stages” button and a new window opens, figure 5.7. It is possible to define maximum 10 different stages for each level.

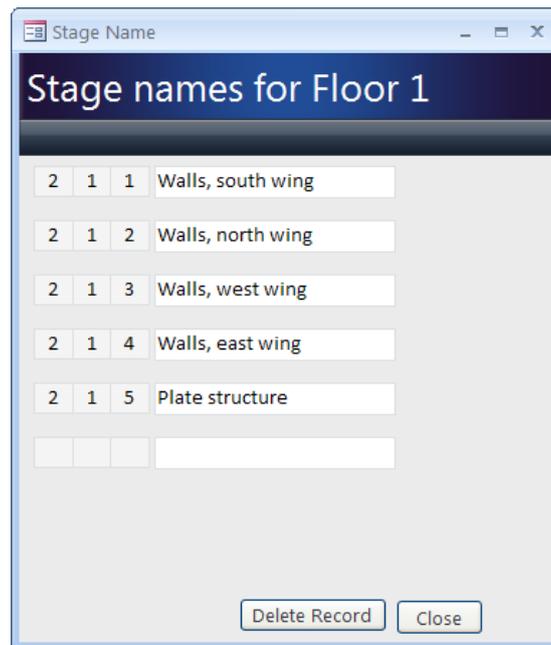


Figure 5.7 - The user can define the stages in the stage name window

When all the stages have been defined they become visible in the “Select Stage” combo-box, figure 5.8.

## Discrete Event Simulations of Construction Related Production Systems

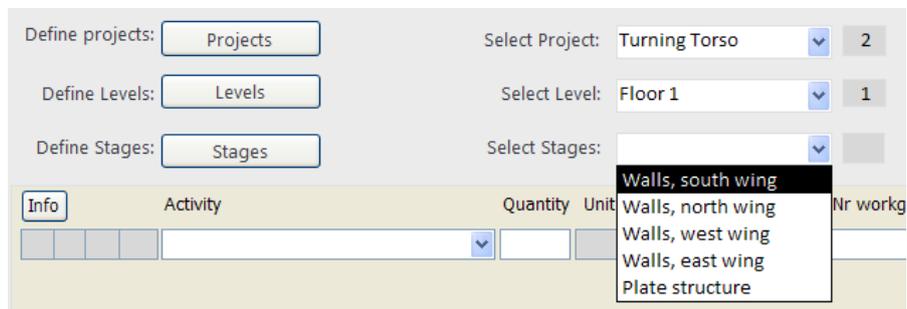


Figure 5.8 - Shows how the user can select a specific stage

### 5.2.4 Define activities

The user has now broken down the project in a very similar way as in the WBS-method. Next, the user selects which activities that should be included in each stage. By selecting the activity from a list in a combo-box the user can define up to 20 activities in each stage, figure 5.9.

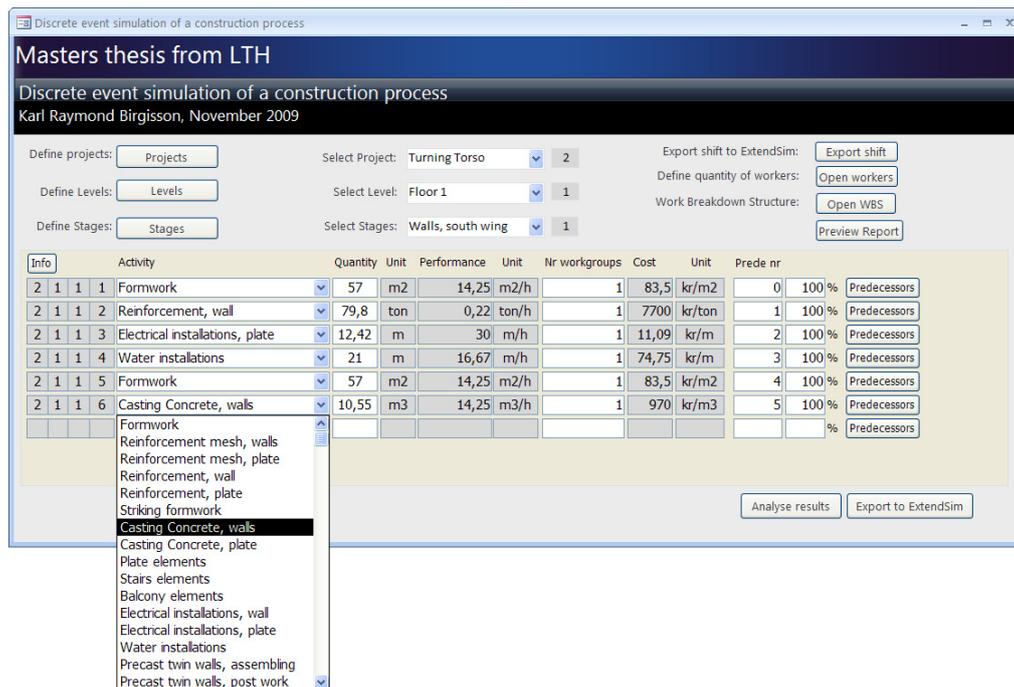


Figure 5.9 - The user can select which activities to be included in each stage

In a database called the price bank are the activity names stored along with information regarding unit times and material costs for the activities. When an activity is selected from the combo-box is the user actually picking the activity from the price bank. The interface retrieves the information about the unit times and the

material cost simultaneously as the user selects an activity name and displays them in the grey textboxes, figure 5.9.

When an activity is selected it is assigned with a four digit number shown to the left of the activity in figure 5.9. The first number refers to the project number, the second to the level number, the third to the stage number and the fourth to the activity number. This numbering system also makes it easier for the user to know which activity that is being edited or processed.

When an activity has been selected, it is also necessary to define the quantity of work by entering the actual values in the text-box according to the definition of the unit in figure 5.9.

### 5.2.5 Define predecessors

The user also needs to define a predecessor for each activity. That means for example that the program must know that activity B can not start until activity A is e.g. 60% done. In the user interface, are two text-boxes related to predecessors and one button. When an activity is selected the interface automatically suggests that that the last selected activity (number 201) will be predecessor for activity 202. If the user wants another activity to be the predecessor it can be changed by pressing the “Predecessor” button, figure 5.10.

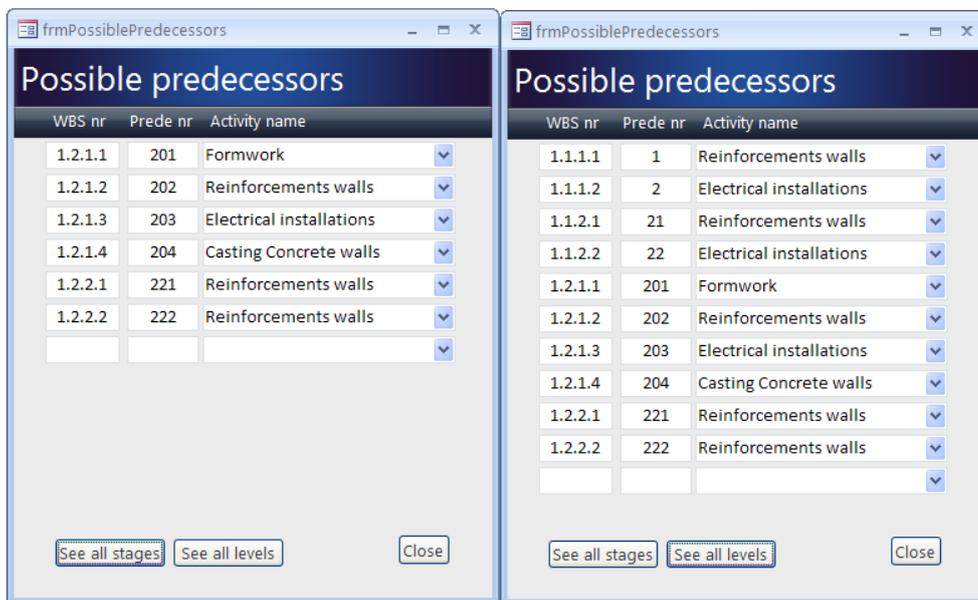


Figure 5.10 - The window on the left shows possible predecessors in all stages within the level and the window to the right shows possible predecessors in all levels within the project

The window lists all possible predecessors. It is possible to filter out activities and only display the activities which are in the actual level, the left picture in figure 5.10. But if needed, it is also possible to see all the activities in the actual project, the right picture in figure 5.10. Here, can the user get the Predecessor number for any activity. When an activity is assigned with the correct predecessor number it is also necessary to define how much (in percent) of the preceding activity that has to be completed before the next successive activity can start.

### 5.2.6 Define total quantity of different types of workers

The last thing that the user has to do is to define the quantity of total workers that are going to be used in the project. To do that, the user needs to press the “open workers” button, figure 5.11.

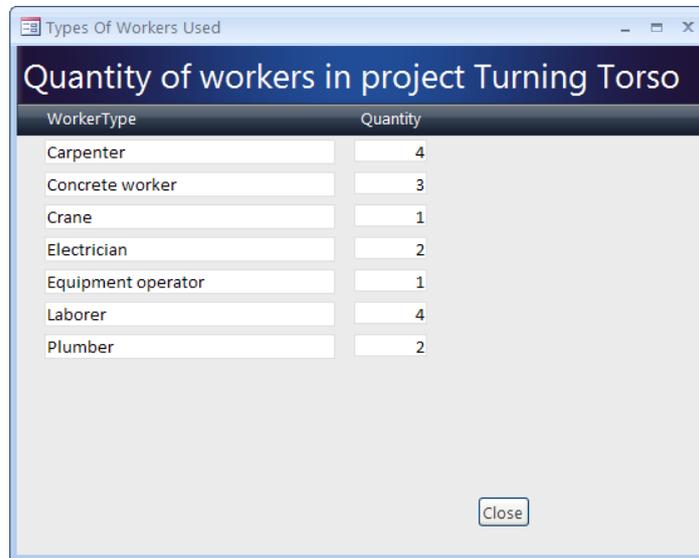


Figure 5.11 - The user can define the quantity of workers used in the project

A workgroup is connected to each specific activity. Each activity can only have one workgroup but the same workgroup can perform different activities. The interface then knows when the user selects an activity which workgroup is attached to the activity and also which types of workers that are included in the workgroup. So when the user presses the “Open Workers” button a query is automatically sent to the databases and the window will only list the types of workers which the user is using in the actual project.

### 5.2.7 See the Work Breakdown Structure

When all data has been inserted to define a project, a work breakdown structure of the project can be seen by pressing the “Open WBS”, see figure 5.12.

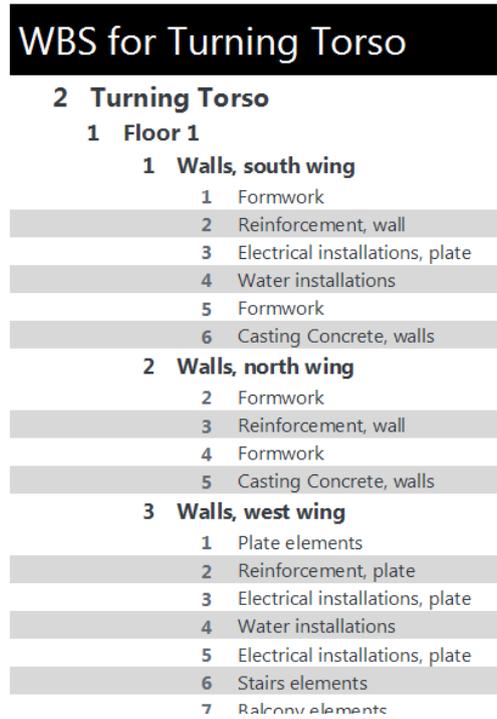


Figure 5.12 - Shows an example of a WBS

### 5.2.8 Pressing the Export to ExtendSim button

When the user has defined all the input data that the model needs the data can be exported to the ExtendSim model by pressing the “Export to ExtendSim” button. The data are then exported to a specific database called DB\_input.

### 5.2.9 Pressing the Analyze results button

After the user has exported the data to the simulation model and run the model the results are exported to another database, called DB\_results. DB\_result can consist of a large amount of data and to help the user to sort out which data is of interest, the user can press the “Analyze results” button in the user interface. When the button is pressed the following window opens, figure 5.13.

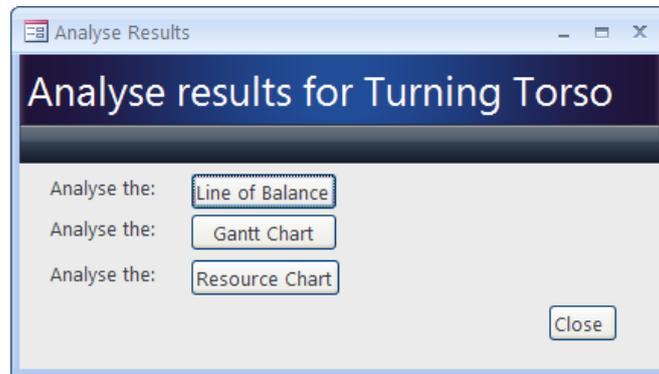


Figure 5.13 - Shows the analyze results window

Here can the user select among three different ways to display the simulation results, e.g. Line-of-Balance, Gantt chart or a Resource chart. For example, if the user chose to press the “Gantt chart” button another window will open, figure 5.14.

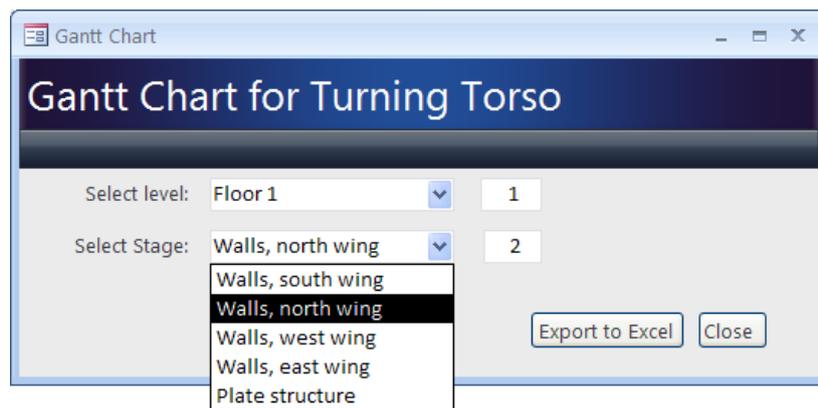


Figure 5.14 - Interface for displaying a Gantt chart for a specific stage

Here can the user choose which level and which stage to display. For instance, if the level Floor 1 and the stage Walls, north wing are selected and the “Export to Excel” button is pressed, does the Gantt charts in excel update and show the results for Floor 1 and Walls, north wing. This works exactly the same for the Line of Balance and the Resource chart.

### 5.3 ExtendSim - model structure and components

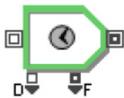
In the simplest terms, ExtendSim models are made up of blocks and connections. As the model runs, item goes into a block, it is processed and/or modified, and it is then sent on to the next block via a connection. The items in the model move from left to right. Each block represents a portion of the process or system that is being modeled. Blocks have names, such as Equation or Queue, that signify the function they perform.

It is possible to assign attributes to an item. Attributes are a very powerful feature that gives items unique properties and characteristics. Attributes can for example be quantity of work or type of worker.

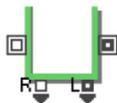
In ExtendSim are large amount of blocks to choose from and it is also possible to create your own blocks. The blocks which were most commonly used in this work are:



Resource item block  
Creates new items.



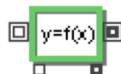
Activity block  
Processes items, the user can define how long time the process takes. In this model, the process time is set to one hour.



Queue block  
Stores items until there is downstream capacity. Can be changed into resource pool queue, then it stores the resources that are needed to complete the activity.



Select item out block  
Sends each item it gets to a selected output based on a specific condition



Equation block  
Can be used to set, modify or check attributes on existing items. Calculates the equation when the item arrives.



Gate block  
Controls the flow of items in a portion of the model (area gating) or based on model conditions (conditional gating). Gates are used in this model to determine when an activity may start. When the predecessor is fulfilled the gate opens.

### 5.3.1 The simulation model

How does the model work? The basic idea for the model is that the item, which moves through the model, can be thought of as a workgroup which moves from block to block and performs certain type of work. The type of the workgroup depends on which attributes that are assigned to the item.

A “default” workgroup is created in a resource item block and goes into a queue block where it waits for further instruction. If we have for example two activities, activity 1 starts right away but activity 2 can not start until activity 1 is 80% completed. When activity 1 is being processed and is 80% completed, a message is sent to the gate block to open the gate for activity 2 because the predecessor has been fulfilled and activity 2 can start. When the gate opens a demand originates and a workgroup from the queue block move to activity 2 and the process begins. Attributes are assigned to the workgroup when it arrives to the activity. When the activity is completed, the workgroup is sent back to the queue block where it loses its attributes and becomes a “default” workgroup again waiting for the next demand to originate.

The core of the model is the following blocks that simulate one activity on a construction site, shown in figure 5.15.

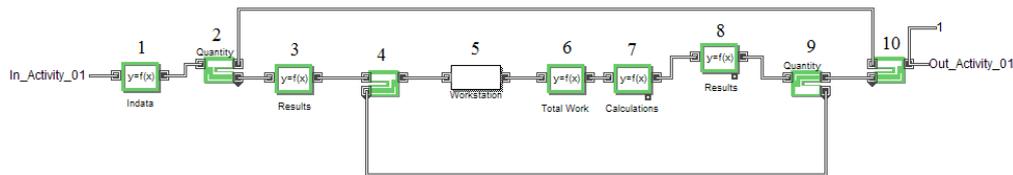


Figure 5.15 - Shows the block combination describing one single activity.

When a workgroup (item) arrives at an activity it starts by going into the first block which is an equation block. The equation block starts by reading information from the database DB\_inputs and assigns that information as attributes to the workgroup. The attributes describe the activity, e.g. the quantity of work that is going to be performed, type of workers in the workgroup, quantity of workers in the workgroup, unit time of the workgroup performance and the costs. Block number two checks if the quantity of work is equal to zero, if the quantity is equal to zero then the user is not going to use this activity and the item is routed past the blocks via the upper connector. The third block is another equation block. This block writes to another database DB\_results, e.g. the current date, quantity of work, the progress and the percent done. The fourth block is a routing block. The fifth block is the workstation. In the workstation block, the workgroup is processed for one hour. The sixth and seventh blocks are also equations blocks. They calculate e.g. the quantity of work left, the progress and how much work is done in percents. The eighth block is exactly like the third block, writes the same type of information to the database DB\_results. The ninth block is a routing block which checks if the quantity of work left is equal to 0. If so, then the workgroup is routed via the top output but if the work left is greater than 0 (work still remains),

the workgroup is routed via the bottom output and is processed again. The workgroup will be looped in this way until the quantity of work in the activity is equal to zero.

### **5.3.2 Resource Pools**

In other project planning programs it can often be difficult to make sure that the same worker is not used twice at the same moment. In this model that is not a problem. Resource pools are used to control the human resources and contain the total amount of workers who will be used during the project. Each time an item enters a workstation block, the model checks how many resources that are needed to complete the activity and after that it checks if the required resources are available in the resource pool. If there are enough available resources in the resource pool, the resources are sent to the workstation and the activity starts. When the activity is finished, the resources are sent back to the resource pool and become then available for use again. If there are not enough available resources in the resource pool, the item in the workstation has to wait until more resources become available.

### **5.3.3 Shifts**

Excel is used to calculate the shifts. The start date is entered into excel and into a formula where excel calculates the shift calendar by taking weekends into account. The results are then exported back to the ExtendSim model.

Shifts are used to define the workday. The default settings in the model are that the workday starts at 8:00 o'clock and is finished 18:00. A week has five workdays, which is from Monday to Friday. If the user wants to change these settings it is possible to do that in the Excel-file.

## **5.4 Model results**

It is important that the results are shown in a clear and efficient way. Excel is used to read information from the database DB\_results and produce visual results. The user interface is used to sort out the data that the user wants to see and analyze.

### **5.4.1 Time plans**

The model produces two kinds of time plans, a Gantt chart (figure 5.16) and Line Of balance chart (figure 5.17).

Discrete Event Simulations of Construction Related Production Systems

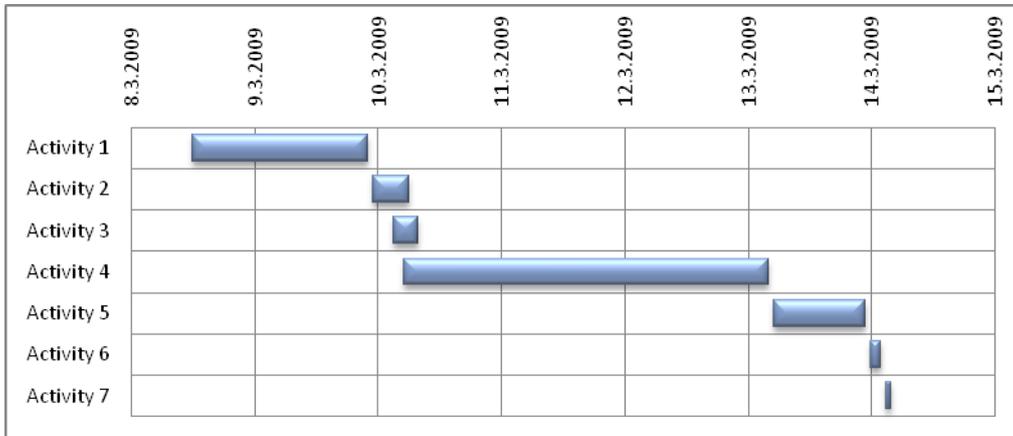


Figure 5.16 - Example of a Gantt chart based on the ExtendSim results

Excel produces two types of Gantt charts. The first shows a specific level and the other shows a specific stage. The user chooses which level and which stage to display in the user interface, see figure 5.14.

Excel also produces a Line-of-Balance graph which shows one stage. The user selects which stage to display in the user interface, figure 5.14. Each line represents a single activity. The y-axis on the graph shows the quantity of work done in percents and the x-axis shows the time. The inclination of the lines represents the speed of the activity. This graph is very helpful when the user is defining the predecessor and makes it easier for the user to see the earliest start for the activities. It usually means trouble if two lines overlap each other but not necessary. It is therefore important that the user is aware of what he (or she) is doing. See figure 5.17.

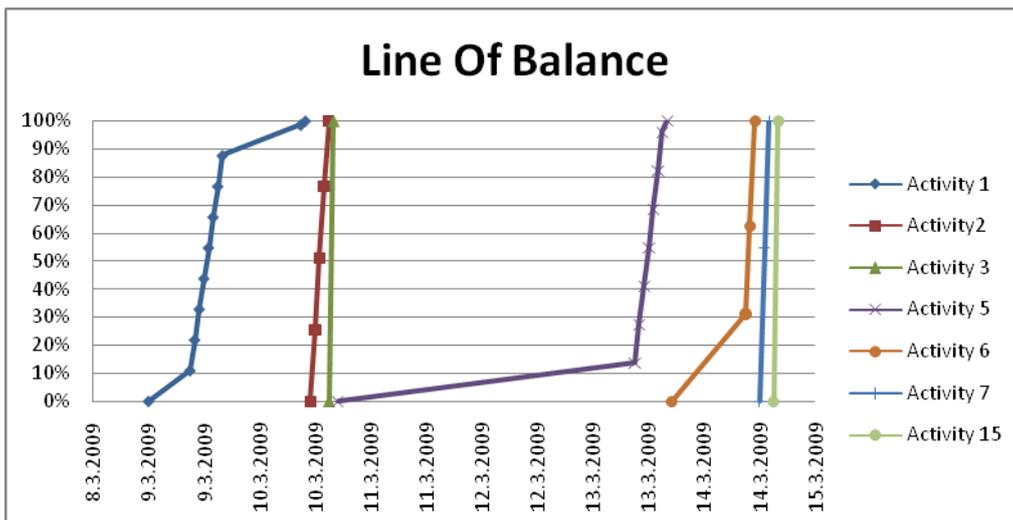


Figure 5.17 - Example of a LoB graph based on the ExtendSim results

### 5.4.2 Resource chart

Excel also creates a Resource chart, figure 5.18. The resource chart is used to show quantity of workers and their utilization. The blue bars in the chart, show the maximum quantity of workers in the project and the red bars show the average quantity of workers actually working.

As stated in chapter 3.1.1 the model runs in a simulation time, an abstraction of real time. The model writes the result data into the database DB\_result every hour when the simulation is running. Since the model keeps track of exactly which type of workers are working and the quantity of the workers who working every hour it becomes possible to calculate the average quantity of workers.

Ideally, the blue and the red bars should be equal but because of waiting time and slack times, the red bars are usually lower. The user can choose to see the chart for the whole project, a specific level, or a specific stage. In figure 5.18, does the y-axis show the quantity of workers and the x-axis shows the type of workers.

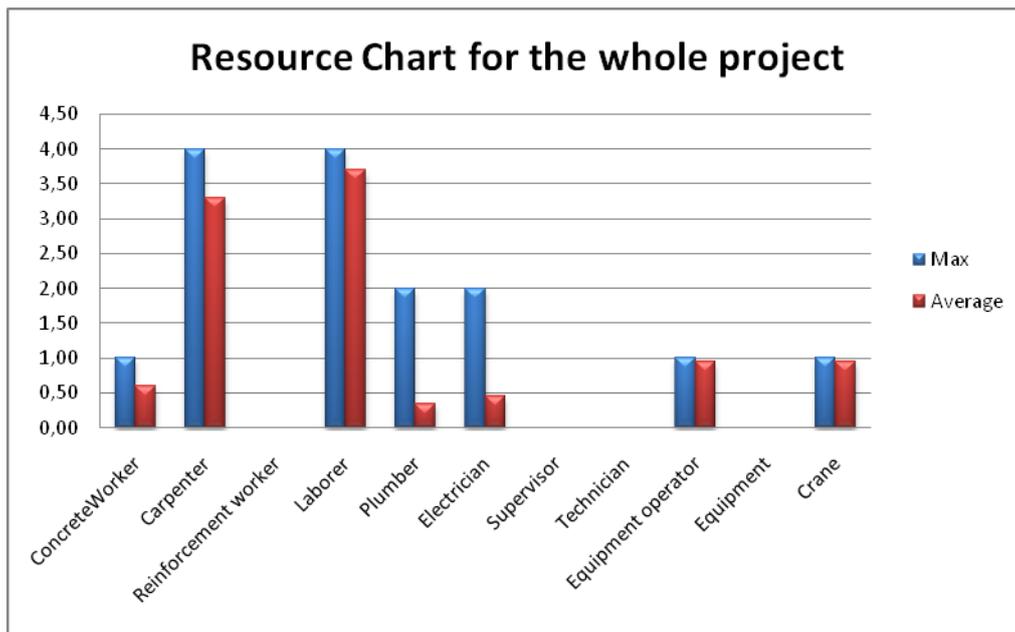


Figure 5.18 - Example of a resource chart based on the ExtendSim results

### 5.4.3 Resource utilization graph

The utilization graph shows the utilization of different types of workers over the construction time, figure 5.19. The y-axis shows the utilization in percents and the x-axis shows the time.

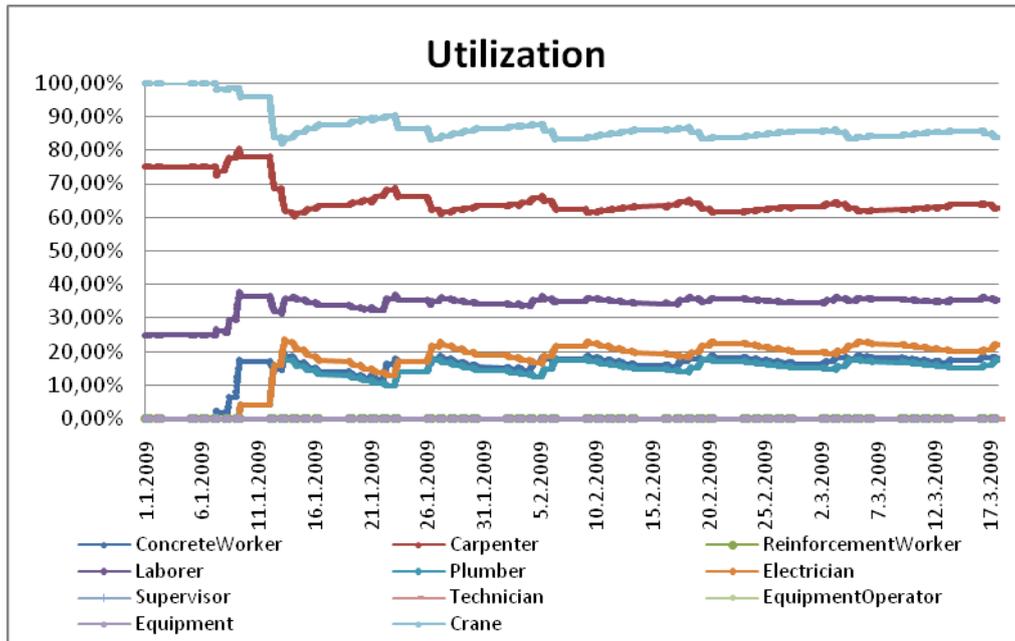


Figure 5.19 - Example of a utilization chart based on the ExtendSim results

### 5.4.4 Costs

The model calculates two types of costs related to the human resources. The first cost is the total cost which is the cost of having employees working over the workday.

The second cost refers to the cost when there is no waiting time and only the time when the workers are actually working, that is when the utilization of workers is equal to 100%.

The second cost is calculated in a similar way the average utilization described in chapter 5.4.2. The model knows exactly what type of workers and the quantity of workers who are working every hour and because the model does also know the cost per hours for the workers it can calculate the cost.

Excel also produces a graph which shows the accumulative material cost over the construction time, figure 5.20.

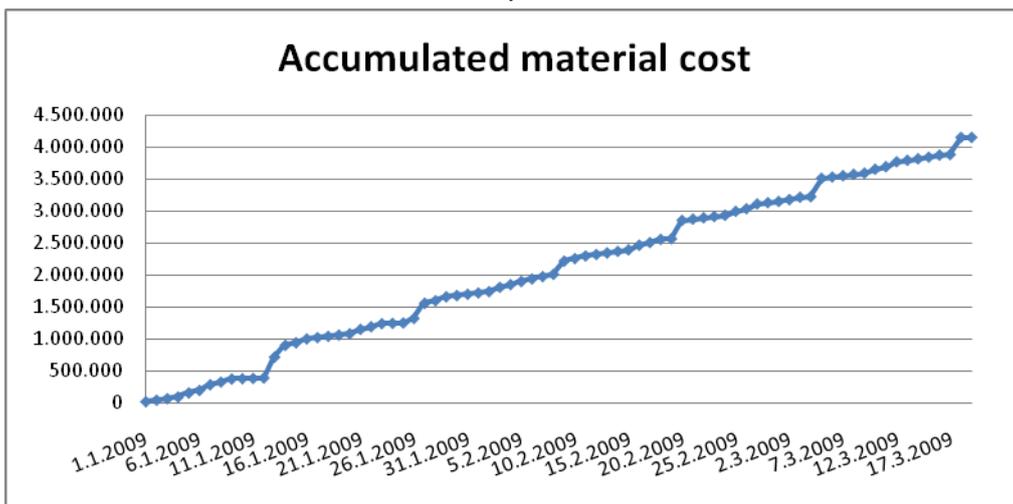


Figure 5.20 - Example of an accumulated material cost graph based on the ExtendSim results

## 6. Testing the model on a real project

### 6.1 Description of the real project used in the simulation

After the model was finished a real project was used to verify that the model calculates correctly. It was done by comparing the simulated results with data obtained from the real project.

#### 6.1.1 General

The project consists of two multifamily buildings located in Lund. The buildings are almost exactly alike and have six floors plus a basement floor. Each floor has six apartments apart from the top floor which has four apartments. Each building has two entrances, each connecting to an elevator shaft and a stair case. All the apartments apart from those on the ground floor have balconies, figure 6.1.

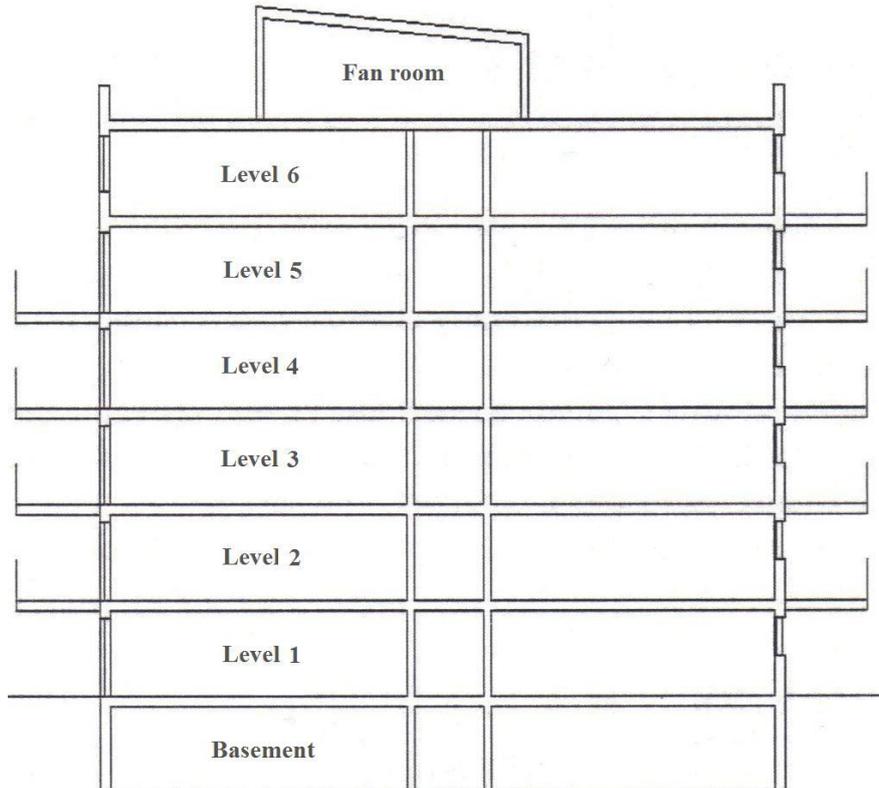


Figure 6.1 - Section of the framework from the real project.  
(Lindén and Wahlström, 2008)

### 6.1.2 Concrete framework description

The buildings frame consists vertically of load bearing interior concrete walls and horizontally of concrete floor slabs. The exterior walls are partly made of concrete and partly made of steel columns and curtain walls. All the concrete walls are casted on the construction site. The floor structure is made of filigran plates on which a top layer of concrete is poured. The floor structure is supported by the concrete walls and the steel columns.

Water installations, ventilation and electricity are embedded into the floor structure. The water installation includes pipes for tap water, heating, and outlets. The electric cables have been installed in advance in the electrical installations pipes and connected to a box. Electrical installations are also placed inside the walls.

### 6.1.3 Description of the construction process

The two buildings are built in parallel where the workers move between the buildings performing specific tasks. For instance, one workgroup assembles the floor structure and another workgroup assembles the formwork and pour the concrete walls.

There are two cranes on the construction site. Each floor is divided into seven stages. Six stages contain the forming and concreting of the walls. The seventh stage consists of erecting the floor structure. Each wall stage contains about 25–30 meters of walls and the duration of assembling the formwork and casting the walls in one stage is one day. So the total duration for all the walls on one floor should be six work days. One extra day is needed to move the formwork to the other building.

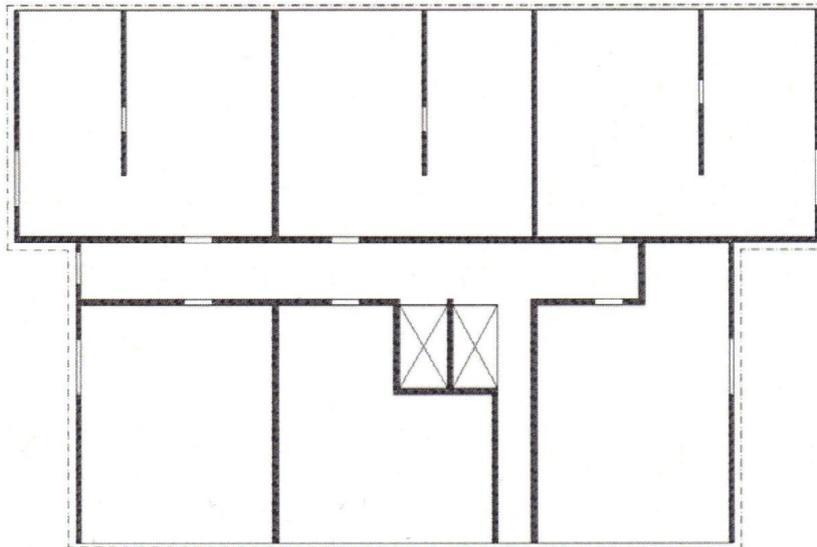


Figure 6.2 - Example of one floor plan (Lindén and Wahlström, 2008)

The work of erecting the concrete walls starts with marking their position on the floor structure according to the drawings. Then they start assembling the first side of the formwork. When that is done, the reinforcement and electrical installations are placed. When the rebars and installations are in place, the other side of the formwork can be assembled. The next step is to cast the concrete and once the concrete has been poured into the formwork and has cured, the formwork is removed and reallocated to the next wall stage to be poured.

In the seventh stage, the floor structure is erected. Each floor consists of 116m<sup>3</sup> of concrete. The duration of the floor stage is seven days. That makes the total time for the seven stages equal to 14 days.

The work of assembling the floor structure also starts with marking the starting point of the filigran elements. Then are the props and stringers placed at the right place according to the structural drawings. A crane is used for lifting the filigran elements and two concrete workers direct the elements into final position. When all the filigran elements are in place, the joints between the elements are sealed and also reinforced by placing reinforcement mesh over the joint. When that is finished, the technical installations are placed. When the technical installations are in place, the top layer of reinforcement is then placed. The last thing is to cast the top layer on the filigran elements. The duration of the pouring activity is one day.

The buildings frame also includes precast stairs and balconies.

## **6.2 The input data**

That is a large amount of input data that is needed for the model to simulate a construction site. The input data can be divided into two types of data, data which the user picks from the price bank database through the user interface, e.g. unit times and data that the user enters into the user interface, e.g. quantity of work to be performed.

The real project consists of 6 levels, in every level are 7 stages and in every stage are 7 activities. That makes 294 activities.

### **6.2.1 Defining activities**

The chapter regarding limitations for the project says “The model is generic to its structure but is tested on activities involved in the erection of a concrete framework casted on-site. The activities concerned are; assemble and disassemble of temporary formwork, tying reinforcement of walls and plates, placing of electrical and water installations, erection of false work, placement of precast concrete elements (e.g. formwork, balconies and stairs), and pouring of concrete walls and slabs.”

The activities are connected to the price bank. When an activity is selected the information given in table 6.1 is automatically written into the input database which the simulation model uses.

Table 6.1 - Shows the workgroup performance and the material cost for the activities

Activity name	Workgroup performance	Material cost
Formwork, assembling	14,25 m <sup>2</sup> /h	83,5 SEK/m <sup>2</sup>
Formwork, striking	129,2 m <sup>2</sup> /h	9,3 SEK/m <sup>2</sup>
Reinforcement mesh, walls	66,67 m <sup>2</sup> /h	36,78 SEK/m <sup>2</sup>
Reinforcement mesh, plates	80 m <sup>2</sup> /h	36,78 SEK/m <sup>2</sup>
Reinforcement, walls	0,22 ton/h	7700 SEK/ton
Reinforcement, plates	0,244 ton/h	7700 SEK/ton
Casting concrete walls	14,25 m <sup>3</sup> /h	970 SEK/m <sup>3</sup>
Casting concrete plates	25,64 m <sup>3</sup> /h	970 SEK/m <sup>3</sup>
Plate element	22,72 m <sup>2</sup> /h	205 SEK/m <sup>2</sup>
Stairs element	1,01 stairs/h	48.000 SEK/pcs
Balcony element	2,91 balconies/h	13.500 SEK/pcs
Electrical installations, walls	20 m/h	20,22 SEK/m
Electrical installations, plates	20 m/h	11,09 SEK/m
Water installations	16,67 m/h	74,75 SEK/m
Precast twin walls, assembling	14,29 m <sup>2</sup> /h	680 SEK/m <sup>2</sup>
Precast twin walls, post work	28,57 m <sup>2</sup> /h	0 SEK/m <sup>2</sup>
Precast twin walls, reinforcement	50 m <sup>2</sup> /h	20 SEK/m <sup>2</sup>

For a more detailed description on the activities see appendix A.

## 6.2.2 Defining weather data in the model

This chapter describes a description of how various weather conditions are described in the simulation model. The effect of a specific weather condition on work performance is based on the results described in chapter 4. Weather-data for Malmö 2008 was used. The data was received from Swedish Metrological and Hydrological Institute, (SMHI, 2009). In table 6.2, the effect of different weather conditions have on a specific activity is shown.

Table 6.2 - Shows how much a specific weather condition affects a specific activity

	Formwork	Reinforcement, wall	Casting, wall	Reinforcement, plate	Casting, plate
<b>Wind</b>	40%	25%	40%	20%	10%
<b>Rain</b>	20%	25%	20%	30%	30%
<b>Temp.</b>	20%	25%	20%	20%	30%
<b>Snow</b>	20%	25%	20%	30%	30%
	<b>100%</b>	<b>100%</b>	<b>100%</b>	<b>100%</b>	<b>100%</b>

These values are based on the comments and recommendation from the responders of the questionnaire.

Consider the actual weather in the 2<sup>nd</sup> of January 2008 and how it would affect the activity formwork. The actual weather data is shown in table 6.3.

Table 6.3 - Shows how the total effect on work performance is calculated

	Weather	Performance	Effect	Total
<b>Wind</b>	9 m/s	80%	40%	32%
<b>Rain</b>	1,2 mm/h	95%	20%	19%
<b>Temp.</b>	0,7 °C	100%	20%	20%
<b>Snow</b>	20 mm/h	70%	20%	14%
			<b>Sum:</b>	<b>85%</b>

The performance values in table 6.3 are according to the answers from the questionnaire. The total performance of the workgroup is calculated according to equation (7):

$$\text{Total performance of the workgroup} = \sum (\text{Performance} * \text{Affect}) \quad (7)$$

By multiplying the performance with the effect and adding the all the weather condition together, the total work performance for the workgroup becomes 85%.

In the beginning of the simulation, the model imports the weather data into an internal database. Then as the model runs and when a workgroup goes into a workstation it starts by checking the database to see how the weather is for that specific day and time. Then the model recalculates the work performance of the workgroup based on actual weather conditions and the workgroup can to work.

### 6.2.3 The data entered into the user interface

The other input data necessary to run the model is the data which the user enters into the user interface i.e. the quantity of work, number of workgroups, and the predecessor number and the percents of the total work that must be completed before the next following activity can start. In table 6.4 are the data for stage 1 in level 1 and in table 6.5 are the data for stage 7 in level 1.

Table 6.4 - Shows the input data for stage 1 in level 1

Activity name	Quantity	Workgroup performance	Nr of workgroups	Prede. number	Prede. percent
1.1.1.Striking formwork	114 m <sup>2</sup>	128,2 h	1	0	0%
1.1.2.Formwork	57 m <sup>2</sup>	14,25 h	1	1	100%
1.1.3.Reinforcement, wall	0,191 ton	0,22 h	1	2	33%
1.1.4.Reinforcement mesh, walls	79,8 m <sup>2</sup>	66,67 h	1	3	100%
1.1.5.Electrical installations, wall	12,42 m	20 h	1	3	100%
1.1.6.Formwork	57 m <sup>2</sup>	14,25 h	1	5	100%
1.1.7.Casting Concrete, walls	10,55 m <sup>3</sup>	14,25 h	1	6	100%

Discrete Event Simulations of Construction Related Production Systems

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Stages from 1 to 6 all contain the same activities but the quantity varies a little.

*Table 6.5 - Shows the input data for stage 7 in level 1 which is assembling plate elements*

Activity name	Quantity	Workgroup performance	Nr of workgroups	Prede. number	Prede. percent
1.7.1.Plate elements	463 m <sup>2</sup>	22,72 h	1	107	100%
1.7.2.Reinforce-ment, plate	2,54 ton	0,244 h	1	121	50%
1.7.3.Electrical installations, plate	615 m	30 h	1	122	100%
1.7.4.Water installations	261 m	16,67 h	1	122	100%
1.7.5.Casting Concrete, plate	116 m <sup>3</sup>	25,64 h	1	123	100%
1.7.6.Stairs elements	1 pcs.	1,01 h	1	125	100%
1.7.7.Balcony elements	6 pcs.	2,91 h	1	126	100%

The total number of workers used in the project is shown in table 6.6.

*Table 6.6 - Total quantity of workers used in the project*

Workers type	Quantities
Carpenter	4
Concrete worker	1
Crane	1
Electrician	2
Equipment operator	1
Laborer	4
Plumber	2

## 7. Verification of simulation model

In this chapter, the simulated results (time and cost) are compared with the data obtained from the real project.

### 7.1 Time plans

Table 7.1 shows the duration of the project. The start date was set to the 1<sup>st</sup> of January 2009 and the casting of the top floor level (stage 7) was completed the 30<sup>th</sup> of March 2009. That makes a total duration of 89 days or 63 workdays.

*Table 7.1 - Shows the results from the simulation*

Start	Finish	Total workdays	Total days
1.1.2009 08:00	30.3.2009 12:00	63	89

It is important to mention that in this run, where the model is being verified, that effect of weather is being neglected. How the weather may affect the outcome will be shown in the next following chapters.

#### 7.1.1 Gantt chart

As described in chapter 5.2.9, can the user display desired level and stage. This report focuses on the results from the stages because when a whole level is shown, the Gantt chart becomes hardly readable because of the reports size and does not fit into the report. It can be assumed that if the stages are correct, then the levels are also correct.

Each level as described in chapter 6.1.3 consists of seven stages, six wall stages and one floor structure stage. Let us start with studying stage 1. The stage consists of the work of erecting walls. The activities in stage 1 are as follows: striking and cleaning the formwork, assembling the first side of the formwork, reinforcement of the walls (both mesh and loose bars), placing electrical installations, assembling the second side of the formwork and finally, casting the concrete. This procedure should take about one working day to complete according to the data obtained from the real project. The results from the simulation model are presented in figure 7.1 and table 7.2.

## Discrete Event Simulations of Construction Related Production Systems

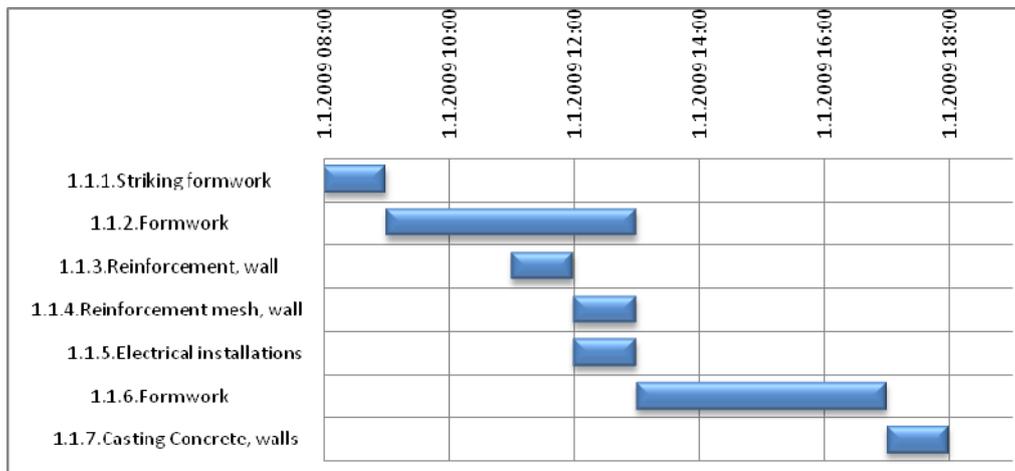


Figure 7.1 - Results of activities' duration for stage 1 presented as a Gantt chart

Table 7.2 - Results for stage 1 presented as values

Activity Name	Start	Duration	Finish
1.1.1.Striking formwork	1.1.2009 08:00	0,04	1.1.2009 09:00
1.1.2.Formwork	1.1.2009 09:00	0,17	1.1.2009 13:00
1.1.3.Reinforcement, wall	1.1.2009 11:00	0,04	1.1.2009 12:00
1.1.4.Reinforcement mesh, walls	1.1.2009 12:00	0,04	1.1.2009 13:00
1.1.5.Electrical installations, wall	1.1.2009 12:00	0,04	1.1.2009 13:00
1.1.6.Formwork	1.1.2009 13:00	0,17	1.1.2009 17:00
1.1.7.Casting Concrete, walls	1.1.2009 17:00	0,04	1.1.2009 18:00

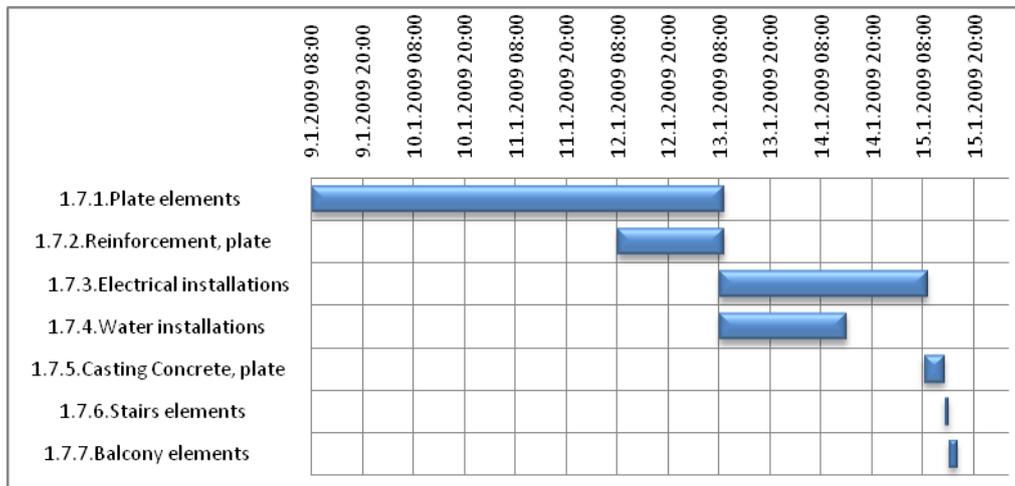
The result in figure 7.1 and table 7.2, reveals that it takes about 10 hours to complete stage 1. By comparing with the real project it takes 9 hours to complete stage 1. Reasons that may explain the difference can be that in the real project, the activities were carried out more in parallel than was assumed in the model. Another explanation would be that the unit times that were used in the simulation model may be a little bit on the conservative side.

Stages from 1 to 6 are all wall stages and are all very similar and have the same results.

## Discrete Event Simulations of Construction Related Production Systems

Now let us look at stage 7, namely the erection of the floor structure. The stage consists of the following activities: assembling plate elements, reinforcement of the top layer, placement of electrical and water installations, and casting the top layer of the concrete. The stage also includes installation of precast stair and balcony elements. This procedure should take seven days according to the data obtained from the real project.

The results from the simulation model are presented in figure 7.2 and table 7.3. As seen in figure 7.2 and table 7.3, the total duration was simulated to about seven days which is consistent with the real project.



*Figure 7.2 - Gantt chart of stage 7*

*Table 7.3 - The results for stage 7*

Activity Name	Start	Duration	Finish
1.7.1. Plate elements	9.1.2009 08:00	4,04	13.1.2009 09:00
1.7.2. Reinforcement, plate	12.1.2009 08:00	1,04	13.1.2009 09:00
1.7.3. Electrical installations, plate	13.1.2009 08:00	2,04	15.1.2009 09:00
1.7.4. Water installations	13.1.2009 08:00	1,25	14.1.2009 14:00
1.7.5. Casting Concrete, plate	15.1.2009 08:00	0,21	15.1.2009 13:00
1.7.6. Stairs elements	15.1.2009 13:00	0,04	15.1.2009 14:00
1.7.7. Balcony elements	15.1.2009 14:00	0,08	15.1.2009 16:00

### 7.1.2 Line of Balance

The results can also be shown according to the Line of Balance method. The result for stage 1 is shown in figure 7.3.

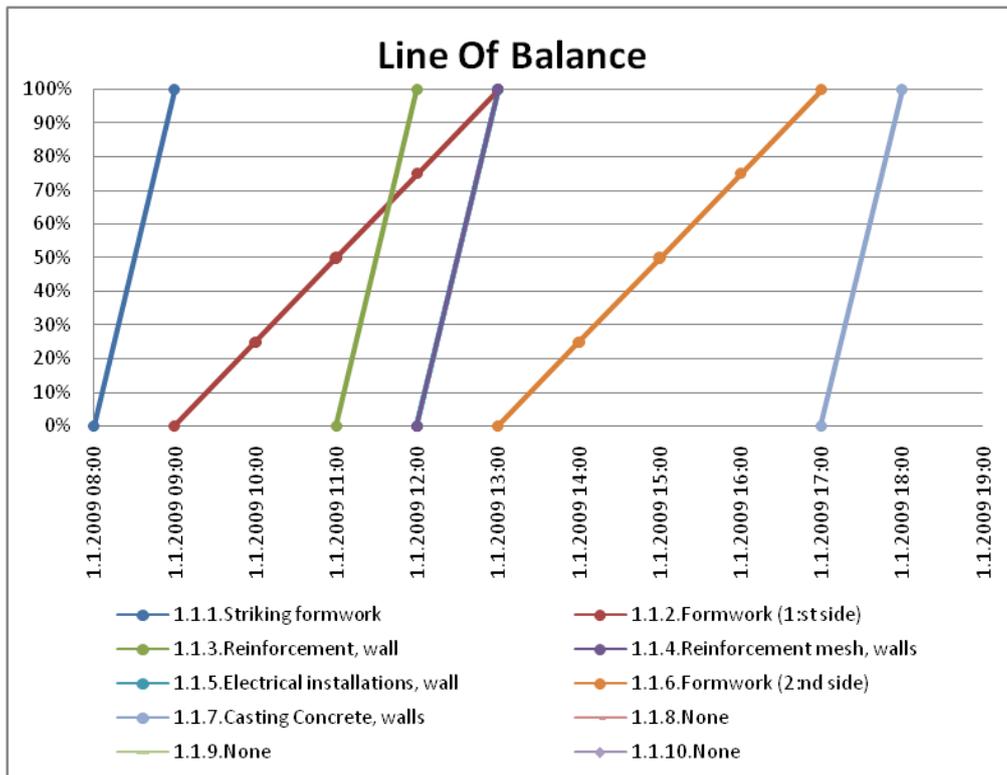


Figure 7.3 - The results for stage 1 presented as a LoB graph

As shown in figure 7.3, the green line which describe the activity “reinforcement wall” which is reinforcement with steel bars overlaps the red line which is the activity formwork (1:st side). This usually means trouble but not in this case. The activities reinforcement wall and reinforcement mesh walls are technically one activity, they are performed by the same workgroup and are worked on at the same time. It can therefore be said that the start time for the activity is 11:00 and the activity is finished 13:00.

The reason for the decision of dividing the reinforcement activity into two sub-activities (bar and mesh), is that the quantity for mesh is usually given in m<sup>2</sup> and for bars in tons. The two activities have also different unit times.

Discrete Event Simulations of Construction Related Production Systems

The LoB chart for stage 7 is shown in figure 7.4. The reason why the blue line goes horizontally from 10<sup>th</sup> to the 12<sup>th</sup>, is that it is a weekend. The reason why the other lines also go slightly horizontal is because it is then between two workdays.

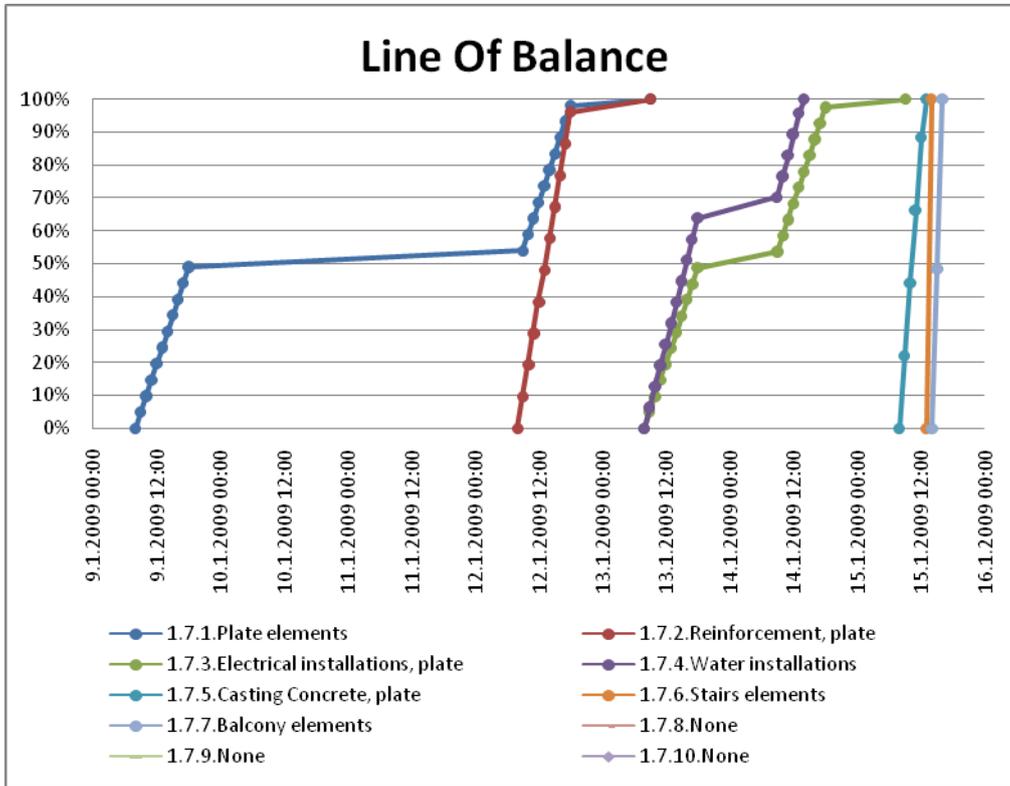


Figure 7.4 - The LoB graph for stage 7

## 7.2 Utilization of workers

The user can choose to display the resource chart for the whole project, or for a specific level, or for a specific stage, see figure 7.5. The chart shows with a blue bar the maximum number of workers working in the project in a specific location (level, stage etc). The red bars show the average number of workers who are working in the same specific location (level, stage etc).

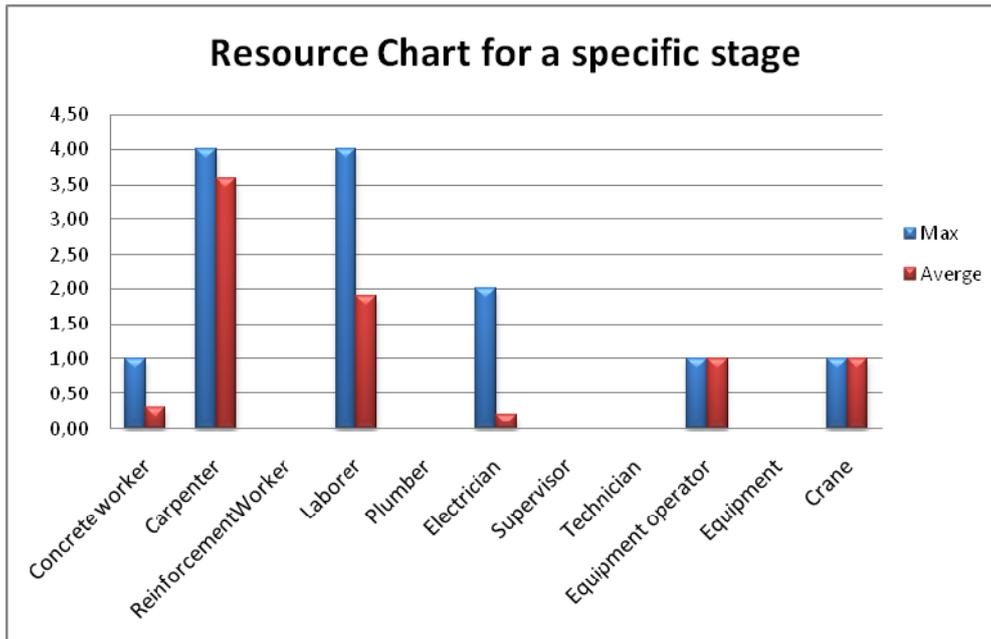


Figure 7.5 –The resource chart for stage 1 in level 1 in the project

In figure 7.5, the blue bars shows that in stage 1 on level 1, the following resources are used:

- 1 Concrete worker
- 4 Carpenters
- 4 Laborers
- 2 Electricians
- 1 Equipment operator
- 1 Crane

But on the average is the following quantity of workers working (red bars):

- 0,3 Concrete worker
- 3,6 Carpenters
- 1,9 Laborers
- 0,2 Electricians
- 1 Equipment operator
- 1 Crane

This shows that the utilization of the concrete worker and laborer is not good. It is understandable that the utilization of the electricians and the plumbers is low because they are often subcontractor and are working on several projects at the same time.

In figure 7.6, the resource usage for all seven stages in level 1 is shown.

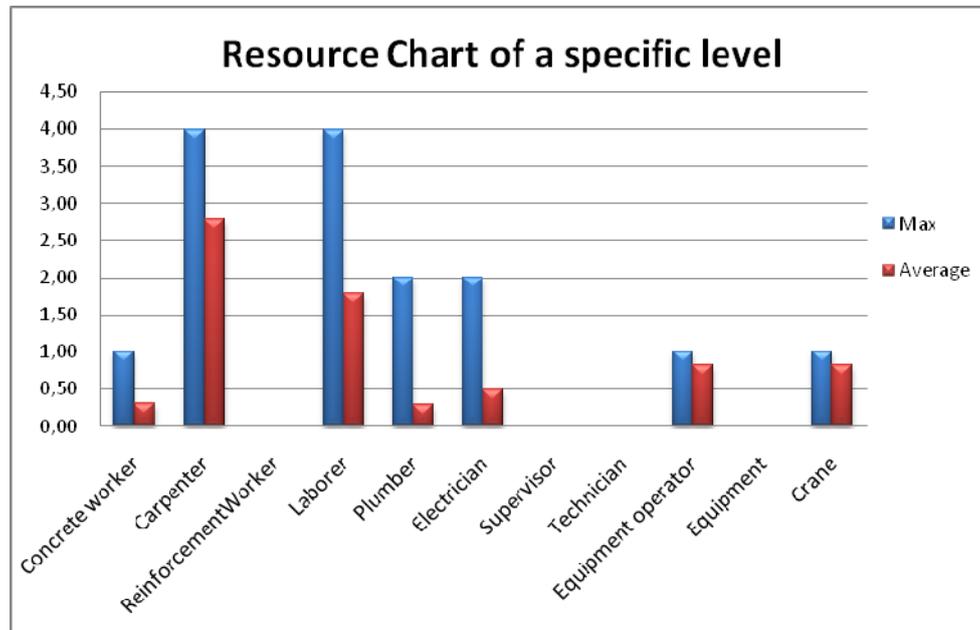


Figure 7.6 - The resource chart for level 1 in the project

In figure 7.6, the blue bars shows that in the whole level 1, the following number of resources are used:

- 1 Concrete worker
- 4 Carpenters
- 4 Laborers
- 2 Plumbers
- 2 Electricians
- 1 Equipment operator
- 1 Crane

But on the average is the following quantity of workers working (red bars):

- 0,3 Concrete worker
- 2,8 Carpenters
- 1,8 Laborers
- 0,3 Plumbers
- 0,5 Electrician
- 0,8 Equipment operator
- 0,8 Crane

Again is the utilization for the workers low.

As figure 7.7 shows, the results for the whole project are almost identical to the results for a whole level according to figure 7.6.

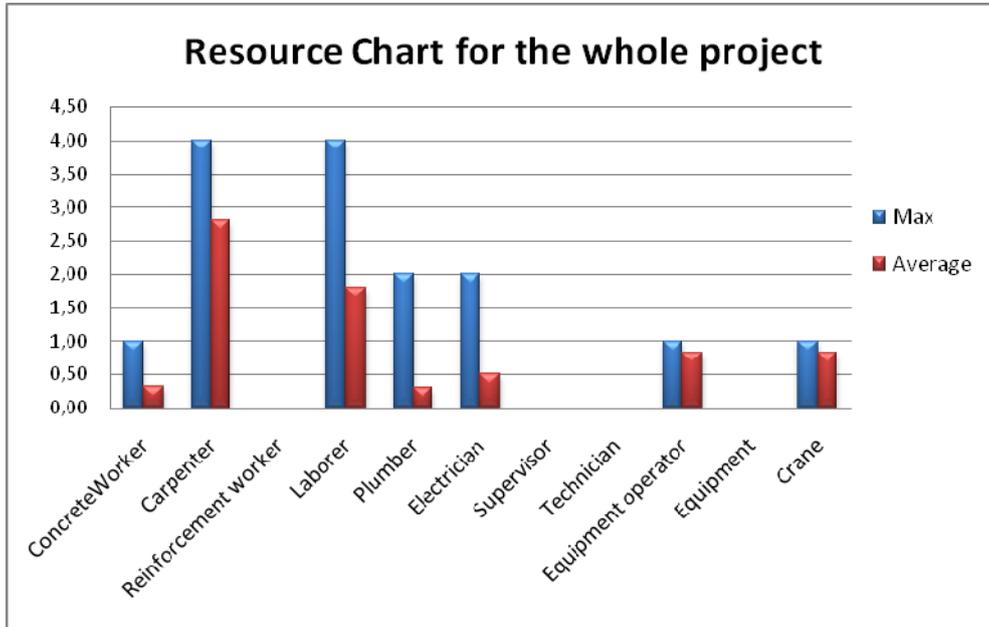


Figure 7.7 - The resource chart for the whole project

But how can it be that the result for the utilization for the workers is so low? One reason for that is that in reality the workers are moving between the two buildings that are erected simultaneously and the simulation model only considers the work carried out in one building. So the same worker is in reality working in both buildings and therefore the real utilization is technically higher than the simulated. But despite that, there is still room for improvement.

In figure 7.8, the resource utilization for the whole project duration is shown. On the y-axis is the utilization in percents shown and on the x-axis is the construction time.

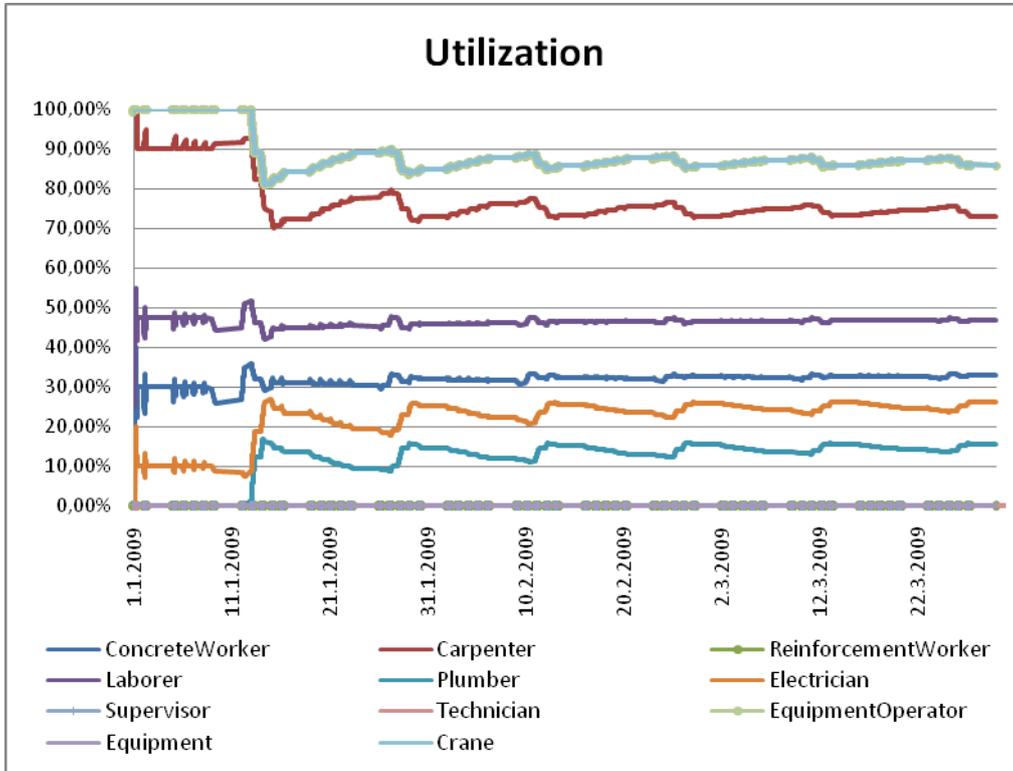


Figure 7.8 - The utilization for the whole project over time.

It can be seen, in figure 7.8, that the utilization drops for the crane, equipment operator and the carpenter around the 13<sup>th</sup> of January. The reason can be seen in table 7.3. The 13<sup>th</sup> of January starts the activity of electrical installations in plates and next activity is the water installations. Those activities do not require crane, equipment operators or carpenters and therefore drops the utilization. But as can be seen in figure 7.8 does the utilization for the electricians and the plumber increase.

## 7.3 Costs

### 7.3.1 Cost of workers

Let us first consider the total cost for all the workers, that is the cost of having workers on the construction site for one workday. A summary of the total costs for workers for one building are shown in table 7.4.

The cost of the plumbers and the electricians are calculated different for the other workers. Plumbers and electricians are in most cases subcontractors and may be working on several projects at the same time. Therefore they often do only work a part of the workday on the project and because of that is only the actual time, when they are on the construction site and working, counted into the total cost.

Table 7.4 - The total cost for workers

Type of worker	Cost per hour	Nr workers	Total man hours	Total Cost
Concrete worker	300	1	630	189.000 SEK
Carpenter	300	4	2520	756.000 SEK
Reinforcement worker	300	0	0	0 SEK
Laborer	250	4	2520	630.000 SEK
Plumber	300	2	96	57.600 SEK
Electrician	300	2	162	97.200 SEK
Supervisor	350	0	0	0 SEK
Technician	400	0	0	0 SEK
Equipment operator	280	1	630	176.400 SEK
Equipment	300	0	0	0 SEK
Crane	625	1	630	393.750 SEK
<b>Total:</b>			<b>7188</b>	<b>2.299.950 SEK</b>

Table 7.5 shows the costs for the actual working time which means that costs for waiting is not included. The difference compared to table 7.4 is 764 200 SEK, so there is lot of room for improvement.

Table 7.5 - The total cost without any waiting time

Type of worker	Cost per hour	Total hours worked	Total Cost
Concrete worker	300	204	61.200 SEK
Carpenter	300	1818	545.400 SEK
Reinforcement worker	300	0	0 SEK
Laborer	250	1164	291.000 SEK
Plumber	300	192	57.600 SEK
Electrician	300	324	97.200 SEK
Supervisor	350	0	0 SEK
Technician	400	0	0 SEK
Equipment operator	280	534	149.520 SEK
Equipment	300	0	0 SEK
Crane	625	534	333.750 SEK
<b>Total:</b>		<b>4470</b>	<b>1.535.670 SEK</b>

### 7.3.2 Material costs

The model calculates the material cost for each activity. In table 7.6, the material cost is shown for the whole project.

Table 7.6 - The material costs for the project

Activity Name	Total material cost
Striking formwork	37.405 SEK
Formwork	335.837 SEK
Reinforcement, wall	51.821 SEK
Reinforcement mesh, walls	103.550 SEK
Reinforcement, plate	117.348 SEK
Reinforcement mesh, plate	0 SEK
Casting Concrete, walls	360.966 SEK
Casting Concrete, plate	675.120 SEK
Stairs elements	288.000 SEK
Balcony elements	486.000 SEK
Electrical installations, plate	40.922 SEK
Electrical installations, wall	8.861 SEK
Water installations	117.059 SEK
Plate elements	569.900 SEK
<b>Total:</b>	<b>3.192.789 SEK</b>

The total material cost was simulated to 3 192 789 SEK. The model also calculates how the material cost adds up over time. The accumulated material cost is shown in figure 7.9.

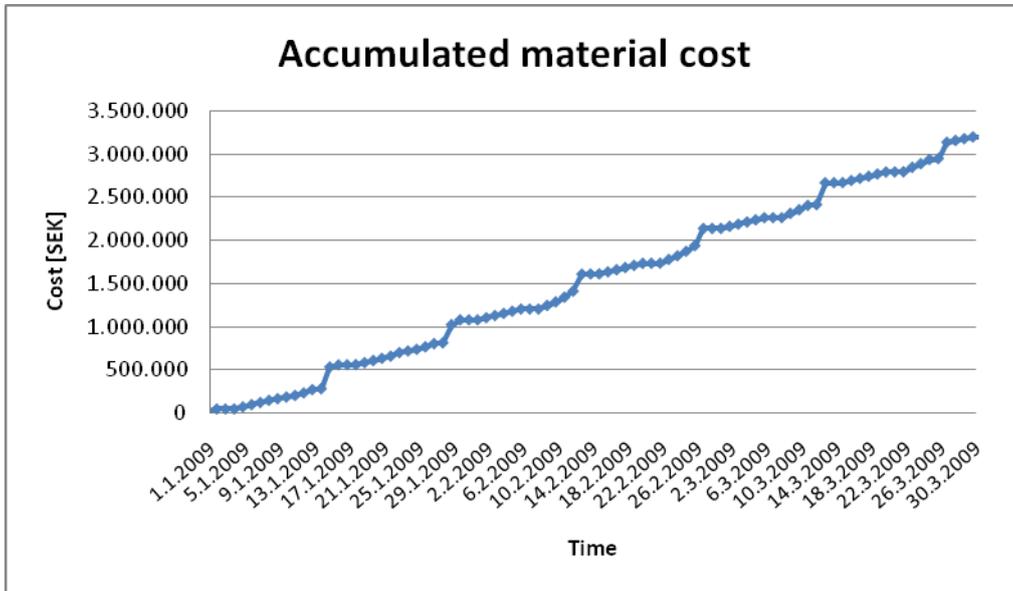


Figure 7.9 - The accumulated material costs of the project

### 7.3.3 Total simulated cost

The total simulated cost is 5 492 739 SEK according to table 7.7.

Table 7.7 - The total simulated cost for the project

	<b>Total cost</b>
Human resources	2.299.950 SEK
Material	3.192.789 SEK
<b>Total:</b>	<b>5.492.739 SEK</b>

### 7.3.4 Comparison of costs with the real project

The cost for the real project is reported in Lindén and Wahlström (2008). When the total cost for the real project was calculated it was only taken into consideration the time when the workers were actually working. That means that costs for having people waiting are not included. Only the cost for concrete workers, carpenters, electricians and plumbers were counted. The costs for the real project are presented in table 7.8. The values concern the cost for both material and workers.

*Table 7.8 - The total cost for the real project*

<b>Activity name</b>	<b>Total cost</b>
Concrete	1.252.170 SEK
Reinforcement	451.413 SEK
Formwork	1.104.747 SEK
Stairs and balcony elements	757.479 SEK
Installations	304.212 SEK
Crane	359.100 SEK
<b>Total:</b>	<b>4.229.121 SEK</b>

To be able to compare with the numbers given in table 7.8, the costs for workers given in table 7.5 are used. Since the cost for laborer and equipment operator is not included in table 7.8, these cost items are subtracted from the total sum given in table 7.5. The revised simulated cost is then becomes:

Human resource cost:  $1\ 535\ 670 - 291\ 000 - 149\ 520 = 1\ 095\ 150$  SEK

Material cost: 3 192 789 SEK

Total cost:  $1\ 095\ 150 + 3\ 192\ 789 = 4\ 287\ 939$  SEK

So the difference is 58 818 SEK or 1,4% which has to be considered as sufficient accuracy.

## 7.4 Work Breakdown Structure

Figure 7.10 shows a part from the WBS for the project. It shows how the project is broken down, first to levels and next to stages and last down to activities.

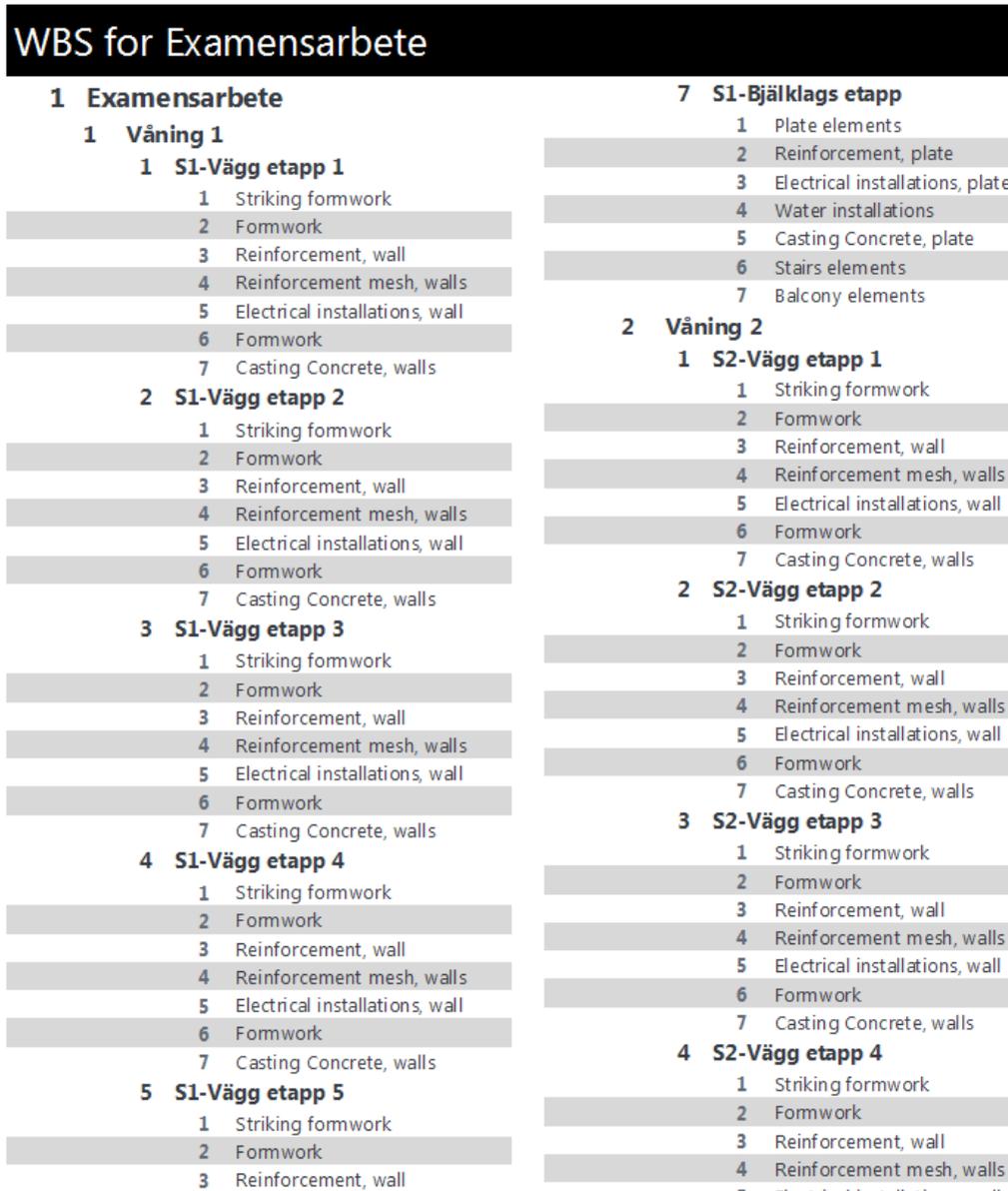


Figure 7.10 – Shows a part of the WBS

## 8. Simulations of five scenarios

### 8.1 Case 1 – Effect of different weather conditions

Two time periods were simulated and compared to analyze the effect that the weather has on the work performance. The first start date was the 1<sup>st</sup> of January 2008 and the second was the 1<sup>st</sup> of May 2008. A section from the weather data-file can be found in appendix B. Chapter 6.2.2 shows how the model takes the weather into consideration.

#### 8.1.1 Start date 1<sup>st</sup> of January 2008

The first scenario can be considered as the winter case. The simulated results when weather conditions are considered are presented in table 8.1. As seen in table 8.1, the project duration compared to the base case (table 7.1) increases by 18 days or with 14 workdays. Therefore, the cost for workers increases in accordance with the extended duration, see table 8.2.

Table 8.1 - The results from the model in case 1, winter conditions

Start	Finish	Total workdays	Total days
1.1.2009 08:00	17.4.2009 12:00	77	107

Table 8.2 – The total cost for workers in case 1, winter conditions

Workers type	Cost per hour	Nr workers	Total man hours	Total Cost
Concrete worker	300	1	770	231.000 SEK
Carpenter	300	4	3080	924.000 SEK
Reinforcement worker	300	0	0	0 SEK
Laborer	250	4	3080	770.000 SEK
Plumber	300	2	109	65.400 SEK
Electrician	300	2	178	106.800 SEK
Supervisor	350	0	0	0 SEK
Technician	400	0	0	0 SEK
Equipment operator	280	1	770	215.600 SEK
Equipment	300	0	0	0 SEK
Crane	625	1	770	481.250 SEK
<b>Total:</b>			<b>8757</b>	<b>2.794.050 SEK</b>

The total cost for the workers was before 2 299 950 SEK so it has increased by 494 100 SEK or 21,48%. The total cost in case 1 is shown in table 8.3.

Table 8.3 - The total cost in case 1, winter conditions

	Total cost
Human resources	2.794.050 SEK
Material	3.192.789 SEK
<b>Total:</b>	<b>5.986.839 SEK</b>

### 8.1.2 Start date 1<sup>st</sup> of May 2008

Another weather scenario was simulated. The start date was set to the 1<sup>st</sup> of May 2008. This can be considered as the summer case. The simulated duration is given in table 8.4.

As seen in table 8.4, the projects duration increases only by 1 day or 1 workday compared to the results in table 7.1.

*Table 8.4 - The results from the model for case 1, summer conditions*

Start	Finish	Total workdays	Total days
1.5.2009 08:00	29.7.2009 11:00	64	90

The total cost for the workers was 2 299 950 SEK according to table 7.3. According to table 8.5 is the total cost for the workers 2 334 000 SEK, so it has only increased by 34 050 SEK, or 1,48%. It is also interesting to notice that the cost of the work with no waiting time increases with 14 570 SEK. That means that the difference between the model results and the real project decreases to 44 248 SEK or 1,03%.

*Table 8.5 - The total cost for workers in case 1, summer conditions*

Workers type	Cost per hour	Nr workers	Total man hours	Total Cost
Concrete worker	300	1	640	192.000 SEK
Carpenter	300	4	2560	768.000 SEK
Reinforcement worker	300	0	0	0 SEK
Laborer	250	4	2560	640.000 SEK
Plumber	300	2	96	57.600 SEK
Electrician	300	2	162	97.200 SEK
Supervisor	350	0	0	0 SEK
Technician	400	0	0	0 SEK
Equipment operator	280	1	640	179.200 SEK
Equipment	300	0	0	0 SEK
Crane	625	1	640	400.000 SEK
<b>Total:</b>			<b>7298</b>	<b>2.334.000 SEK</b>

*Table 8.6 - The total cost in case 1, summer conditions*

	Total cost
Human resources	2.334.000 SEK
Material	3.192.789 SEK
<b>Total:</b>	<b>5.526.789 SEK</b>

If the simulated results for the winter conditions are compared with the results from the summer conditions does the total cost increase with 460 050 SEK or 8,3% and the total time increases with 17 days or 18%.

## 8.2 Case 2 – How experience affects productivity

Let us now only take the experience factor into consideration and see how it will affect the construction time and cost. The input data into the model are presented in table 8.7 according to figure 4.7.

*Table 8.7 - The input data for increased experience*

Activity	1 <sup>st</sup> floor	2 <sup>nd</sup> floor	3 <sup>rd</sup> floor	4 <sup>th</sup> floor	5 <sup>th</sup> floor	6 <sup>th</sup> floor
Formwork	100%	125%	135%	135%	135%	135%
Reinforcement	100%	120%	130%	135%	135%	135%
Casting	100%	105%	105%	105%	105%	105%

Table 8.7 shows the improvement on work performance for three different activities, e.g. 125% means a 25% improvement compared to a normal performance.

The simulated results considering the effect of experience is presented in table 8.8.

*Table 8.8 - The results from the model considering the effect of experience*

Start	Finish	Total workdays	Total days
1.1.2009 08:00	19.3.2009 15:00	56	78

As seen in table 8.8, the projects duration decreases by 11 days or 7 workdays compared to the base case. Consequently, the costs of workers decreases in accordance with the shorter duration see table 8.9. The costs for workers decreased with 265 950 SEK. The total project cost is summarized in table 8.10. The total cost is reduced by 4,8% compared with the base case.

*Table 8.9 – The corresponding costs for workers in case 2*

Worker type	Cost per hour	Nr workers	Total man hours	Total Cost
Concrete worker	300	1	560	168.000 SEK
Carpenter	300	4	2240	672.000 SEK
Reinforcement worker	300	0	0	0 SEK
Laborer	250	4	2240	560.000 SEK
Plumber	300	2	77	46.200 SEK
Electrician	300	2	135	81.000 SEK
Supervisor	350	0	0	0 SEK
Technician	400	0	0	0 SEK
Equipment operator	280	1	560	156.800 SEK
Equipment	300	0	0	0 SEK
Crane	625	1	560	350.000 SEK
<b>Total:</b>			<b>6372</b>	<b>2.034.000 SEK</b>

Table 8.10 - The total cost in case 2

	<b>Total cost</b>
Human resources	2.034.000 SEK
Material	3.192.789 SEK
<b>Total:</b>	<b>5.226.789 SEK</b>

### 8.3 Case 3 – Combinations of cases 1 and 2

Let us now see how the construction time and cost are affected if the start date is the 1<sup>st</sup> of January and both weather and experience factors are taken into consideration at the same time.

The simulated project duration considers both effects from weather and workers experience. The results are presented in table 8.11. The duration is almost exactly the same as for the case with summer scenario. It takes only one day more than compared to the base case given in table 7.1.

Table 8.11 - The results from the model in case 3

<b>Start</b>	<b>Finish</b>	<b>Total workdays</b>	<b>Total days</b>
1.1.2009 08:00	31.3.2009 17:00	64	90

The total cost for the project according to case 3 can be seen in table 8.12.

Table 8.12 - Summary of the total cost for case 3

	<b>Total cost</b>
Human resources	2.334.000 SEK
Material	3.192.789 SEK
<b>Total:</b>	<b>5.526.789 SEK</b>

By comparing the result with the base case does the total cost increase by 34 050 SEK or 0,6%.

## 8.4 Case 4 – Precast twin walls

In case 4, precast twin walls were used instead of a temporary formwork system which was used in the base case. Both the weather effect and experience effect were neglected. The purpose was to see the impact on both time and cost.

Using prefabricated twin walls implied for reducing the seven stages down to only two stages. The first stage consists of assembling and sealing the precast twin wall elements, placing reinforcement over the joints, and pouring concrete between the concrete panels in two separate sequences. After the twin walls have been poured, the supporting props are removed and the surfaces are repaired. Stage two is almost similar to the seventh stage according to the base case except that the upper half of the twin walls is poured with concrete at the same time as the top layer of the floor structure is poured. A summary of the input data for case 4 is presented in table 8.13 and 8.14.

*Table 8.13 - The input data for stage 1 (wall activities)*

Activity name	Quantity	Workgroup performance	Nr workgroups	Prede. number	Prede. percent
1.1.1.Precast twin walls, assembling	345 m <sup>2</sup>	14,29 h	1	0	0%
1.1.2.Precast twin walls, reinforcement	345 m <sup>2</sup>	50 h	1	1	70%
1.1.3.Casting Concrete, walls	17,25 m <sup>2</sup>	14,25 h	1	2	100%
1.1.4.Precast twin walls, post work	345 m <sup>2</sup>	28,57 h	1	3	100%

*Table 8.14 - The input data for stage 2 (slab activities)*

Activity name	Quantity	Workgroup performance	Nr workgroups	Prede. number	Prede. percent
1.2.1.Plate elements	463 m <sup>2</sup>	22,72 h	1	4	100%
1.2.2.Reinforcement, plate	2,54 ton	0,244 h	1	21	50%
1.2.3.Electrical installations, plate	615 m	30 h	1	22	100%
1.2.4.Water installations	261 m	16,67 h	1	22	100%
1.2.5.Casting Concrete, plate	133,25 m <sup>3</sup>	25,64 h	1	23	100%
1.2.6.Stairs elements	1 pcs	1,01 h	1	25	100%
1.2.7.Balcony elements	6 pcs	2,91 h	1	26	100%

The project duration for case with using twin walls is presented in table 8.15. The project duration decreases by 17 days or 11 workdays compared to the original case, table 7.1.

Table 8.15 - The results from the model in case 4

Start	Finish	Total workdays	Total days
1.1.2009 08:00	13.3.2009 11:00	52	72

### 8.4.1 Gantt chart

The Gantt chart for stage 1 is presented in figure 8.1. The start and finish time for the twin wall activities are given in table 8.16.

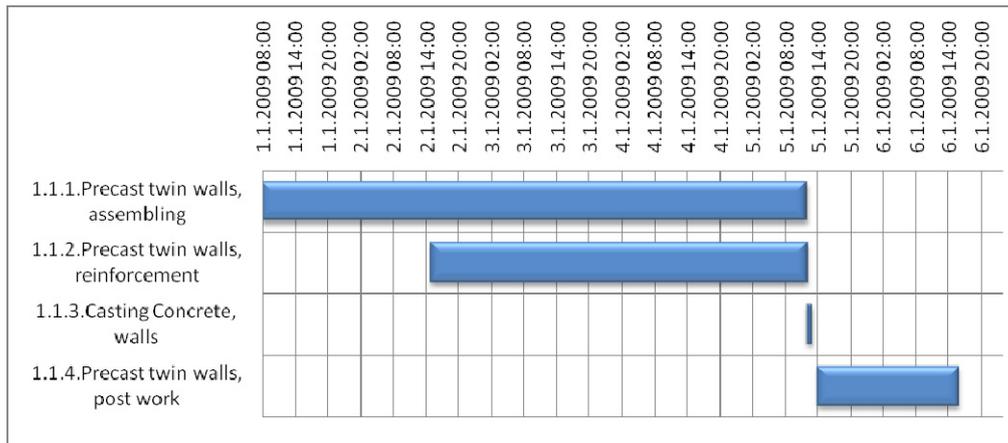


Figure 8.1 – Gantt chart for stage 1

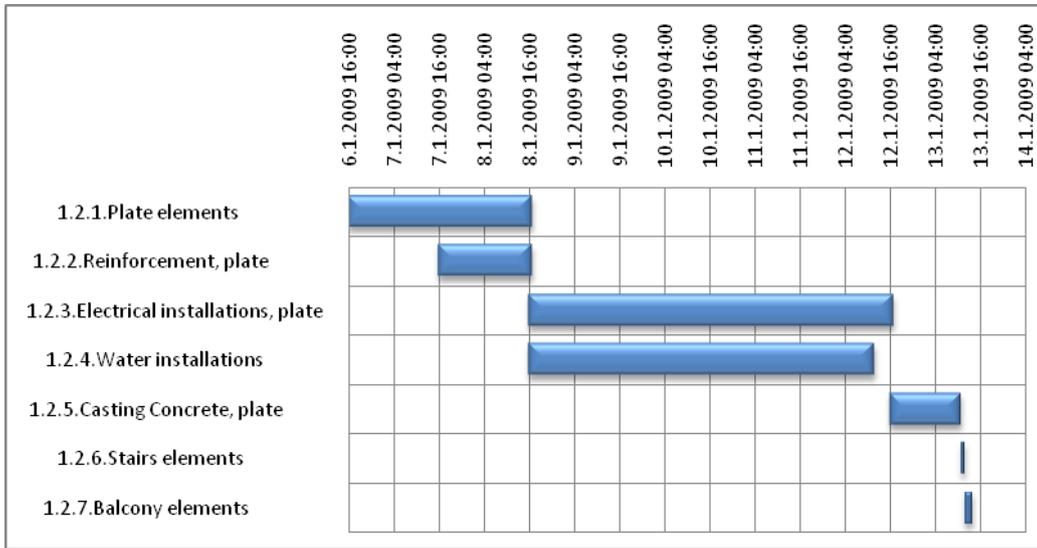
Table 8.16 - Start and finish times for twin wall activities (stage 1)

Activity Name	Start	Duration	Finish
1.1.1.Precast twin walls, assembling	1.1.2009 08:00	4,17	5.1.2009 12:00
1.1.2.Precast twin walls, reinforcement	2.1.2009 15:00	2,88	5.1.2009 12:00
1.1.3.Casting Concrete, walls	5.1.2009 12:00	0,04	5.1.2009 13:00
1.1.4.Precast twin walls, post work	5.1.2009 14:00	1,08	6.1.2009 16:00

The results, shown in table 8.16, show that the duration for assembling the precast twin walls is 3 days and 8 hours per floor. By comparing the results with the duration of casting the walls on site which took about 6 days, the difference becomes 2 days and 2 hours for each floor or 37%.

The Gantt chart for stage 2 is presented in figure 8.2

## Discrete Event Simulations of Construction Related Production Systems

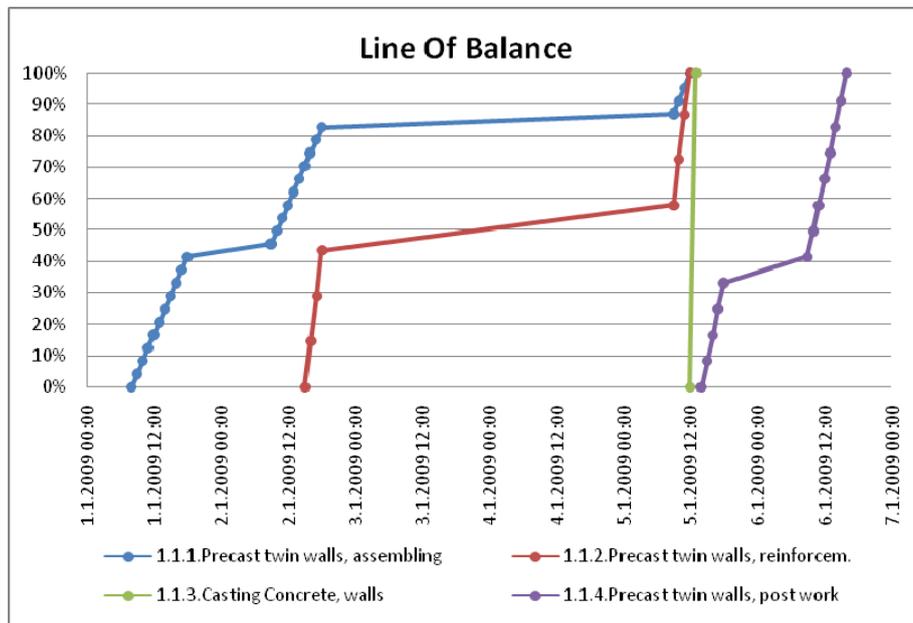


*Figure 8.2 - Gantt chart for stage 2*

The graph given in figure 8.2 reveals that the results are almost identical to stage seven in the base case, shown in figure 7.2.

### 8.4.2 Line of Balance

Stage 1 can also be shown according to the Line of Balance method, figure 8.3.



*Figure 8.3 - The LoB chart for stage 1*

The chart in figure 8.3 shows that no activities are overlapping which indicates that no activities are in space conflict.

### 8.4.3 The utilization

The utilization for case 4 is shown in figure 8.4

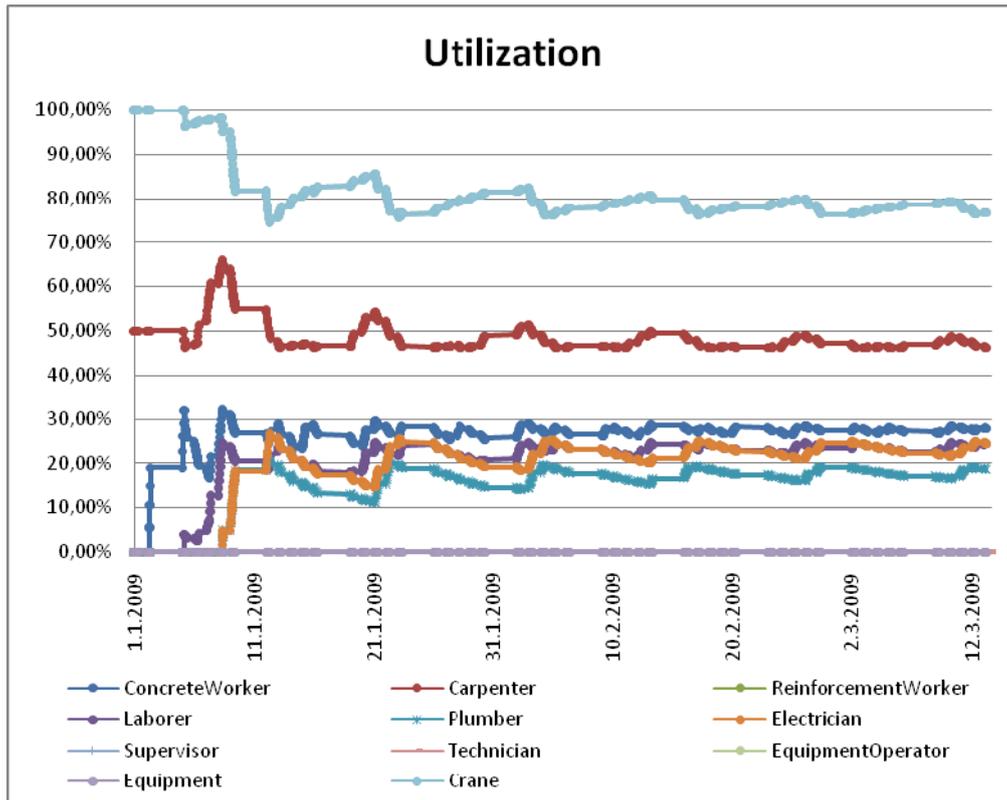


Figure 8.4 – Resource utilization plot in case 4

As seen in figure 8.4, the utilization for the laborer and the concrete workers is not good. Concerning laborer, the utilization factor is only about 25% and for carpenters 47%.

### 8.4.4 Costs

The total costs for the workers are shown in table 8.17. The total cost for workers is 1 903 800 SEK. By comparing the results with the base case it becomes clear that the total cost for the workers has decreased by 396 150 SEK.

Table 8.17 - The total cost for workers in case 4

Type of worker	Cost per hour	Nr workers	Total man hours	Total Cost
Concrete worker	300	1	520	156.000 SEK
Carpenter	300	4	2080	624.000 SEK
Reinforcement worker	300	0	0	0 SEK
Laborer	250	4	2080	520.000 SEK
Plumber	300	2	96	57.600 SEK
Electrician	300	2	126	75.600 SEK
Supervisor	350	0	0	0 SEK
Technician	400	0	0	0 SEK
Equipment operator	280	1	520	145.600 SEK
Equipment	300	0	0	0 SEK
Crane	625	1	520	325.000 SEK
<b>Total:</b>			<b>5942</b>	<b>1.903.800 SEK</b>

In table 8.18, the cost for materials is presented. The results reveal that the total material cost has increased by 750 940 SEK (3 943 729 – 3 192 789). The total cost including both material and workers are presented in table 8.19.

Table 8.18 - The material cost in case 4

Activity Name	Total material cost
Striking formwork	0 SEK
Formwork	0 SEK
Reinforcement, wall	0 SEK
Reinforcement mesh, walls	0 SEK
Reinforcement, plate	117.348 SEK
Reinforcement mesh, plate	0 SEK
Casting Concrete, walls	100.395 SEK
Casting Concrete, plate	775.515 SEK
Stairs elements	288.000 SEK
Balcony elements	486.000 SEK
Electrical installations, plate	40.922 SEK
Electrical installations, wall	0 SEK
Water installations	117.059 SEK
Plate elements	569.490 SEK
Precast twin walls, assembling	1.407.600 SEK
Precast twin walls, reinforcement	41.400 SEK
<b>Total:</b>	<b>3.943.729 SEK</b>

*Table 8.19 - The comparison of total costs in the base case and in case 4*

	<b>Cost on site</b>	<b>Precast twin walls</b>
Human resources	2.299.950 SEK	1.903.800 SEK
Material	3.192.789 SEK	3.943.729 SEK
<b>Total:</b>	<b>5.492.739 SEK</b>	<b>5.847.529 SEK</b>

After comparing the results for the total costs it becomes clear that by using the precast twin walls, the total cost will increase with 354 790 SEK or 6%. However, by using precast twin walls, the duration of the construction time decreases with 19%. Therefore it is possible to begin complementary works earlier and in the end, it might be possible to shorten the finish time of the building. The sooner a building can be utilized, the sooner the users can start pay back the investment cost. The influence of weather will also decrease when the construction duration is decreased.

## 8.5 Case 5 – Use the model to increase efficiency

Let's see if it is possible to use the model to make case 4, the project with twin walls, more effective.

By looking at the utilization graph shown for the precast twin walls in figure 8.4, it can be seen that there is a lot of room for improvement. By adding another crane to the project it would become possible to use two workgroups at the same time for the precast twin walls activities in order increase the resource utilization. The new input data is given in table 8.20.

Table 8.20 - The revised input data for stage 1 (twin wall activities)

Activity name	Quantity	Workgroup performance	Nr workgroups	Prede. number	Prede. percent
1.1.1.Precast twin walls, assembling	345 m <sup>2</sup>	14,29 h	2	0	0%
1.1.2.Precast twin walls, reinforcement	345 m <sup>2</sup>	50 h	1	1	70%
1.1.3.Casting Concrete, walls	17,25 m <sup>2</sup>	14,25 h	1	2	100%
1.1.4.Precast twin walls, post work	345 m <sup>2</sup>	28,57 h	2	3	100%

In stage 2, it becomes possible to use two workgroups working on assembling balconies, at the same time. Also by analyzing the Gantt chart, figure 8.2, for stage 2 in case 4, it can be seen that the activities “Electrical installations” and “Water installations” can start earlier or at the same time as the reinforcement. The input data is given in table 8.21.

Table 8.21 - The revised input data for stage 2 (slab activities)

Activity name	Quantity	Workgroup performance	Nr workgroups	Prede. number	Prede. percent
1.2.1.Plate elements	463 m <sup>2</sup>	22,72 h	1	4	100%
1.2.2.Reinforcement, plate	2,54 ton	0,244 h	1	21	50%
1.2.3.Electrical installations, plate	615 m	30 h	1	21	50%
1.2.4.Water installations	261 m	16,67 h	1	21	50%
1.2.5.Casting Concrete, plate	133,25 m <sup>3</sup>	25,64 h	1	23	100%
1.2.6.Stairs elements	1 pcs.	1,01 h	1	25	100%
1.2.7.Balcony elements	6 pcs.	2,91 h	2	25	100%

The results from the simulations for the new scenario can be seen in table 8.22. The project duration decreases by 38 days or 26 workdays compared with the base case. Compared with case 4, the duration has decreased by 21 days or 15 workdays.

Table 8.22 - The project duration according for case 5

Start	Finish	Total workdays	Total days
1.1.2009 08:00	20.2.2009 17:00	37	51

The total resource cost based on the new duration is given in table 8.23. The results from table 8.23 show that the total resource cost decreases with 175 900 SEK (1 903 800 - 1 727 900) even though one crane and one equipment operator have been added.

Table 8.23 – Total cost for workers in case 5

Type of workers	Cost per hour	Nr workers	Total man hours	Total Cost
Concrete worker	300	1	370	111.000 SEK
Carpenter	300	4	1480	444.000 SEK
Reinforcement worker	300	0	0	0 SEK
Laborer	250	4	1480	370.000 SEK
Plumber	300	2	96	57.600 SEK
Electrician	300	2	126	75.600 SEK
Supervisor	350	0	0	0 SEK
Technician	400	0	0	0 SEK
Equipment operator	280	2	740	207.200 SEK
Equipment	300	0	0	0 SEK
Crane	625	2	740	462.500 SEK
<b>Total:</b>			<b>5032</b>	<b>1.727.900 SEK</b>

The cost for both material and workers are given in table 8.24. By comparing the results with case 4, it can be seen that the total cost decreases by 175 900 SEK or 3,1%. If the results are compared with the base case, the total cost is still higher or by 3%, but the construction time has been decreased by 38 days which is 43%. That means that the building can be taken into use more than a month earlier which also means an earlier income from rental or from a sale.

Table 8.24 – The total cost for case 5

	Total cost
Human resources	1.727.900 SEK
Material	3.943.729 SEK
<b>Total:</b>	<b>5.671.629 SEK</b>

## 9. Discussion

The purpose of this work was to develop a model which simulates on-site construction activities in terms of time, cost and resource usage. Another purpose was to demonstrate the use of the model by simulating different type of scenarios. The goal was that the model would enable the user to analyze different scenarios to find out the most effective outcome.

Construction-oriented production systems are exposed to many factors that influence the work performance, e.g. weather conditions or the workforce experience. Reliable inputs are very important in simulations since the results will never be more accurate than the input data. An important task of the work has been to collect data about how different type of aspects influence work performance. A questionnaire was created to gain information about the effect on construction activities from different weather conditions. The results from the questionnaires provided some interesting insights about how weather conditions influence work performance. The results were used in some of the simulation experiments. However, since the questionnaire survey was limited it would be interesting to enlarge the number of respondents in order to confirm the findings in this report.

The central part of this work was to create the simulation model. The model is generic and can technically be used in planning of any type of project. The user can, just by adding activities in the price bank database, use this model for planning various types of work, e.g. interior finishing.

Verification of the model showed that the difference between the simulated results and the real project was rather small. For instance, completing a wall section was simulated to 10 hours but in the real project it took 9 hours. Possible reasons that may explain the difference can be that in the real project, the activities were carried out more in parallel compared to what was assumed in the model. Another explanation would be that the unit times that were used in the simulation model may be a little bit on the conservative side. The simulated results for the slab activities (the seventh stage) showed on good correlation.

The simulated cost deviated 1,4% compared to the real cost which has to be considered as sufficient accuracy.

The first simulation scenario concerned how weather affects the work performance. A summer and winter scenario was simulated. Both time and cost were compared. The simulated results showed that the total cost increased with 460 050 SEK or 8,3% and the total time increased with 17 days or 18% for the winter scenario compared with the summer scenario. One of the respondents from the questionnaire stated that a normal labor cost is about 20–30% higher during the winter months. The simulated result showed that the cost for the workers increased with 21,5%. Of course, this can vary depending on the actual winter conditions.

## Discrete Event Simulations of Construction Related Production Systems

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The second scenario studied how experience gained from repetitive work procedures affects productivity. Also here, the results from the questionnaire were used. The simulated results showed that the total cost was reduced by 265 950 SEK or 4,8% compared with the base case and the total time decreased with 11 days or 12%. The experience factor was used for the second, third and fourth floor, but not for the fifth and sixth floor. It was believed that the time for lifting material and equipment increases with the number of floor levels which level out the positive effect gained from repetition.

In the third case, combinations of both winter conditions and experience effects were simulated. The simulated results were compared with the base case. The cost increased with 34 050 SEK or 0,6% and the total time increased with 1 day or 1,1%.

In case four, a different construction method (twin walls) was used and compared with the base case. The simulation showed a total cost increase compared with the base case with 354 790 SEK or 6%, but the total time decreased with 17 days or 19%.

In case five, the model was used to analyze how the use of twin walls could be improved. By analyzing the resource utilization it was possible to change some of the production parameters (e.g. adding a crane and a workgroup), it was possible to decrease the total cost (compared with case 4) with 175 900 SEK or 3,1%. Compared to the base case, the total cost was still 3% higher but the total time was reduced by 38 days or 43%. Even though it costs more to use precast twin walls, it does have its advantages. Often, the surface quality is higher and the project duration time can be reduced substantially.

It was clearly demonstrated that it is possible to use the model in order to identify means for improvement of efficiency. To be able to see the utilization for all the workers and the crane helps the user in many ways. Especially, the graphical results clearly show were to perform parallel work and also to test different resource usage strategies to see how it effects the project duration.

Both the verification process and the simulation experiments have demonstrated the capability and the benefits of the model. The model can take different scenarios such as weather conditions and the experience effect into account. It is also possible to simulate alternative construction methods, e.g. twin walls and different combination of human resources. The user interface clearly simplifies the work with entering input data.

The model presented in this report is only at its beginning phase and therefore can be developed much more. There are many interesting possibilities to further develop. For example, after the model was tested in the different cases, it became clear that one predecessor is not enough. There should be at least three or four. Another very interesting development possibility is to add risk analysis to the model. By using Monte Carlo simulation it would become possible to analyze each activity in terms of risks, e.g. worst, best, and most frequent outcome.

## Discrete Event Simulations of Construction Related Production Systems

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Using simulation models in project planning definitely has its advantages but the best solution should be to combine the strengths from both the traditional methods and simulation. It would therefore be interesting to connect the model direct with programs like Vico software which supports Building Information Modeling (BIM) and 5d CAD, instead of using Microsoft Excel to show the results.

This model was developed from the idea that smaller construction companies, that do not need large, complicated, and expensive software tools could buy a license to use the model for planning projects and to increase their efficiency.



## **10. Conclusions**

In this work, a model for discrete-event simulation of on-site construction activities has been developed. The model has been tested on a real project with satisfying results. The model can be used for simulation of any type of construction related production systems.

The model has been provided with a user interface to simplify the entering of data to the model and for displaying results. The user interface makes the overall usage of the model very easy and it is rather simple to test different ideas or methods. It is believed that the model can be used without having any special knowledge in simulation theory.

Furthermore, the possibilities of using the simulation model for planning and improving construction projects have been demonstrated in five different scenarios. The results from the cases showed that the model can be used to analyze the project, use different construction methods and to increase the efficiency. It has also been demonstrated how factors such as weather conditions and workforce experience can be simulated.

This work has clearly shown the potential of using discrete-event simulation to increase the efficiency in construction projects. The high rate of development of computers programs today will probably result in an increased use of discrete-event simulations in project daily planning in the future.



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### **11.3 Interviews**

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## Appendix A - Description of activities

### Formwork

In activity Formwork are used prefabricated modules with a metal frame, usually of steel or aluminum and covered on the application (concrete) side with plywood panel. The width of the frames is 0,4 m or more and height is up to 3,25 m.

It takes 0,39 man hours to produce 1 m<sup>2</sup> of formwork. (Nybyggnadslistan 15:00 - 002).

In this project is the activity broken down into two activities:

- Formwork, the activity includes assembling the forms and normal maintenance and repair of the forms.
- Striking formwork, the activity includes disassembling the forms and cleaning them.

Assembling the formwork takes 90% of the time and the striking formwork takes 10% of the time, therefore becomes the unit times:

It takes 0,351 man hours to assemble 1 m<sup>2</sup> of formwork.

It takes 0,039 man hours to strike 1 m<sup>2</sup> of formwork.

The workgroup for the activities consist of:

- 4 Carpenter
- 1 Laborer
- 1 Equipment Operator
- 1 Crane

The workgroup also has priority access to the hook.

So the total performance:

- of the workgroup for assembling the formwork is  $5/0,351 = 14,25$  m<sup>2</sup>/h.
- of the workgroup for striking the formwork is  $5/0,039 = 129,2$  m<sup>2</sup>/h.

The material cost:

- of assembling the formwork is 83,5 SEK/m<sup>2</sup>
- of striking the formwork is 9,3 SEK/m<sup>2</sup>

### **Reinforcement**

In activity Reinforcement is used normal reinforcement bars or prefabricated reinforcement mesh. The bars are from 10 mm and up to 16 mm in diameter and the bars in the mesh are over 6 mm in diameter.

#### **Reinforcement, walls:**

It takes 18,2 man hours to install 1 ton of reinforcement bars. (Nybyggnadslistan 17:03 - 300).

#### **Reinforcement, plates:**

It takes 16,4 man hours to install 1 ton of reinforcement bars. (Nybyggnadslistan 17:01 - 101).

#### **Reinforcement mesh, walls:**

It takes 0,06 man hours to install 1 m<sup>2</sup> of reinforcement mesh. (Nybyggnadslistan 17:03 - 304).

#### **Reinforcement mesh, plates:**

It takes 0,05 man hours to install 1 m<sup>2</sup> of reinforcement mesh. (Nybyggnadslistan 17:05 - 506).

The activity Reinforcement includes sorting, organizing and labeling of the reinforcement bars after size, steel quality, location and smaller adjustments by hand or machine such as cutting of the reinforcement bars.

The workgroup for the activity consist of:

- 1 Concrete worker
- 3 Laborer

So the total performance:

- of the workgroup in installing reinforcement bars, walls is  $4/16,4 = 0,22$  ton/h
- of the workgroup in installing reinforcement bars, walls is  $4/18,2 = 0,244$  ton/h
- of the workgroup in installing reinforcement mesh, walls is  $4/0,06 = 66,67$  m<sup>2</sup>/h
- of the workgroup in installing reinforcement mesh, plates is  $4/0,05 = 80$  m<sup>2</sup>/h

So the material cost is:

- for reinforcement bars, 7700 SEK/ton
- for reinforcement mesh, 36,78 SEK/m<sup>2</sup>

### **Casting concrete**

In activity Casting concrete are both the walls and plate casted with pump

#### **Casting concrete walls:**

It takes 0,351 man hours to cast 1 m<sup>3</sup>. (Nybyggnadslistan 18:02 - 200).

#### **Casting concrete plates:**

It takes 0,195 man hours to cast 1 m<sup>3</sup>. (Nybyggnadslistan 18:04 – 400).

The activity Casting concrete includes receiving of the concrete, treatment of concrete in reinforced or unreinforced construction, leveling of the surface with the shovel or broom and hose the concrete surface with water if needed.

The workgroup for the activity consist of:

- 1 Concrete worker
- 4 Laborer
- 1 Equipment operator
- 1 Crane

So the total performance:

- of the workgroup in casting concrete walls is  $5/0,351 = 14,25$  m<sup>3</sup>/h
- of the workgroup in casting concrete plates is  $5/0,195 = 25,64$  m<sup>3</sup>/h

The material cost is: 970 SEK/m<sup>3</sup>

### **Precast Filigran-elements**

In activity Plate element is used prefabricated concrete plate elements called filigran-elements.

It takes 0,22 man hours to assemble 1 m<sup>2</sup> of formwork. (Nybyggnadslistan. 15:03 - 313).

The activity Plate element includes assembling false work up to 3,25 m height and sealing and reinforcement over the joints.

The workgroup for the activity consist of:

- 4 Carpenter
- 1 Laborer
- 1 Equipment Operator
- 1 Crane

So the total performance of the workgroup is  $5/0,22 = 22,72$  m<sup>2</sup>/h.

The material cost is: 205 SEK/m<sup>2</sup>

### **Stairs element**

In activity Stairs element is used prefabricated stairs element.

It takes 2,73 man hours to install 1 stairs element. (Nybyggnadslistan. 20:05 - 500).

The workgroup for the activity consist of:

- 1 Carpenter
- 2 Laborer
- 1 Equipment Operator
- 1 Crane

So the total performance of the workgroup is  $4/2,73 = 1,01$  stairs/h.

The material cost is: 48.000 SEK/pcs

### **Balcony element**

In activity Balcony element is used prefabricated balcony element.

It takes 1,03 man hours to install 1 stairs element. (Nybyggnadslistan. 20:06 - 602).

The workgroup for the activity consist of:

- 1 Carpenter
- 2 Laborer
- 1 Equipment Operator
- 1 Crane

So the total performance of the workgroup is  $3/1,03 = 2,91$  balconies/h.

The material cost is: 13.500 SEK/pcs

### **Electrical installations**

In activity Electrical installations are general electrical installations performed both in plates and walls.

It takes 0,1 man hours to install 1 m of electrical installation.

The activity Electrical installations include both installing electrical pipes and device boxes.

The workgroup for the activity consist of:

- 2 Electrician

So the total performance of the workgroup is  $2/0,1 = 20$  m/h.

The material cost for walls is: 20,22 SEK/m

The material cost for plates is: 11,09 SEK/m

### **Water installations**

In activity Water installations are general water installations performed in plates.

It takes 0,12 man hours to install 1 m of electrical installation. (Normtid VVS, nybyggnad och ombyggnad.)

The workgroup for the activity consist of:

- 2 Plumbers

So the total performance of the workgroup is  $2/0,12 = 16,67$  m/h.

The material cost is: 74,75 SEK/m

### **Precast twin walls**

In activity Precast twin walls consist of assembling of precast elements. The length of the elements is usually from 3m to 5m and the height is 2,445m.

The activity consists of three smaller activities, assembling the elements, the post work and reinforcement over the joints:

#### **Precast twin walls, assembling:**

It takes 0,14 man hours to assemble 1 m<sup>2</sup> of precast twin walls. (BetongBanken, 2009)

#### **Precast twin walls, post work:**

The post work takes 0,07 man hours per 1 m<sup>2</sup> of precast twin walls. (BetongBanken, 2009)

#### **Precast twin walls, reinforcement:**

It takes 0,02 man hours to install the reinforcement in per m<sup>2</sup> of precast twin wall. (BetongBanken, 2009)

Reinforcement, electrical installations and water installations are casted inside the walls so they do include in the activity.

The workgroup for precast twin walls, assembling and the post work is:

- 2 Carpenters
- 1 Equipment operator
- 1 Crane

The workgroup for the precast twin walls, reinforcement is:

- 1 Concrete worker

So the total performance of the workgroup is

- for assembling precast twin walls,  $2/0,14 = 14,29$  m<sup>2</sup>/h

## Discrete Event Simulations of Construction Related Production Systems

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- for precast twin walls, post work,  $2/0,07 = 28,57 \text{ m}^2/\text{h}$
- for precast twin walls, reinforcement,  $1/0,025 = 40 \text{ m}^2/\text{h}$

The material cost is:

- for precast twin walls, assembling,  $680 \text{ SEK}/\text{m}^2$
- for precast twin walls, reinforcement,  $20 \text{ SEK}/\text{m}^2$

**Appendix B - Example of weather data used in case 1 and 3**

Date	Wind [m/s]	Rain [mm]	Temp. [°C]	Snow [mm]	Date	Wind [m/s]	Rain [mm]	Temp. [°C]	Snow [mm]
1.1.2008	0	1,5	0,2	0	1.4.2008	1	0	8,8	0
2.1.2008	9	1,2	0,7	20	2.4.2008	0	2,4	5,8	0
3.1.2008	7	0,1	-2,2	40	3.4.2008	4	0	7,1	0
4.1.2008	5	0	-2,2	40	4.4.2008	0	0	6,8	0
5.1.2008	6	5,8	-1,1	40	5.4.2008	6	2,3	6,2	0
6.1.2008	5	0	2,1	60	6.4.2008	7	9,6	5,9	0
7.1.2008	4	6,2	2,4	30	7.4.2008	5	0	5,5	0
8.1.2008	5	0,4	4,7	0	8.4.2008	7	1	5,2	0
9.1.2008	4	0,9	4,1	0	9.4.2008	4	5,4	4,7	0
10.1.2008	7	1,5	4,4	0	10.4.2008	2	0	4,9	0
11.1.2008	9	2,3	6,1	0	11.4.2008	4	0	4	0
12.1.2008	4	0,1	5,8	0	12.4.2008	3	5,9	4,8	0
13.1.2008	7	0	4,2	0	13.4.2008	1	0	6,9	0
14.1.2008	4	0	2,6	0	14.4.2008	1	0	8,2	0
15.1.2008	10	5,2	5,1	0	15.4.2008	0	0	7,8	0
16.1.2008	6	0	6,5	0	16.4.2008	3	0	6,5	0
17.1.2008	4	2,3	4,7	0	17.4.2008	0	4,6	6,7	0
18.1.2008	7	7,5	5,4	0	18.4.2008	4	0	8,3	0
19.1.2008	5	0	7,4	0	19.4.2008	5	0	5,9	0
20.1.2008	4	0,7	4,3	0	20.4.2008	11	0	6,5	0
21.1.2008	9	0	4,5	0	21.4.2008	4	0	6,8	0
22.1.2008	7	0	1,2	0	22.4.2008	0	0	7,5	0
23.1.2008	3	8	1,6	0	23.4.2008	3	0	8,3	0
24.1.2008	1	0,3	6,7	0	24.4.2008	0	0	7,9	0
25.1.2008	3	0,3	5,8	0	25.4.2008	2	0	7,4	0
26.1.2008	1	8,9	6,3	0	26.4.2008	1	0	10,2	0
27.1.2008	6	0	4,3	0	27.4.2008	1	0	10,2	0
28.1.2008	2	1,1	3,8	0	28.4.2008	3	0	12,9	0
29.1.2008	9	0	4,8	0	29.4.2008	6	0	14,6	0
30.1.2008	5	2,4	4,3	0	30.4.2008	2	0	15,5	0