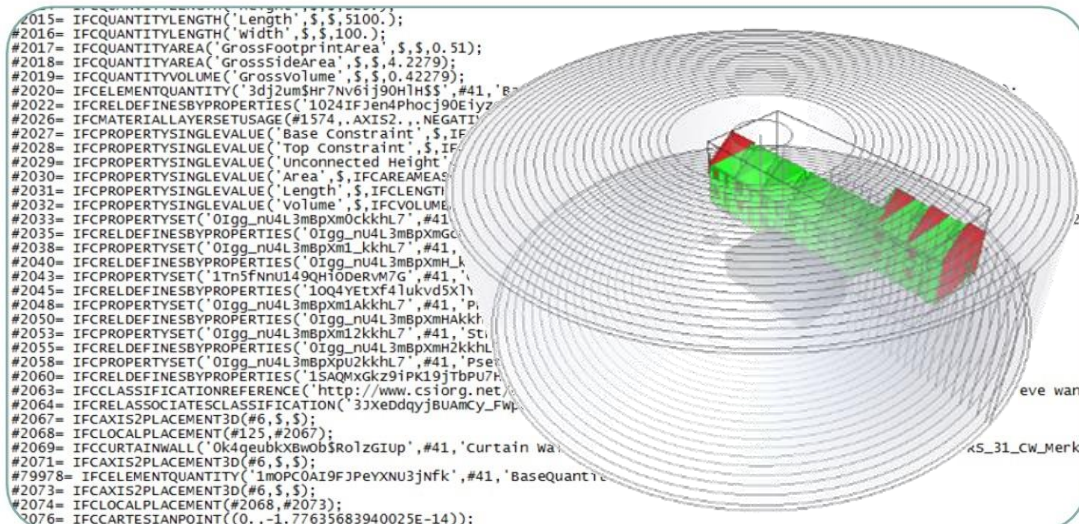# The optimization of crane deployment by using BIM

Development of a tool, based on knowledge and experience within the field of residential construction projects

Master Thesis of Construction Management and Engineering 2015-2016
R.J. (Rob) Simons

Colophon

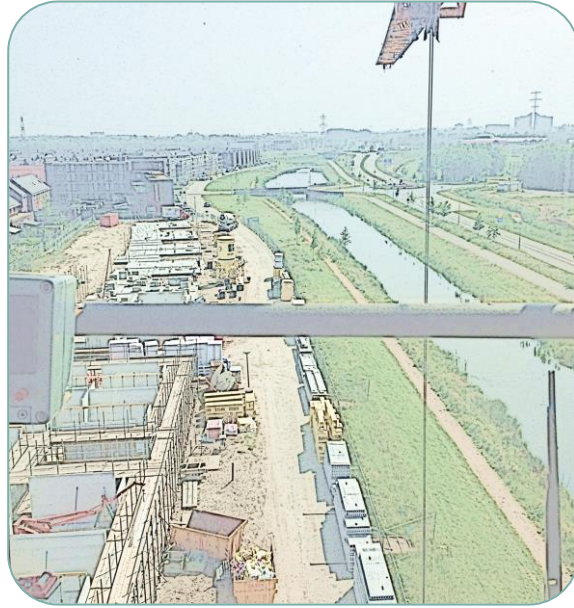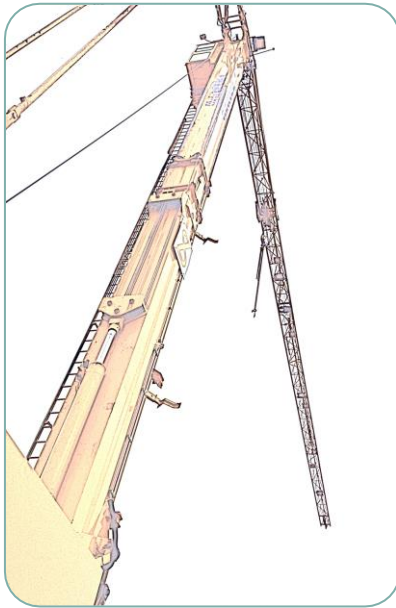**Title:**   The optimization of crane deployment by using BIM

Subtitle: Development of a tool, based on knowledge and experience within the field of residential construction projects

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Preface

This master thesis presents my research on "The optimization of crane deployment by using BIM". The thesis is the final part of the master program "Construction Management and Engineering" (CME), which is part of the department of the Built Environment at Eindhoven University of Technology (TU/e). During my graduation, I worked in close collaboration with the TU/e and the construction company Dura Vermeer Rosmalen Bouw B.V. I learned a lot and I am very grateful for all the people who helped me during the interviews, observations and development of the simulation tool.

Through this way, I would like to thank my university supervisors Jakob Beetz and Thomas Krijnen, for their input and guidance during my graduation period. They supported me during the development of the simulation tool and given me helpful feedback. In addition, I would like to thank Dura Vermeer Rosmalen Bouw B.V., especially my supervisor Wout Somers, who supported me and were willing to help me when needed. I am also very grateful for all the other people who helped me during my graduation period, especially the respondents of the interviews and colleagues of Dura Vermeer Bouw Rosmalen B.V.

Off course, I would like to thank my family and girlfriend, who where a big support throughout my academic career and graduation period. Hopefully, you are pleased to read my master thesis and contributes it to the scientific research, so that new ideas for further research arise.

Rob Simons

Rosmalen, 27 September 2016

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Summary

One of the biggest problems within the construction industry are construction delays on construction sites (El-Razek, Bassioni, & Mobarak, 2008) (James, et al., 2014). Construction delays are most common during the construction phase of projects (Rao & Culas, 2014). Construction delays are generally caused by poor managerial and technical skills of contractors; such as poor site mobilization, poor subcontractors work and ineffective planning and scheduling (Rao & Culas, 2014). Construction delays can already be prevented during the preparation of construction projects, in which effective site mobilization and planning are important. Crane deployment is one of the most critical components of a construction schedule (Al-Hussein, Niaz, Yu, & Kim, 2006) (Li, Chan, Huang, Guo, Lu, & Skitmore, 2009). Ineffective crane deployment during the preparation of construction projects is a big problem within the construction industry. The determination of crane deployment and other construction activities are often uncertain, because these predictions are based on personal experiences of the crane planner (Li, Chan, Huang, Guo, Lu, & Skitmore, 2009) (Nahmias, 2009) (Sugimoto, Seki, Samo, & Nakamitsu, 2015). Due to such uncertain determinations of crane deployment, it is often the case that the actual crane utilization is larger than expected. The aim of the research is to discover a more optimal crane utilization, considering the minimization of time for residential construction projects. The minimization of utilization time should result in a reduction of crane rental costs.

First, a literature review and semi-structured interviews are used as exploratory research techniques to investigate causes of construction delays. Based on the obtained information, the problem statement becomes more specific, related to crane deployment. Further research is done to crane deployment by using subsequent semi-structured interviews and observations at the construction site. The literature review, interviews and observations are elaborated in chapter 2, 3 and 4. The results of the literature review, interviews and observations are used as an input for the development of the simulation tool (chapter 5). The tool is verified by comparing the simulation results with results from the interviews and observations (chapter 6). In addition, the tool is validated by using a residential construction project of seven terraced dwellings. In addition, feedback is obtained from two construction site engineers. Based on the verification and validation process, the tool is adjusted and additional simulations are done. Finally, conclusions are drawn (chapter 7) and subjects for further research become clear (chapter 8).

The aim of this research is to optimize the crane deployment during the preparation of residential construction projects by developing a simulation tool. This tool is developed within a three-dimensional environment, in which the crane and its specifications are integrated. The tool takes into account the lifting of building elements and the minimization of the total lift duration of the crane. Different information is imported within the tool, such as crane specifications, capacities per crane range and material specifications. In addition, the tool supports IFC data structures, which are becoming increasingly important within the construction industry. IPython is used for the development of the simulation tool, which uses IfcOpenShell. IfcOpenShell is a software library for programming with the IFC file format (Krijnen, 2016). The developed simulation tool prototype has limitations, such as building elements, which do not match to the reality and environmental factors are not taken into account. The tool within this research focuses on the determination of crane location,

material storage location and calculates if building elements can be lifted and what their total lift duration is.

The simulation tool is validated by implement a residential project of seven terraced dwellings within the tool. By using brute-force analysis, different combinations of crane location and material storage location are chosen to obtain simulation results. The results show if the window frames and floors can be lifted and what their total lift duration is. This total lift duration is compared with the as-planned and as-built crane hours of the window frames and floors. The total as-built lift duration and lift duration of the simulations shows big differences. The hook and unhook time have huge impact on these differences, therefore these times are adjusted and new simulations are done. Based on the new simulations, the total costs of three combinations is calculated. These costs are based on crane rental costs and the costs of rubble on the construction site. Finally, one combination of crane location and material storage is the cheapest and most convenient. This combination is 10% cheaper in comparison with the third combination and 15% compared with the second combination.

Through this kind of optimization tool, a more optimal crane deployment can be determined, which finally results in a reduction of crane expenses. By using computer related techniques, the crane deployment can be optimized by using a three-dimensional environment and integrate information (BIM). The total lift duration is an important parameter of crane deployment, which consists of horizontal-, vertical- and rotation speed. In addition, the hook and unhook time of building elements is very important, because this time is the biggest part of the total lift duration. Within the three-dimensional environment, it can become clear which building elements can be lifted, are out of range and are too heavy. However, environmental factors should be taken into account by using a construction site plan. Finally, this kind of tool supports the crane planner by using a three-dimensional visualization and graphs to determine a more optimal crane location and material storage location.

The research shows that the optimization of crane deployment is very promising for the construction industry, in which a three-dimensional environment and the minimization of lift time are taken into consideration. However, this research only focuses on one type of self-erecting crane, applied within a residential construction project. Other types of cranes can be implemented within a three-dimensional simulation tool, such as a crawler crane, telescopic crane and tower crane. In addition, it would be very useful to simulate the deployment of more cranes, taken into consideration their movements, the crane occupation in hours and safety factors, such as ground reinforcement and wind speed. The crane deployment for one or more utility construction projects can also be investigated further. When the crane deployment for more construction projects can be determined, it is possible to plan in months instead of weeks. It is also possible to optimize the crane deployment for different construction methods, such as prefabricated, timer-framed and pouring work. The ultimate goal is to gather the optimal crane hours from an optimization tool and to automatic schedule the most optimal hours within the construction planning (4D).

Samenvatting

Eén van de grootste problemen binnen de bouwindustrie zijn bouwvertragingen op bouwplaatsen (El-Razek, Bassioni, & Mobarak, 2008) (James, et al., 2014). Bouwvertragingen komen het meest voor tijdens de bouwfase van projecten (Rao & Culas, 2014). Bouwvertragingen worden voornamelijk veroorzaakt door het slecht leiding geven en slechte technische vaardigheden van aannemers, zoals een ondoordachte bouwplaatsinrichting, onnauwkeurig werk van onderaannemers en het inefficiënt plannen (Rao & Culas, 2014). Bouwvertragingen kunnen al worden voorkomen tijdens de voorbereiding van projecten, waarbij de bepaling van een goede bouwplaatsinrichting en projectplanning erg belangrijk zijn. Kraaninzet is één van de meest belangrijke onderdelen van een bouwplanning (Al-Hussein, Niaz, Yu, & Kim, 2006) (Li, Chan, Huang, Guo, Lu, & Skitmore, 2009). Inefficiënte kraaninzet tijdens de voorbereiding van bouwprojecten is een groot probleem binnen de bouwsector. De bepaling van kraaninzet en andere bouwactiviteiten zijn vaak onzeker, omdat deze voorspellingen gebaseerd zijn op persoonlijke kennis van de kraanplanner (Li, Chan, Huang, Guo, Lu, & Skitmore, 2009) (Nahmias, 2009) (Sugimoto, Seki, Samo, & Nakamitsu, 2015). Door deze onzekere bepaling van kraaninzet, komt het vaak voor dat het huidige kraangebruik groter is dan verwacht. Het doel van het onderzoek is om een optimalere kraaninzet te verkrijgen, waarbij gelet moet worden op het minimaliseren van de tijd voor woningbouwprojecten. Het minimaliseren van kraaninzet, zou moeten leiden tot een vermindering van kosten voor kraanhuur.

Allereerst worden de oorzaken van bouwvertragingen onderzocht door middel van een literatuurstudie en half-gestructureerde interviews. Op basis van de verkregen informatie wordt de probleemstelling specifieker, welke betrekking heeft op kraaninzet. Verder onderzoek wordt gedaan naar kraaninzet door het gebruik van aanvullende half-gestructureerde interviews en observaties op de bouwplaats. De literatuurstudie, interviews en observaties zijn uitgewerkt in hoofdstuk 2, 3 en 4. De resultaten van de literatuurstudie, interviews en observaties worden gebruikt voor de ontwikkeling van een simulatietool (hoofdstuk 5). De tool wordt geverifieerd door het vergelijken van de simulatieresultaten met de resultaten van de interviews en observaties (hoofdstuk 6). Daarnaast wordt de tool gevalideerd door het gebruik van een woningbouwproject van zeven rijtjeswoningen. Verder wordt er feedback verkregen van twee uitvoerders. Op basis van het verificatie en validatie proces wordt de tool aangepast en aanvullende simulaties worden uitgevoerd. Uiteindelijk worden er conclusies getrokken (hoofdstuk 7) en onderwerpen voor verder onderzoek worden duidelijk gemaakt (hoofdstuk 8).

Het doel van dit onderzoek is om kraaninzet te optimaliseren tijdens de voorbereidingsfase van woningbouwprojecten, door het ontwikkelen van een simulatietool. Deze tool is ontwikkeld in een driedimensionale omgeving, waarin de kraan en zijn specificaties zijn geïntegreerd. De tool houdt rekening met het heffen van bouwelementen en het minimaliseren van de totale hijsduur van de kraan. Verschillende informatie is in de tool geïntegreerd, zoals kraanspecificaties, capaciteiten per kraanrange en materiaalspecificaties. Daarnaast ondersteunt de tool IFC data structuren, welke steeds belangrijker worden in de bouwsector. IPython wordt gebruikt voor de ontwikkeling van de tool, welke gebruik maakt van IfcOpenShell. IfcOpenShell is een software bibliotheek voor het programmeren met het IFC bestandsformaat (Krijnen, 2016). Het ontwikkelde prototype van de simulatietool heeft beperkingen, zoals bouwelementen die niet overeenkomen met de realiteit en er wordt

geen rekening gehouden met omgevingsfactoren. De tool binnen dit onderzoek richt zich op het bepalen van de kraanlocatie, locatie van materiaalopslag en berekent of bouwelementen kunnen worden gehesen en wat de totale hijsduur van deze elementen is.

De simulatietool wordt gevalideerd door het implementeren van een woningbouwproject van zeven rijtjeswoningen. Brute-force analyse wordt gebruikt om resultaten te verkrijgen, waarbij verschillende locatiecombinaties van kraan en materiaalopslag worden gesimuleerd. De resultaten laten zien of kozijnen en vloeren kunnen worden gehesen en wat de totale hijsduur van deze elementen is. De totale hijsduur wordt vergeleken met geplande en uitgevoerde kraanuren van de kozijnen en vloeren. Er zijn grote verschillen zichtbaar tussen de daadwerkelijk uitgevoerde kraanuren en gesimuleerde hijsuren. De aan- en afpiktijd hebben grote invloed op deze verschillen, waarna deze tijden worden aangepast en nieuwe simulaties worden uitgevoerd. Op basis van deze nieuwe simulaties zijn de totale kosten van drie combinaties berekend. Deze kosten zijn gebaseerd op de kraanhuur kosten en kosten voor het gebroken puin op de bouwplaats. Uiteindelijk is één locatiecombinatie van kraan en materiaalopslag het goedkoopst en meest handig. Deze combinatie is 10% goedkoper dan de derde combinatie en 15% ten opzichte van de tweede combinatie.

Door het gebruik van dergelijke optimalisatie tool kan een optimalere kraaninzet worden verkregen, wat uiteindelijk resulteert in een afname van kraankosten. Door het gebruik van computer gerelateerde technieken kan het kraangebruik worden geoptimaliseerd, door te simuleren in een driedimensionale omgeving waarin informatie is geïntegreerd (BIM). De totale hijsduur is een belangrijke parameter van kraaninzet, welke bestaat uit horizontale-, verticale- en rotatiesnelheid. Daarnaast is de aan- en afpiktijd van ieder bouwelement erg belangrijk, omdat deze het grootste deel van de totale hijsduur omvatten. Binnen een driedimensionale omgeving kan duidelijk worden gemaakt welke bouwelementen kunnen worden gehesen, buiten bereik of te zwaar zijn. Echter moet er ook rekening gehouden worden met omgevingsfactoren, welke kunnen worden weergegeven in een plattegrond van de bouwplaats. Uiteindelijk kan dergelijke tool de kraanplanner ondersteunen om een optimalere locatie voor de kraan en materiaalopslag te bepalen.

Het onderzoek toont aan dat een optimalisatie van kraaninzet veelbelovend is voor de bouwsector, waarbij rekening gehouden wordt met een driedimensionale omgeving en het minimaliseren van de hijsduur. Echter richt dit onderzoek zich alleen op één soort mobiele kraan, welke toegepast wordt op een woningbouwproject. Andere soorten kranen kunnen ook worden geïmplementeerd binnen een driedimensionale simulatietool, zoals een rupskraan, telescoopkraan en torenkraan. Daarnaast zou het nuttig zijn om de inzet van meerdere kranen te simuleren, waarbij rekening gehouden wordt met de kraanbewegingen, kraanbezetting in uren en veiligheidsfactoren, zoals grondversterking en de windsnelheid. Verder kan de kraaninzet voor meerdere bouwprojecten worden onderzocht. Als de kraaninzet voor meerdere bouwprojecten kan worden bepaald, kan er in maanden worden gepland in plaats van in weken. Het is ook mogelijk om de kraaninzet voor verschillende bouwmethodieken te optimaliseren, zoals montagebouw, houtskeletbouw en gietbouw. Het uiteindelijke doel is om de optimale kraanuren te verkrijgen van een optimalisatie tool en deze automatisch in een bouwplanning te visualiseren (4D).

Abstract

Construction delays on construction sites are one of the biggest problems within the construction industry, which are mainly caused by an ineffective planning process. Crane deployment is an important part of the planning process, because many construction activities are highly dependent on it. Ineffective crane deployment can directly result in construction delays. Within this research three research methods were used; a literature review, interviews and observations on the construction site. By using these research methods, more information was gathered concerning scheduling, building models and crane deployment. The aim of the research was to develop a simulation tool for residential construction projects, which supports the crane planner during the determination of crane deployment. The results of this research shows that crane utilization for residential projects, can be very promising for the construction industry and finally could results in a reduction of crane expenses. In addition, the tool supports IFC data structures, which are standardized data structures and are becoming increasingly important within the construction industry. It would be very useful to simulate the crane deployment for more type of cranes, taken into consideration their movements, the crane occupation in hours and safety factors, such as ground reinforcement and the wind speed. Finally, the optimization of crane deployment can be applied within utility construction projects.

Glossary

3D	Three Dimensions
4D	Three Dimensions + Time
5D	Four Dimensions + Cost
6D	Five Dimensions + Life Cycle Management
AEC	Architecture, Engineering and Construction
BIM	Building Information Modelling
CAD	Computer Aided Design
CPM	Critical Path Method
CSV	Comma-Separated Values
IAI	International Alliance for Interoperability
IFC	Industrial Foundation Classes
ISO	International Organization for Standardization
LOD	Level of Detail
OCCT	Open Cascade Technology
STEP	The Standard for the Exchange of Product Model Data
WBS	Work Breakdown Structure

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1. Introduction

This chapter introduces the context of the problem statement, concerning ineffective crane deployment during the preparation of construction projects, which may cause construction delays and additional project costs. The main question and sub-questions are stated, as well as the research design and the expected results are further elaborated.

1.1 Problem statement

One of the biggest problems within the AEC industry are construction delays on construction sites (El-Razek, Bassioni, & Mobarak, 2008) (James, et al., 2014). In addition, construction delays are a complex, costly and risky problem within construction projects (Alaghbari, Kadir, Salim, & Ernawati, 2007). Construction delays are most common during the construction phase of projects (Rao & Culas, 2014). They can be defined as the time overrun either beyond completion date specified in a contract, or beyond the date that the project participants agreed upon for delivery of a construction project (Assaf & Al-Hejji, 2006). Construction delays can also be defined as an act or event, which extends required time to perform or complete work of the contract, manifests itself as additional days of work (Zack, 2003).

Construction delays are generally caused by poor managerial and technical skills of contractors; such as poor site mobilization, poor subcontractors work and ineffective planning and scheduling (Rao & Culas, 2014). These delays have a negative effect on construction projects and its project stakeholders, such as time and cost overruns (Alaghbari, Kadir, Salim, & Ernawati, 2007) (Rao & Culas, 2014) (James, et al., 2014). Three effective methods to reduce delays during construction projects can be distinguished: effective strategic planning, clear information and communication planning, site management and supervision (Rao & Culas, 2014). However, construction delays can already be prevented during the preparation of construction projects, in which effective site mobilization and planning are important.

Many construction activities are highly dependent on crane deployment, which is one of the most critical components of a construction schedule (Al-Hussein, Niaz, Yu, & Kim, 2006) (Li, Chan, Huang, Guo, Lu, & Skitmore, 2009). Crane deployment plans are often created by the contractor, which consists of crane configurations (load capacity, lifting range and speed), building element information (weights, size), crane locations and construction site information (Lei, Taghaddos, Hermann, & Al-Hussein, 2013) (Han, Lei, Bouferguène, Al-Hussein, & Hermann, 2014) (Sugimoto, Seki, Samo, & Nakamitsu, 2015) (Marzouk & Abubakr, 2016). Ineffective crane deployment during the preparation of construction projects is a big problem within the construction industry. The determination of crane deployment and other construction activities are often uncertain, because these predictions are based on personal experiences of the planner (Li, Chan, Huang, Guo, Lu, & Skitmore, 2009) (Nahmias, 2009) (Sugimoto, Seki, Samo, & Nakamitsu, 2015). Due to such uncertain determinations of crane deployment, it is often the case that the actual crane utilization is larger than expected. Generally, this problem is solved by deploying extra day and night work shifts and an increased number of cranes, which results in additional project costs (Sugimoto, Seki, Samo, & Nakamitsu, 2015).

1.2 Research question(s)

The aim of the research is to discover a more optimal crane utilization, considering the minimization of time for residential construction projects. The minimization of utilization time should result in a reduction of crane rental costs. In order to achieve this aim, the following main question will have to be answered:

"How can the crane utilization be optimized based on building models, considering the minimization of time?"

In addition, several sub-questions will have to be answered, to contribute to answering the main question. These sub-questions are as follows:

- *SQ1. What are the expected gains to optimize the crane deployment within residential construction projects?*
- *SQ2. How do these opportunities relate to the current construction industry?*
- *SQ3. Which parameters concerning construction time are important for the crane deployment within residential construction projects?*
- *SQ4. What are functional requirements for a tool to help in this process within residential construction projects?*
- *SQ5. How can the consequences of choices in the planning process concerning crane deployment be communicated during the construction process?*

1.3 Research design

To achieve the objectives of this research, the research questions listed in section 1.2 have to be answered. The whole research focusses on residential construction projects, because these projects are often less complex as utility construction projects, which makes it more useful to implement it in a new tool. The research model in Figure 1 shows how the research is structured.

A first problem statement is defined, in which construction delays are seen as one of the biggest problems within the AEC industry. Based on this problem statement, two exploratory research techniques are used; literature review and semi-structured interviews. Exploratory research techniques are very useful to investigate little understood phenomena, to identify important variables and to generate issues for further research (Marshall & Rossman, 2015). The literature review is based on primary sources; such as papers, textbooks, reports, scientific articles and conference contributions. Based on the obtained information, the problem statement has become more specific. Using the final problem statement, further research is done by using subsequent semi-structured interviews and observations at the construction site. The literature review, interviews and observations are further elaborated in chapter 2, 3 and 4.

The results of the literature review, interviews and observations are used as an input for the development of the simulation tool (chapter 5). Thereafter, the tool is verified by comparing the tool with results from the interviews and observations (chapter 6). In addition, the tool is validated by using one residential construction project. Feedback is also obtained from two construction site engineers. Based on the verification and validation process, the tool is

adjusted and new simulations are done. Finally, conclusions can be drawn (chapter 7) and subjects for further research become clear (chapter 8).
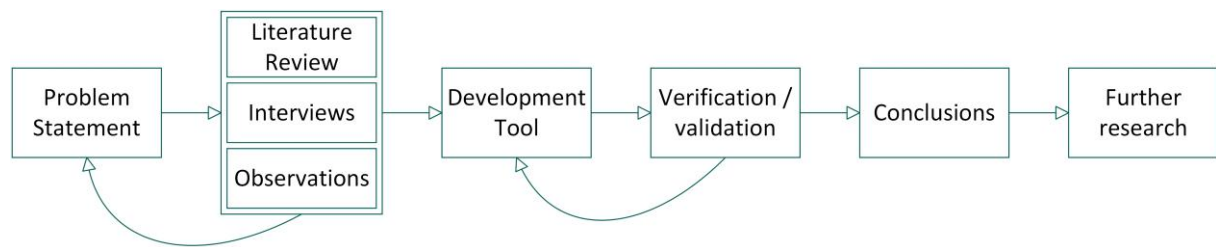
Figure 1. Research model.

1.4 Expected results

The aim of the research is to develop a simulation tool, which contributes to determine a more optimal crane utilization during the preparation of residential construction projects. Crane specifications are integrated in the tool, to avoid construction delays and additional project costs caused by ineffective crane utilization. The simulation tool should assist the crane planner to determine a more optimal crane utilization, whereby the data is standardized and analysed by using the simulation tool. The tool should reduce the time to create crane utilization plans, to improve their accuracy and to reduce crane rental expenses.

Limited research has been done, in which both crane configurations, building element information and crane locations are integrated in a simulation tool. This research contributes to solve this problem by developing a simulation tool, in which aforementioned data is integrated.

2. Literature review

In this chapter, the different aspects concerning the research problem of this master thesis are elaborated further. As previously described, construction delays are one of the biggest problems within the AEC industry. These delays are usually caused by poor managerial and technical skills of the contractors; such as poor site mobilization, poor subcontractors work and ineffective planning and scheduling. Crane deployment is such a factor, which consists of both site mobilization, planning and scheduling. The determination of crane deployment and other construction activities are often uncertain, because these predictions are based on personal experiences of the planner. Due to such uncertain determinations of crane deployment, it is often the case that the actual crane utilization is larger than expected. Generally, this problem is solved by deploying extra day and night work shifts and an increased number of cranes, which results in additional project costs.

This literature review consists of four main subjects: Planning process, Building Information Modelling, Crane Deployment and Industrial Foundation Classes. The subject "Planning process" is investigated concerning planning methods, planning during the estimation phase of projects and planning analysis. Secondly, the subject "Building Information Modelling" is studied in general, the levels of BIM and the development of a 4D BIM model. The subject "crane deployment" is examined based on previous research on crane utilization in combination with BIM. The subject "Industrial Foundation Classes" is investigated in general, on previous research and how IFC is structured. Finally, this chapter is enclosed with a conclusion to summarize all findings. The purpose of this literature review is to gain knowledge about the four main subjects and to apply it in the continuation of this master thesis.

2.1.1 Construction planning and scheduling

Within the AEC industry, construction planning will play an increased role due to the growth of the industry and the general shortage of skilled planners (Allen & Smallwood, 2008). There is a substantial difference between planning and scheduling. As mentioned by Mawdesley, Askew and O'Reilly (1996), project planning is the general term which includes programming, scheduling and organizing. The aim of project planning is to ensure that all performed project activities, are carried out in a successful way (Mawdesley, Askew, & O'Reilly, 1996). Scheduling is defined as the understanding and producing of a set of sequenced construction activities (Baldwin, Kong, Huang, Guo, Wong, & Li, 2008). Heesom and Mahdjoubi (2004) also discovered the differences between planning and scheduling. They mentioned that a planning shows the project activities and their relationships, whilst the activities do not show specific start and end dates. A schedule shows temporal information to define the project duration (Heesom & Mahdjoubi, 2004).

Hendrickson (2000) distinguishes three stages of the planning process for construction companies. First, the planning process starts with the estimation phase, in which the construction planning of a project is predicted through different analyses. Second, during the monitoring and control phase, the construction manager tracks the progress of the project. Finally, the evaluation phase is to compare and evaluate the estimation phase to the results of the construction project. The planner has the job to forecast the planning of a construction project, which is quite difficult because each construction project is different (Hendrickson, 2000). In addition, construction projects have an increased complexity and uncertainty, which makes construction planning a difficult task for planners to anticipate and visualize likely future events (Li, Chan, Huang, Guo, Lu, & Skitmore, 2009). This complexity requires a higher degree of assistance from computer related techniques to accomplish effective planning and management (Chau, Anson, & Zhang, 2005). Li, Chan, Huang, Guo, Lu and Skitmore (2009) mentioned visual prototyping as such a computer related technique, in which construction activities are visualized by computer simulation. In this literature review we will focus on the estimation phase, which takes place during the preparation of construction projects.

2.1.2 Estimation phase

According to Ribeiro and Ferreira (2010), the preparation and estimation of a project specific construction planning is crucial for any construction company. A proper project preparation and estimation will have directly influence on the project execution, so it is very important to implement the most optimal solutions and to anticipate on project risks previously (Ribeiro & Ferreira, 2010). However, to implement the most optimal planning solutions beforehand, knowledge from different experts has to be applied. This planning knowledge has to be captured into an information database, to optimize the preparation of construction projects (Li, Chan, Huang, Guo, Lu, & Skitmore, 2009) (Ribeiro & Ferreira, 2010). Shared knowledge can be achieved from previous completed projects and expert knowledge, which finally reduces the uncertainty of construction planning estimations. Shared knowledge also contributes to the improvement of the quality of optimal planning solutions, and reduces the time and costs in order to optimize the construction planning (Tserng & Lin, 2004). Generally, construction companies have not developed a shared knowledge culture, which takes into account both knowledge and technology. Usually, construction projects have a limited duration, whereafter the project information and

lessons learned are blurred or even lost when the project ends. Nowadays, most construction companies rely on their current planning and re-estimation procedures (Ribeiro & Ferreira, 2010).

2.1.3 Planning analysis

Construction plans are often presented as Gantt charts (Figure 2), in which the time progress is visualized in a graphical way (Memon, Majid, & Mustaffar, 2006) (Li, Chan, Huang, Guo, Lu, & Skitmore, 2009). Within these Gantt charts, the CPM can be implemented, which shows the activities that have to be completed on time or else the entire project will take longer (Meredith & Mantel, 2009).

ID	Task Name	Duration	Start	Finish	Predecessors
1	Start	0 days	01/21/2002	01/21/2002	
2	a	5 days	01/21/2002	01/25/2002	1
3	b	4 days	01/21/2002	01/24/2002	1
4	c	6 days	01/28/2002	02/04/2002	2
5	d	2 days	01/25/2002	01/28/2002	3
6	e	5 days	01/25/2002	01/31/2002	3
7	f	8 days	02/05/2002	02/14/2002	4,5
8	Finish	0 days	02/14/2002	02/14/2002	6,7
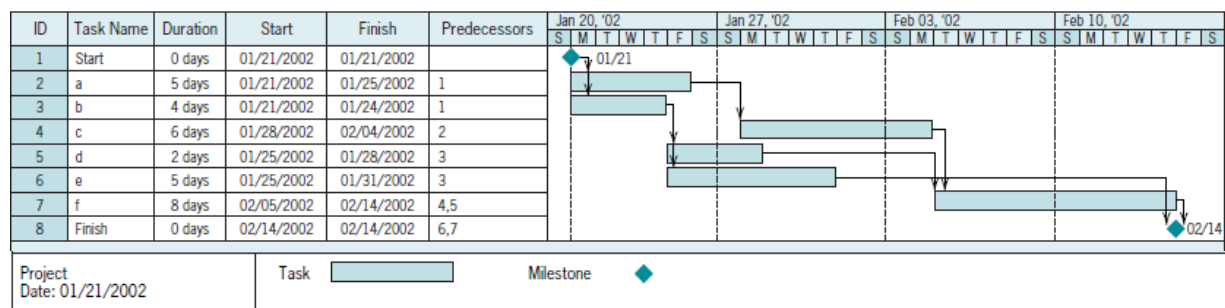
Figure 2. Gantt chart (Meredith & Mantel, 2009).

Gantt charts can be misinterpreted, due to the large numbers of activities presented and the difficulty of notations and relationships (Mahalingam, Kashyap, & Mahaja, 2010). Due to this large number of factors, a computer can be an efficient tool to help project planners. However, many construction schedules are created and analysed without computer-assisted technologies (Li, Chan, Huang, Guo, Lu, & Skitmore, 2009). Since the 1990s, four-dimensional computer aided design (3D model and time) is increasingly used to create and analyse project schedules (Heesom & Mahdjoubi, 2004). 4D simulations could assists project planners during the pre-construction and construction phase, to detect potential problems and in order to optimize the project planning (Heesom & Mahdjoubi, 2004). This 4D computer-assisted technique could also assists for the utilization of site logistics and site layout, such as crane deployment (Zhang, Anson, & Wang, 2000).

Three commonly used 4D computer-assisted tools within the AEC industry are Autodesk Navisworks Simulate, Vico Office and Synchro Professional (Morkos, Macedo, Fischer, & Somu, 2012). Autodesk Navisworks Simulate is developed by the largest software developer in the AEC industry, Synchro Professional is specialized in 4D tool development and Vico Office can integrate both costs as schedule 3D models (Morkos, Macedo, Fischer, & Somu, 2012). According to Mauldin (2012), Autodesk Navisworks Simulate is intended for visualisation purposes and business development. Vico Office will be a very helpful tool when costs, production and scheduling are integrated into the 3D model, and if there is someone available within the company who works at least 20 hours each week with the software. Finally, Synchro Professional is recommended for time analysis or to use 4D simulation models for the daily planning with subcontractors (Mauldin, 2012). Synchro Professional has most 4D capabilities in comparison with Autodesk Navisworks Simulate and Vico Office, and is therefore most recommended as 4D computer-assisted tool (VIA University College, 2015). However, none of these 4D computer-assisted tools is suitable for

analysing and optimizing site mobilization, such as crane deployment of construction projects. In the remainder of this literature review, we will go more deeply into the subject 4D.

2.2.1 Building Information Modelling

BIM can be seen as one of the most promising developments in the AEC industry. BIM can be defined as the collaboration and information share between different project stakeholders, so that all relevant information is stored throughout the lifecycle of a construction project, in which one or multiple digital building models are used to manage and support the construction process (Straatman, Pel, & Hendriks, 2012). All project stakeholders work with the same shared information, which is always up-to-date and available for all involved project stakeholders. Straatman, Pel and Hendriks (2012) distinguish three BIM definitions to avoid confusion: BIM methodology, BIM model and BIM data. The BIM methodology covers the applications of the BIM-model, work processes and modelling methods to specific, repeatable and reliable data retrieval from the models. The BIM model consists of one or more 3D building models, in which all data is recorded and shared between project stakeholders throughout the lifecycle of a construction project. The data in these models is related to physical and functional characteristics of construction projects. BIM data covers the requirements and standards for the application of BIM and the exchange of data. This ensures that both the sender as receiver could understand and interpret the exchanged data (Straatman, Pel, & Hendriks, 2012). The purpose of using BIM is to improve the collaboration between project stakeholders, reduce the project lead time and project costs and finally to improve the project quality (BSI & BuildingSMART, 2010). Straatman, Pel and Hendriks (2012) distinguishes two types of BIM; little and big BIM. Little BIM will be used to support the internal business process, while big BIM will be used as collaborative tool between different project stakeholders (Straatman, Pel, & Hendriks, 2012). Also a comparison between open and closed BIM can be made. Open BIM involves the collaboration between exchange formats (e.g. IFC), which are not owned by a particular software vendor. Within closed BIM, the collaboration takes place through exchange formats of a particular software vendor, for example Autodesk Revit formats (BIM Task Group, 2011).

2.2.2 Levels of BIM

Several levels of BIM implementation are available; while first the BIM maturity is described by four different levels in Figure 3 (BIM Task Group, 2011). According to the BIM Task Group (2011), level 0 is based on 2D CAD with no specific collaboration requirements and paper-based data sharing. Level 1 is based on 2D and 3D designs, however the graphical data is lacking intelligence and there is no integration between the design and functions like scheduling and cost estimation. In level 2 the 3D environment is required, in which data is attached to the graphical objects and where data exchange can take place. However, data exchange in level 2 can take place through exchange formats of a particular software vendor, also called closed BIM. Level 3 includes the full collaboration by using a web-based model, also called open BIM (BIM Task Group, 2011).
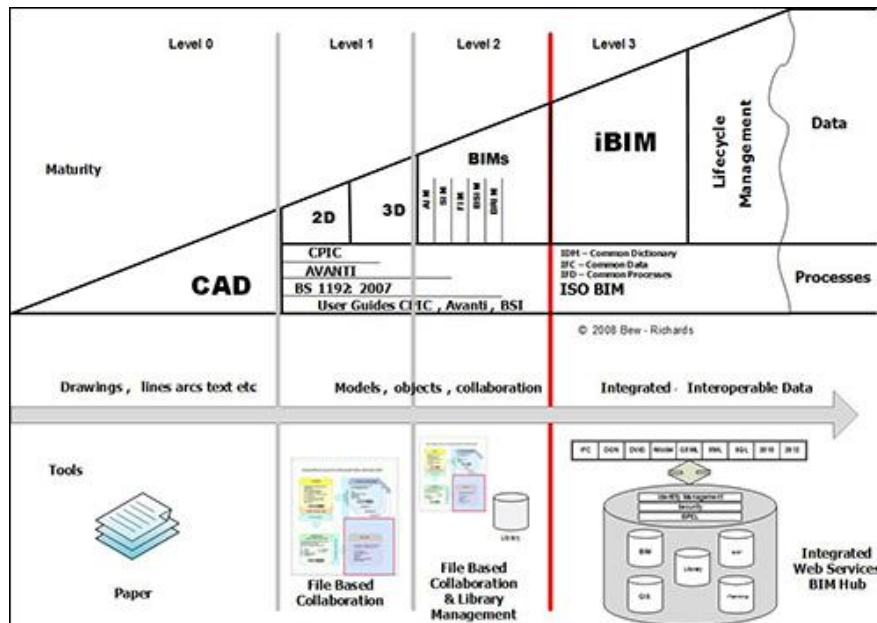
Figure 3. Levels of BIM (BIM Task Group, 2011).

In addition, a distinction between different LODs concerning BIM can be made (Spekkink, 2012). These LODs should provide a better information exchange between project stakeholders in a contractual environment. The five LODs which are distinguished are: LOD 100, LOD200, LOD300, LOD 400 and LOD 500 (Spekkink, 2012). Each LOD correspond to a project stage, namely; LOD 100 - conceptual design, LOD 200 - schematic design, LOD 300 - construction documents, LOD 400 - construction, LOD 500 - as-built conditions for the project (Spekkink, 2012).

Besides the distinction between maturity levels and LODs, Khoshnava, Ahankoob, Preece and Rostami (2012) distinguish four dimensions of BIM; 3D, 4D, 5D and 6D. In a 3D BIM model, the construction project can be visualized and clash detections can take place. In a 4D BIM model the project schedule is integrated and visualized in the 3D model. 5D BIM consists of the 3D model, in which the cost estimation and quantity take-off is integrated. Finally, in a 6D BIM model the life cycle management is integrated in the model, which is useful for future maintenance (Khoshnava, Ahankoob, Preece, & Rostami, 2012).

2.2.3 Development 4D BIM model

According to Khoshnava, Ahankoob, Preece and Rostami (2012) in a 4D BIM model the project schedule is integrated and visualized in the 3D model. In 2009, Dawood and Sikka identified, developed and quantified 4D-based key performance indicators. Their aim was to develop an approach to demonstrate the value of 4D tools for the AEC industry. They concluded that the use of 4D BIM resulted in 17% increase of the planning efficiency and 30% reduction in time used for meetings. This is shown that 4D BIM has the potential to improve the construction process, however it is not yet widely used in the AEC industry (Dawood & Sikka, 2009). The adoption of 4D BIM should be stimulated in the field of the AEC industry. Mahalingam, Kashyap and Mahaja (2010) analysed the practical difficulties of the implementation of 4D BIM on the construction site, as well as observations of the involved project stakeholders. Their aim was to contribute to the understanding of 4D BIM integration on site, which results in an increased acceptability and usefulness by project stakeholders. They discovered that 4D BIM is most beneficial during the project design or

planning stage and during the construction stage. In the project design stage it is primarily useful for the communication about construction plans and processes to the clients. During the construction phase 4D BIM is primarily useful in order to detect conflicts or clashes and as visualisation tool for project stakeholders (Mahalingam, Kashyap, & Mahaja, 2010). Chau, Anson and Zhang (2005) presented the previous development and implementation of a prototype 4D site management model (4DSMM). Their aim was to connecting scheduling data to the 3D model and to visualize graphic simulations of the construction process. They developed a new information platform system, graphics for construction and site utilization (GCPSU) to implement it to the model 4DSMM. As result they demonstrated the connection of 4D BIM to construction management tools like WBS, scheduling, decision support tools and other useful assistance tools for construction planners. Further research can be done to the development of a web-based collaborative system, in which the 4D BIM is integrated in this application. This application should provide an advanced construction progress monitoring to detect potential planning issues (Chau, Anson, & Zhang, 2005) (Kim, Kim, & Kim, 2013).

There are three important inputs to create a 4D simulation model (Chau, Anson, & Zhang, 2003). First, a 3D geometrical model is needed, which can be divided in structural elements (building components), operational objects (activities) and temporary facilities (like material storage for example). In addition, planning information, as activity durations and sequence relationships are required, which are incorporated in planning software. Finally, a construction processor is needed to integrate the 3D model with the construction planning, which results in a 4D simulation model. The aim of the 4D simulation model can be that the construction progress of building components can be visualized and tracked (Chau, Anson, & Zhang, 2003). The building components can be tracked by using different colour codes, which can be grouped into "on time" and "delayed" groups (Chang, Kang, & Hsieh, 2007) (Chen, Tsai, Kang, & Liu, 2013). Three software tools which can be combined to develop a 4D BIM model are; Autodesk Revit, Asta Powerproject and Navisworks Manage.

2.3 Crane deployment
Many construction activities are highly dependent on crane deployment, which is one of the most critical components of a construction schedule (Al-Hussein, Niaz, Yu, & Kim, 2006) (Li, Chan, Huang, Guo, Lu, & Skitmore, 2009). Crane deployment plans are often created by the contractor, which consists of crane configurations (load capacity, lifting range and speed), building element information (weights, size), crane locations and construction site information (Lei, Taghaddos, Hermann, & Al-Hussein, 2013) (Han, Lei, Bouferguène, Al-Hussein, & Hermann, 2014) (Sugimoto, Seki, Samo, & Nakamitsu, 2015) (Marzouk & Abubakr, 2016). Ineffective crane deployment during the preparation of construction projects is a big problem within the construction industry. The determination of crane deployment and other construction activities are often uncertain, because these predictions are based on personal experiences of the planner (Li, Chan, Huang, Guo, Lu, & Skitmore, 2009) (Nahmias, 2009) (Sugimoto, Seki, Samo, & Nakamitsu, 2015). Due to such uncertain determinations of crane deployment, it is often the case that the actual crane utilization is larger than expected. Generally, this problem is solved by deploying extra day and night work shifts and an increased number of cranes, which results in additional project costs (Sugimoto, Seki, Samo, & Nakamitsu, 2015).

Tantisevi and Akinci (2009) developed a combined product and process 4D model, which is able to obtain mobile crane movements automatically, to identify spatial conflicts on the construction site. The input of the model consists of 3D building information and project specified activities, which are related to building components. The output of the model involves construction activities, crane movements, crane operations and geometric transformations. In the developed model, the user defines a construction method by selecting types of building components (e.g. mounting a concrete hollow-core slab) and a type of crane. This research is based on an inverse kinematic approach called Cyclic Coordinate Descent (CCD), which iteratively adjusts the configuration of one joint of a manipulator until all positional and orientation constraints are satisfied. The CCD approach results in quantities of relative movement of each joint in the final state of the crane. Geometric transformations of the crane are gathered by calculating the differential values of the joint movement between the initial and final state of the crane, and transform them into a matrix. These geometric transformation outputs were used for the visual simulation of crane movements and the detection of spatial conflicts. The developed model was validated by using a case study, to automatically generate crane movements for three types of mobile cranes. The 3D building data, schedule- and crane specification information of the 4D model was integrated in an ASCII text file. The developed tool does not support the input of an industry standard data format (e.g. IFC), which can be easily generated from AEC based software. Finally, the crane movements were visually analysed by comparing a part of geometric transformations with the actual movements of the crane during the construction of a project. The research showed that the movements of the geometric transformations and the actual movements have the same sequence. However, the research showed that it is difficult to determine the rotation of the boom and superstructure of the crane, and to determine the position of the hook during placement of building elements (Tantisevi & Akinci, 2009).

Kang and Miranda (2009) developed a mathematical computer tool, which visualizes and simulates crane activities in a detailed and reality based way. The tool was based on two sub-models; a kinematics model and a dynamic model. The kinematics model is able to mathematically describe crane operations and its movements under ideal conditions. The dynamic model simulates the unpredictable dynamic movements, to enhance the accuracy of the crane simulations. To verify the feasibility of these sub-models, the process of the developed tool was numerical analysed and visualized. The tool was based on interactive functions, such as the end-user could determine the crane location and its movements. This tool resulted in a smooth visualization of the virtual and interactive environment, to gain a better understanding of the construction process. In the future, it is advisable to integrate this tool with project planning tools, in order to increase the degree of automation of the simulation process (Kang & Miranda, 2009).

Irizarry and Karan (2012) integrated analysis results of Geographic Information Systems (GIS) with BIM, to visualize potential conflicts between the crane locations and number of tower cranes in the 3D views. The developed model was able to select an optimal amount of cranes and its site location, by using optimization algorithm and GIS. Within the model, all possible combinations of tower cranes and storage-, demand- and crane locations were considered. The model was implemented within a commercial building project to validate it. The model results in one or more feasible areas, which cover all demand and supply

locations for an optimal location of the tower cranes. When potential conflicts are detected, they were visualised in the 3D views. These visualisations will enhance the functionally of the model to real-time construction projects. In the future, it will become practical more useful when crane deployment tools will support standardized data structures, such as IFC data files. In addition, the optimization of crane deployment in 3D models should be integrated within mobile computing tools for construction projects (Irizarry & Karan, 2012).

Lei, Taghaddos, Hermann and Al-Hussein (2013), introduced an integrated mobile crane management system for industrial projects in a two-dimensional way. The system uses a database for the calculations and results, in which the load capacity, lift range, utilization and mobile crane locations are calculated. These calculations were based on originally developed algorithms and adoptions from other domains, such as robotics. The system was tested within an industrial project to validate the effectiveness and efficiency. This management system reduces the effort of the planner in the process to determine the crane utilization. However, more research has to be done to develop a 4D animation tool, in which the site layout is visualized to detect potential conflicts concerning crane deployment (Lei, Taghaddos, Hermann, & Al-Hussein, 2013).

Al Hattab, Zankoul and Hamzeh (2014) developed a simulation model to optimize the utilization of two tower cranes. The model simulates the schedule activities in overlapping work zones, to achieve best deployment rates to reduce idle times, project durations and costs. A daily schedule was produced through look-ahead planning, which was integrated within an Excel-AnyLogic based optimization model. This model was integrated within a case study to validate and to select the best choice concerning crane deployment. The analysis was based on the selection of several combinations, to select the minimum duration and idle times for the crane operations. The results of the analysis were visualized in graphs, which shows that the model is efficient and effective to improve the utilization of cranes within overlapping areas (Al Hattab, Zankoul, & Hamzeh, 2014).

Wang, et al. (2015) developed an integrated tool, which combines BIM and Firefly Algorithm (FA) to obtain automatically an optimal tower crane utilization plan. This crane optimization was based on economic, practical and safety perspectives. The tool consists of three parts; a BIM platform, a mathematical model for tower crane layout planning and a BIM-based crane visualisation and simulation part. The BIM platform was used as input for the mathematical model, FA determined the optimal tower crane and supply locations, which was finally visualised and analysed through BIM-based simulation. The tool was validated by integrating it within a commercial building project. In addition, the results of this tool were discussed by the project team, who confirmed the practicality of the tool for construction companies (Wang, et al., 2015).

Sugimoto, Seki, Samo and Nakamitsu (2015) developed a simulation system to evaluate the utilization rates of cranes for the construction of nuclear power plants. They used 4D simulation technology, consisting of 3D models and time dimension, to analyse the validity of the developed crane-deployment plans. To calculate the utilization rates of the cranes effectively and automatically, two functions were integrated within the system. The first function visualizes the data between 3D elements, cranes and schedules. The second function was able to estimate quantities of installation material required in the pre-

construction phase. The system was developed as add-on function within Navisworks Manage 2014, which is an Autodesk product. Computational experiments were performed to validate the system, in which the utilization rates were shown by graphs in 2D and 3D. The developed system resulted in a reduction in time to create crane deployment plans and to improve their accuracies (Sugimoto, Seki, Samo, & Nakamitsu, 2015).

Finally, Marzouk and Abubakr (2016) developed a framework to select multiple types of tower cranes and their location on the construction site. The framework consisted of three models: decision making-, optimization- and BIM-based model. The decision making model was to select the most suitable type of tower crane for a specific construction activity. The optimization model assists in the selection of tower crane specifications, the amount of cranes needed and the optimum layout of the cranes. Finally, the BIM-based model was used to verify the locations of the genetic algorithm model, by applying clash detections and develop a 4D plan. The model was developed to select the optimum number of tower cranes, which satisfy the coverage requirements based on the crane jib length. In addition, the model determined the locations based on Cartesian coordinates and the lift modules of each crane. It can be concluded that 4D BIM planning is very useful to understand the sequence of crane operations and checking if it there are potential clashes during crane operations, however more advanced query functions can be added, such as the modelling of mobile cranes (Marzouk & Abubakr, 2016).

Aforementioned literature provides an overview of research developments within the field of crane utilization. This research is mainly based on crane movements and potential location conflicts between multiple tower cranes. Within the AEC industry little research is done concerning the utilization of mobile cranes, which is based on both crane speed and building element level (e.g. floors, window frames). In addition, none of the developed tools in the articles supports standardized data structures, such as IFC data files. IFC files are becoming increasingly important within the AEC industry, which makes it desirable that a crane deployment tool supports IFC data files.

2.4.1 IFC data model
Data sharing within the AEC industry is becoming very fragmented, which is caused by the numerous involved construction parties within projects. The quality of data sharing can be improved by using software applications, standards and data models (Harrison, Donn, & Skates, 2003). Some of these early models include Building Product Model, Unified Approach Model, General construction object model and COMBINE (Danso-Amoako, Issa, & Cox, 2006).

Nowadays, Industrial Foundation Class open and standardized data models are commonly used within the AEC industry, which is developed by the International Alliance for Interoperability (Danso-Amoako, Issa, & Cox, 2006) (Ruddle, 2015). IFC has been developed in close relation with STEP, which is family of the ISO to determine how to exchange digital product information (Beetz, Laat, Berlo, & Helm, 2010). IFC is defined in EXPRESS data specification language to describe the processes, resources, products, actors etc. (Liebich & Chipman, 2015). Nowadays two IFC standards are used: IFC2x3 and IFC4 (Liebich, 2013). IFC4 is the improved standard of IFC2x3, which is used since 2014 and IFC2x3 will no longer be used after 2016. IFC4-Addendum1 is the latest version of IFC4, which is used since 2015

(Liebich & Chipman, 2015). The integration of IFC standards enables the interoperability between different BIM software applications within the AEC industry (Laakso & Kiviniemi, 2012).

2.4.2 Investigation IFC

A lot of research is done to the open and standardized IFC structure. Fu, Aouad, Lee, Mashall-Ponting and Wu (2006), developed an IFC-viewer which was defined as the holistic interface of the nD modelling tool. This IFC-viewer provides a way to reveal and retrieve information of the IFC model structurally and visually (Fu, Aouad, Lee, Mashall-Ponting, & Wu, 2006). Vanlande, Nicolle and Cruz (2008) investigated a BIM technology, which allows the management of information during the full lifecycle of an AEC project. They used IFC files to facilitate the sharing process, which should results in a better qualification and validation of data (Vanlande, Nicolle, & Cruz, 2008). There was also research done concerning the structure of information in the AEC industry, based on the IFC standards (Man & Sun, 2011). Zhiliang, Zhenhua, Wu and Zhe (2011) investigated the methods and opportunities of applying the IFC standard to construction cost estimating for tendering in China. They concluded that the IFC standard is very useful to express information for construction cost estimation for tendering (Zhiliang, Zhenhua, Wu, & Zhe, 2011). Gökçe, Gökçe and Katranuschkov (2013) presented a new product catalog structure based on the IFC standard. This developed structure could integrate the product, costs and management data (Gökçe, Gökçe, & Katranuschkov, 2013).

As mentioned earlier, construction planning will play an increased role within the AEC industry (Allen & Smallwood, 2008). The construction planning can be integrated in the IFC structure, of which various studies have been conducted. Froese and Yu (1999) developed process models, which were project management related parts of the IFC standard. Different modelling issues were discussed; such as cost estimates, construction processes, resources, products and project documents issues (Froese & Yu, 1999).

Faraj, Alshawi, Aouad, Child and Underwood (2010), developed and implemented a collaborative working environment for construction, which is called the Web-based IFC Shared Project EnviRonment. A project web-database was developed, which can be used by construction applications; such as design, visualization, estimating, planning, specifications and supplier information. The environment enables construction companies to perform, contribute and manage their construction activities (Faraj, Alshawi, Aouad, Child, & Underwood, 2000).

Tanyer and Aouad (2005), developed and implemented a 4D planning tool, which was part of an IFC-based project database. The tool combines the 4D simulation and cost estimation together and was intended to perform what-if analyses within construction projects (Tanyer & Aouad, 2005). As mentioned earlier, Zhiliang, Zhenhua, Wu and Zhe (2011), investigated the methods and opportunities of applying the IFC standard to construction cost estimating for tendering in China. They discovered seven parts of IFC-based information entities: price, cost-items, resource, product, division-item-, quantity and schedule information. The schedule information to describe the project planning was based on objects, relationships and the properties of the IFC2x3 structure (Zhiliang, Zhenhua, Wu, & Zhe, 2011).

Zhang, Yu, Li and Hu (2014), developed an IFC-based graphic information model for virtual construction. The model includes the physical object model, the realistic model, the construction information model and the animation model. Using the model, a 4D construction analysis and management system was developed. Relationships and descriptions according to the schedule, quantity, resources and costs based IFC structures were investigated to obtain data exchange in the system. The results show that the model could contribute to the data sharing and exchange between virtual construction systems and other IFC-based applications. Applying of the model within virtual construction systems could also results in a reduction of modelling effort and an increased value of virtual construction results. The animation model within the model simulates the construction activities by using different colour codes, to enhance the realistic view within 4D applications (Zhang, Yu, Li, & Hu, 2014).

2.4.3 IFC data structure

The IFC structure is composed of four main layers (resource, core, interoperability and domain layer), which consists of many types, entities, functions, rules, property- and quantity sets (Liebich & Chipman, 2015). A type consists of basic information, which is gathered from a primitive, enumeration or a select of entities. Entities are a class of information defined by common attributes and constraints. Attribute names within an entity are shown by using CamelCase naming convention with no prefix. Types, entities, functions and rules are defined as "Ifc" and continue with the English words in CamelCase naming convention. Property sets are a list of properties, which are units of information that are dynamically defined as a particular entity instances. Property sets start with the prefix "Pset_" and continue with the English words in CamelCase naming convention. Quantity sets are a list of quantities, which are a measurement of scope-based metrics; such as length, volume, area, weight, count or time. Quantity sets start with the prefix "Qto_" and continue with the English words in CamelCase naming convention (Liebich & Chipman, 2015).

The resource layer is the lowest layer, which consists of individual schemas composed of resource definitions such as `IfcRepresentationResource`, `IfcDateTimeResource` and `IfcActorResource` (Liebich & Chipman, 2015). Resource data structures cannot exist independently, but can only exist if they are referred by one or more entities deriving from `IfcRoot`. The most general layer is the core layer, which consists of `IfcKernel`, `IfcControlExtension`, `IfcProcessExtension` and `IfcProductExtension` (Liebich & Chipman, 2015). This layer provides the basic structure, relationships and other specializations in the IFC data model. All entities defined in the core layer and above derived from `IfcRoot`, have an unique name, identification, description and history information (Liebich & Chipman, 2015). The interoperability layer contains entity definitions, which are specific to a general product, process or recourse specialization across several project stakeholders. This layer will be used to exchange and share construction information, such as `IfcSharedBldgElements` and `IfcSharedFacilitiesElements` (Liebich & Chipman, 2015). Finally, the domain layer is the highest layer, in which entities are self-contained and cannot be referred by other layers. The domain layer consists of specific data schemas, containing final specializations of entities. Definitions are arranged according to the specific project stakeholders, such as `IfcArchitectureDomain` and `IfcConstructionMgmtDomain` (Liebich & Chipman, 2015).

2.5 Conclusions

The most important aspects of this literature review are discussed in this chapter. Construction planning can be seen as an important factor within the AEC industry. The industry is growing and there is a general shortage of skilled planners, which makes it a difficult task to estimate future events. Computer related techniques could assist to accomplish a more effective planning and management process. During the estimation phase, the planning process has directly influence on the project execution, so it is important to implement the most optimal solutions and anticipate on project risks previously. It is advisable to capture different knowledge from experts into an information database to implement it within a computer related tool. Within the AEC industry, Gantt charts are usually used for the planning process. These Gantt charts can be combined with BIM, which is one of the most promising developments within the construction industry. Big- and open BIM can be applied for a successful way of planning. In addition, it is recommended to use a 3D model with LOD 400 during the construction process. To implement planning and the 3D model with each other, 4D BIM can be applied. Applying 4D BIM resulted in 17% increase of planning efficiency and 30% reduction in time used for meetings (Dawood & Sikka, 2009). However, 4D BIM is not yet widely used within the AEC industry. The 4D computer-assisted technique could also assists for the utilization of site logistics and site layout, such as crane deployment. Many construction activities are highly dependent on crane deployment, which is one of the most critical components of a construction schedule. Crane deployment is often based on predictions of personal experiences of the planner. Due to such uncertain determinations of crane deployment, it is often the case that the actual crane utilization is larger than expected. Computer-assisted technologies and information databases can be integrated into a tool to assist the planner to determine a more optimal crane utilization. Research concerning crane deployment and BIM is mainly based on crane movements and potential location conflicts between multiple tower cranes. Within the AEC industry, little research is done concerning the utilization of mobile cranes, which is based on both crane speed and building element level (e.g. floors, window frames). In addition, none of the developed tools in the research supports standardized data structures, such as IFC data files (Open BIM). IFC data files are becoming increasingly important within the AEC industry, which makes it desirable that a crane deployment tool supports IFC data files.

3. Semi-structured interviews

During the exploratory research, eight semi-structured interviews were held in two phases with employees of Dura Vermeer Bouw Rosmalen. During these semi-structured interviews, a set of questions were answered to collect information. These questions and the transcript of the interviews are shown in Appendix 1. The respondents were free to talk, but the questions of the interview were used as guideline. Each interview was recorded, elaborated and was sent to the respondent within a week.

3.1.1 First phase

The first phase of the interviews was intended to identify which tools are currently used to create and coordinate construction schedules. In addition, problems concerning construction delays and desirable functional requirements to develop a simulation tool were discovered. During this phase, five interviews were held with a BIM coordinator, project leader, construction site engineer and two BIM engineers. These five respondents have direct contact with each other during the work preparation and construction phase of residential construction projects within Dura Vermeer Bouw Rosmalen. In addition, these respondents have experience with creating and/or coordinating of construction schedules for residential projects. These five interviews were held at the office of Dura Vermeer Bouw Rosmalen B.V.

3.1.2 Creating and coordinating construction schedules

The first phase of the interviews showed that Dura Vermeer Bouw Rosmalen uses two types of schedules for residential projects; the engineering schedule and the joint planning session schedule. The engineering schedule is used during the production/engineering phase of residential projects, while the joint planning session is used between the contractor and subcontractors during the preparation/execution of residential projects. Both types of schedules are based on the Gantt Chart technique. Usually, the project leader, construction site engineer and BIM engineer create the schedules in close collaboration with the subcontractors. Generally, they use Microsoft Excel to create the schedules and pictures from 3D models for a smoother communication. The created schedules are based on experience from previous projects, where fixed intervals for the construction of residential projects (constructed with limestone elements) have been applied. Two, five and nine weeks are these fixed intervals (Table 1). Two weeks is from the foundation phase until the ground floor. Five weeks is from the ground floor until the start of finishing work. Finally, the finishing work is nine weeks until the handover of the first seven dwellings. The construction speed for the handover of terraced dwellings is seven dwellings per week and for semi-detached dwellings five dwellings per week.

Table 1. Fixed intervals residential construction projects.

Residential construction project			Weeks
Foundation phase	→	Ground floor	2
Ground floor	→	Start finishing work	5
Finishing work	→	Handover first dwellings	9
Handover	→	7 terraced- or 5 semi-detached dwellings	1

There is no software used to coordinate the construction schedules, which is tracked by drawing a state line on a printed schedule and to communicate it to the subcontractors. All subcontractors and all tasks should be included in the schedule. In addition, it is important that schedule sequences, free days, building numbers, environmental factors both onsite as around the construction site are integrated. Finally, the delivery moments of building elements, scaffolding and crane deployment are very important. Both the project leader as the two BIM engineers pointed out that crane deployment is one of the most important factors of the construction schedule.

3.1.3 Construction delays

It sometimes happens that delays occur, both during the preparation as the construction phase. The government can cause delays when permits are requested or possible modifications are submitted. Purchaser options can also cause delays, because each client has different needs. Some examples of purchaser options are a dormer, skylight, building extension, electricity/water installations or the movement of inner window frames and inner walls. The modelling knowledge of subcontractors can cause delays, because not all subcontractors work according to the agreed guidelines with BIM and the integrated information. These agreed guidelines can be the name convention or the assignment of building elements to the agreed IFC entity. Currently, subcontractors fail to meet production of building elements, especially for floors, roofs and stairs. There is a big demand for these elements; however, there are too little subcontractors for these elements and their capacity is too low. In addition, unworkable weather, complaint from local residents in the neighbourhood, polluted soil and the lack of availability of personnel can cause construction delays. During the construction phase, each day there is a day start, where every foreman of the subcontractor shows their progress and possible delays. The construction schedule is updated and sent by email to the subcontractors. In addition, the modifications in the schedule are communicated to the subcontractors by telephone.

3.1.4 Simulation tool

Both the project leader as the construction site engineer revealed that a visualisation and analysis of the construction progress within a 3D model would be ideal for the construction site engineer. In addition, the deployment of cranes and scaffolding may also be included in the tool. Especially the crane deployment is an important factor of the construction schedule, because there is a lot of money involved.

3.2.1 Second phase

The second phase of the interviews was intended to identify how an optimal crane deployment for residential construction projects is currently achieved. In addition, desirable functional requirements for a simulation tool to optimize crane utilization should be clarified. During this phase, three interviews were held with a coordinator operations office and two construction site engineers. These three respondents determine the crane deployment of residential construction projects within Dura Vermeer Bouw Rosmalen. Two interviews were held at the office of Dura Vermeer Bouw Rosmalen B.V., the third interview was held at the office on the construction site.

3.2.2 Crane deployment

The second phase of the interviews showed that most common used cranes within Dura Vermeer are the crawler crane, self-erecting crane, telescopic crane and tower crane.

Crawler crane

These type of cranes are mounted on an undercarriage with a set of crawlers, which provides stability and mobility (Figure 4). Crawler cranes have a lifting capacity from 36 tons until 3200 tons, which is quite high (Norman Spencer, 2012). A big advantage is that they move around onsite easily and they have not to be stamped. In addition, crawler cranes are able to move with a load. By using a crawler crane, it is less risky to stuck in soft ground, because the weight is distributed over a larger area. The main disadvantage is that crawler cranes are very heavy, and it is difficult to move them from one to another construction site without high costs. Trucks, rail cars or ships are used to move them to another construction site (Norman Spencer, 2012).

Figure 4. Crawler crane (Riel, 2013).

Figure 5. Self-erecting crane (Riel, 2013).

Self-erecting crane

This is a type of tower crane, which is also described in this section. The biggest difference between these two types of cranes is the ability of the self-erecting crane to assemble and dismantle automatically (Norman Spencer, 2012). A self-erecting crane can be assembled and dismantled within forty minutes, which makes is very flexible in usage. Self-erecting cranes have a lifting capacity from 1.7 tons until 50 tons (Riel, 2013). Self-erecting cranes are applied when construction projects have limited space and construction time (Figure 5).

Telescopic crane

This type of crane has a boom, which consists of a number of tubes fitted in each other (Figure 6). Usually, a hydraulic mechanism extends or retracts the tubes to increase or decrease the length of the boom (Norman Spencer, 2012). Telescopic cranes have a lifting capacity from 0.5 tons until 580 tons (Riel, 2013). Telescopic cranes are often applied during short-term construction projects. These type of cranes are not lift as fast as self-erecting cranes. However, telescopic cranes are around 24% cheaper in comparison with self-erecting cranes (M.J. van Riel, 2016). This 24% is based on the minimal hourly rental price of a telescopic crane (€63,50) compared with the rental price of a self-erecting crane (€83,50). In addition, a telescopic crane can be assembled and dismantled within fifteen minutes.

Figure 6. Telescopic crane (Riel, 2013).

Tower crane

This type of crane is kind of balance crane, in which the jib suspends the load from the trolley and the counter-jib carries a counterweight, usually concrete blocks (Figure 7). A tower crane is fixed to the ground, which is often the best combination of height and lift capacity and is generally used for the construction of tall buildings (Norman Spencer, 2012). At the top of the tower there is a cabin were the crane operator controls the crane, however it is also possible to control the crane from the ground. In order to hook and unhook the loads, the crane operator works in close collaboration with a rigger. The crane operator and rigger are in close contact by using a walkie-talkie and hand signals. Tower cranes have a lifting capacity from 3.1 tons until 20 tons (Riel, 2013). A telescopic crane is usually used to assemble the tower crane, and the tower crane can be used to lift smaller cranes to the roof of a project. The assemble and dismantle time of the tower crane is often long, which makes is more expensive. In addition, the location of the crane should be chosen very accurate, because the crane cannot be moved easily to another location.

Figure 7. Tower crane (Spek, 2009).

During residential construction projects, mobile cranes are used; usually self-erecting and telescopic cranes. Crawler cranes will be used when the residential project has a prefabricated frame. Dura Vermeer Equipment Service in Haaften has tower cranes under own management, while mobile cranes are hired from subcontractors. The types of cranes have different boom movements, so they cannot lift weights everywhere in the crane range. When modelling a type of crane in a 3D environment, it is important to understand where the crane cannot lift anything. Figure 8 shows the areas where the self-erecting crane and tower crane cannot lift anything, which is visualized by using a red colour. Figure 9 visualizes the areas where the crawler crane and telescopic crane cannot lift anything.
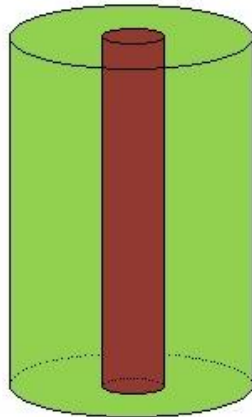
Figure 8. Modelled visualization
self-erecting crane / tower crane.
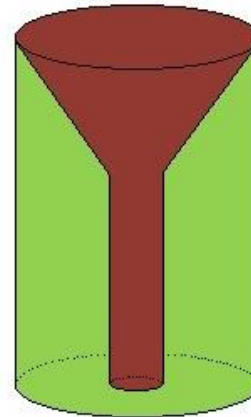
Figure 9. Modelled visualization
crawler crane / telescopic crane.

Important parameters to determine the amount and type of cranes are the weight of the lifted elements, location of crane(s), jack distances, dimensions, rental price, load capacity and the lift range of the crane. In addition, the storage and mounting location are also important parameters. The crane location is determined by using construction site plans and crane specifications are obtained from the subcontractor who provides the cranes. Often, the lift speed is decisive for the construction time of a project, which is also dependent on the crane operator and the construction workers. The most important activities concerning crane usage are placing and filling the concrete hollow-core slabs (floors). Construction cranes are also used to lift limestone elements, brickwork, cellular concrete elements, window frames and scaffolding equipment. Mounting the prefabricated roof panels is less important for crane usage, because they are outsourced to the subcontractor and are light building elements.

During the residential project of seven dwellings in Drunen, the Spierings SK377-AT3 self-erecting crane has been deployed for around 80% of the crane hours (Riel, 2013). However, the type of crane deployment is highly dependent on the choice of the construction site engineer. The construction site engineer can determine the crane deployment based on usability or from a financial perspective. It is important to make the right decisions in order to minimize the crane deployment hours and finally the rental costs. The minimal rental price of the self-erecting crane SK377-AT3 is €83,50 per hour. When decrease the total crane hours with 10 hours, a total of €835,- can be saved. Nowadays, these decisions are highly dependent on the experience of the construction site engineer, which results in the usage of different types of cranes and possibly too high rental costs of the crane. In addition, there are minimum hours to rent a crane, which can also affect the choice of crane type.

3.2.3 Crane speed

By using a construction crane, the storey floors of 7 dwellings can be placed in one day (eight hours), in which one storey consists of ten concrete hollow-core slabs. In addition, the storey floors can be filled for fifteen until twenty dwellings in one day. All limestone elements can be lifted for seven dwellings in one day. The window frames for seven dwellings can be placed within one day. A self-erecting crane is assembled and dismantled within forty minutes, and a telescopic crane within fifteen minutes.

3.2.4 Inefficient crane deployment

Optimal crane utilization is very important, because the rental of cranes is very expensive. Delays may occur when a crane is located on a wrong place, so the crane should be moved. It can happen that the crane is located at the transport road or the crane cannot lift the building elements concerning their range and/or load capacity. In addition, delays may occur when the crane operator does not fulfil the instructions of the construction site engineer. The crane operator must be on the correct location, which is determined by the construction site engineer. Other factors, which cause delays, are the transport of material and environmental factors, such as parking within the lift range of the crane. It is important to solve these issues in advance. Safety measures must be taken into account when crane operations are deployed, such as general safety measures (helmet, construction shoes, safety glasses) and stamping on a stable underground. In addition, the lift range must be shielded to the public, the machinist should have an expertise certificate and safety equipment during the lifting of elements is required. Chains are required when concrete hollow-core slabs are lifted. Lifting the brickwork needs that the bricks are covered with foil. When limestone elements are lifted, it is required to use a safety net. When a pallet hook is used, a safety belt on the hook is mandatory.

3.2.5 Crane optimization tool

Within Dura Vermeer Bouw Rosmalen B.V. no specific crane deployment tool is used. Own experience, crane specifications, construction site plans and photos of the construction site are used to determine the crane deployment of residential projects. When there are doubts concerning crane deployment, an expert of the subcontractor is asked to give advice about crane deployment. The respondents agree that a crane optimization tool can contribute to a more efficient crane utilization. Lift moments should be deployed more efficiently, which finally can save thousands of euros.

4. Observations

Within three days, observations were held to gather more information about crane utilization in practice. These observations were done within the project "Riet Park", which is

located in Rosmalen, the Netherlands. The project consists of twenty semidetached dwellings with a site area of 8.750 m² and a total gross floor area of 5.200 m². The observations were based on tracking the lifting activities of the crane. Within this project, the SK377-AT3 self-erecting crane was deployed for several activities. The crane is showed in Figure 10. The observed building activities are further elaborated below.

Figure 10. Self-erecting crane SK377-AT3 (Simons, 2016).

Limestone elements

The limestone elements were lifted by using the crane with a limestone clamp, which is shown in Figure 11. Within one clamp, ten limestone elements can be placed on the final location. During the observation, each limestone element has the dimensions

120x538x997mm and a weight of 119 kg each. A full clamp weighs around 1.450 kg, of which the clamp weighs 260 kg. Two riggers were involved during hooking and unhooking of the elements; one at the material storage and one at the final location. The total average time to place limestone elements on the final location was determined based on thirty crane lifts. The measurements are shown in Appendix 2 in Table A2.1. It takes in total around 1 minute and 40 seconds to place one full clamp with limestones on the final location. This total time per full clamp can be divided into hooking (30 sec.), flight (20 sec.), unhooking (30 sec.) and flight (20 sec.).

Figure 11. Limestone elements (Simons, 2016).

Brickwork

The brickwork was lifted by using the crane with a brick forceps, which is shown in Figure 12. Within one forceps, four-hundred bricks can be placed on the final location. A full clamp weighs around 930 kg, of which the forceps weighs 170 kg. One rigger was involved during hooking and unhooking of the bricks, who walked up and down. The total average time to place brickwork pallets on the final location was determined based on twenty crane lifts. The results of this observation are shown in Appendix 2 in Table A2.2. It takes in total around 3 minutes to place one forceps with bricks on the final location. These 3 minutes can be divided into hooking (25 sec.), flight (20 sec.), unhooking (1 min. 55 sec.) and flight (20 sec.).

Figure 12. Brickwork (Simons, 2016).

Cellular concrete elements

The cellular concrete elements were lifted by using the crane with lifting belts, which is shown in Figure 13. During one lift, ten cellular concrete elements can be placed on the final location. Each cellular concrete element has the dimensions 2.600x750x70mm and a weight of 82 kg each. A full clamp weighs 820 kg, of which the weight of the belts can be neglected. Two riggers were involved during hooking and unhooking of the elements; one at the material storage and one at the final location. The total average time to place the elements on the final location was determined based on twenty crane lifts. The measurements are visualized in Appendix 2 in Table A2.3. It takes in total 1 minute and 40 seconds to place one pallet with elements on the final location. This total time per lift can be divided into hooking (30 sec.), flight (20 sec.), unhooking (30 sec.) and flight (20 sec.).

Figure 13. Cellular concrete elements (Simons, 2016).

The limestone elements, brickwork and cellular concrete elements are modelled as `IfcWallStandardCase`. Their geometric representation is given by the `IfcProductDefinitionShape,` which gives multiple geometric representations. These geometric representations are a two-dimensional open curve defining the axis of each standard wall and a swept solid representation, which defines the three-dimensional shape of each wall. In addition, `IfcLocalPlacement` gives the placement of each wall. The IFC data of the placement and geometric representation of a limestone element is shown in Table 2. The crane observations showed that the limestone elements, brickwork and cellular elements are lifted per pallet or small amounts. In the IFC-model these building elements are modelled as large parts, therefore they do not match what should be lifted by using the crane.

Table 2. Placement and geometric representation limestone element.

Placement	#161= IFCLOCALPLACEMENT(#120,#160);
Geometric representation	#167= IFCSHAPEREPRESENTATION(#96,'Axis','Curve2D',(#165)); #185= IFCSHAPEREPRESENTATION(#98,'Body','SweptSolid',(#175)); #188= IFCPRODUCTDEFINITIONSHAPE($,$,(#167,#185));
Element type	#192= IFCWALLSTANDARDCASE('00rpqOXJTEIfSD2ORXlo2p',#41,'Basic Wall:NLRS_22_WA_kzs element dragend woningscheidend 120 CS12_gen:835755',$, 'Basic Wall:NLRS_22_WA_kzs element dragend woningscheidend 120 CS12_gen:755007',#161,#188,'835755');

Concrete hollow-core slabs

First, the hollow-core slabs were placed by using the crane with a floor clamp, which is visualized in Figure 14. During one lift, one concrete-hollow slab can be placed on the final location. Within this project, most hollow-core slabs have the dimensions 7.600x1.200x200mm and a weight of 2.809 kg each. A floor clamp with one hollow-core slab weighs around 3.289 kg, of which the clamp weighs 480 kg. Three riggers were involved during the placement of the floors; one at the material storage and two at the final location. The total average time to place the slabs on the final location was determined based on seven crane lifts. The results of this observation are visualized in Appendix 2 in Table A2.4. It takes in total 3 minutes and 30 seconds to place one hollow-concrete slab on the final

location. This total time per lift can be divided into hooking (50 sec.), flight (25 sec.), unhooking (1 min. 55 sec.) and flight (20 sec.).

Figure 14. Concrete hollow-core slabs
(Simons, 2016).

The concrete hollow-core slabs are modelled as `IfcSlab`. The `IfcProductDefinitionShape` gives their geometric representation, which contains a swept solid representation. A swept solid representation defines the three-dimensional shape of each slab. In addition, `IfcLocalPlacement` gives the placement of each slab. The IFC data of the placement and geometric representation of a slab is visualized in Table 3. The crane observations showed that the concrete hollow-core slabs are lifted per slab. The floors within the IFC-model are modelled as whole parts per storey, therefore they do not match what should be lifted by using the crane.

Table 3. Placement and geometric representation concrete hollow-core slab.

Placement	#1134= IFCLOCALPLACEMENT(#143,#1133);
Geometric representation	#1183= IFCSHAPEREPRESENTATION(#98,'Body','SweptSolid',(#1182)); #1185= IFCPRODUCTDEFINITIONSHAPE($,$,(#1183));
Element type	#1187=IFCSLAB('00rpqOXJTEIfSD2ORXlo3L',#41,'Floor:NLRS_23_FL_kanaalplaat 200_gen:835789',$,'Floor:NLRS_23_FL_kanaalplaat 200_gen',#1134,#1185, '835789',.FLOOR.);

After the hollow-core slabs are placed, the grooves have to be filled with concrete. A crane with a concrete bucket is used for pouring this concrete, which is shown in Figure 15. A full concrete bucket weighs around 1.850 kg, of which the bucket weighs 350 kg. Four riggers were involved during filling the grooves of the floors; one at the material storage and three at the final location. It takes in total 57 minutes to fill the grooves from 204 m² concrete hollow-core slabs. In total, around 3.450 kg concrete is used to fill the grooves of these floors. The grooves of the floors are not visualized within the IFC-model.

Figure 15. Fill concrete
hollow-core slabs (Simons, 2016).

Window frames
The window frames were placed by using the crane with lifting chains, which is shown in Figure 16. During one lift, one window can be placed on the final location. Each window frame has other dimensions and weights. Each square meter window weights around 50 kg and the weight of the lifting chains can be neglected. Four riggers were involved during the

placement of the window frames; one at the material storage, two at the second floor and one at the final location. The total average time to place the window frames on the final location was determined based on five crane lifts. The measurements of this observation are shown in Appendix 2 in Table A2.5. It takes in total 4 minutes and 30 seconds to place one window frame on the final location. This total time per lift can be divided into hooking (1 min. 40 sec.), flight (40 sec.), unhooking (1 min. 40 sec.) and flight (30 sec.).

Figure 16. Window frames (Simons, 2016).

The window frames are modelled as IfcCurtainWall, which is represented by four types of IfcMember. IfcProductDefinitionShape gives the geometric representation of each IfcMember, which contains of a swept solid representation. A swept solid representation defines the three-dimensional shape of each IfcMember. IfcLocalPlacement gives the placement of each IfcMember, which is based on the placement of IfcCurtainWall. The IFC data of the placement and geometric representation of a window frame is visualized in Table 4. The crane observations showed that each window frame is lifted separately. The window frames within the IFC-model are modelled in four parts (IfcMember). It is possible to compose these four parts, in which the whole window frame can be obtained.

Table 4. Placement and geometric representation window frame.

Placement	#2068= IFCLOCALPLACEMENT(#125,#2067); #2074= IFCLOCALPLACEMENT(#2068,#2073); #2170= IFCLOCALPLACEMENT(#2068,#2169); #2260= IFCLOCALPLACEMENT(#2068,#2259); #2307= IFCLOCALPLACEMENT(#2068,#2306);
Geometric representation	#2093= IFCSHAPEREPRESENTATION(#98,'Body','SweptSolid',(#2083)); #2096= IFCPRODUCTDEFINITIONSHAPE($,$,(#2093)); #2098= IFCMEMBER('0k4qeubkXBwOb$RolzGIUo',#41,'Curtain Wall:NLRS_31_CW_Merk A:980104',$,'Curtain Wall:NLRS_31_CW_Merk A:980104',#2074,#2096,'979907'); #2188= IFCSHAPEREPRESENTATION(#98,'Body','SweptSolid',(#2178)); #2191= IFCPRODUCTDEFINITIONSHAPE($,$,(#2188)); #2193= IFCMEMBER('0k4qeubkXBwOb$RolzGIUr',#41,'Curtain Wall:NLRS_31_CW_Merk A:980108',$,'Curtain Wall:NLRS_31_CW_Merk A:980108',#2170,#2191,'979908'); #2272= IFCSHAPEREPRESENTATION(#98,'Body','SweptSolid',(#2268)); #2275= IFCPRODUCTDEFINITIONSHAPE($,$,(#2272)); #2277= IFCMEMBER('0k4qeubkXBwOb$RolzGIUq',#41,'Curtain Wall:NLRS_31_CW_Merk A:980104',$,'Curtain Wall:NLRS_31_CW_Merk A:980104',#2260,#2275,'979909'); #2319= IFCSHAPEREPRESENTATION(#98,'Body','SweptSolid',(#2315)); #2322= IFCPRODUCTDEFINITIONSHAPE($,$,(#2319)); #2324= IFCMEMBER('0k4qeubkXBwOb$RolzGIUt',#41,'Curtain Wall:NLRS_31_CW_Merk A:980104',$,'Curtain Wall:NLRS_31_CW_Merk A:980104',#2307,#2322,'979910');
Element type	#2069= IFCCURTAINWALL('0k4qeubkXBwOb$RolzGIUp',#41,'Curtain Wall:NLRS_31_CW_Merk A:979906',$,'Curtain Wall:NLRS_31_CW_Merk A:986175',#2068,$,'979906');

The sliding doors are modelled as `IfcWindow`, in which `IfcProductDefinitionShape` gives the geometric representation. `IfcProductDefinitionShape` contains a mapped representation, which is referring to a representation map. However, information within this referenced map is missing, as a result the sliding doors are not visualized within the three-dimensional visualization. The IFC data of the placement and geometric representation of a sliding door are shown in Table 5.

Table 5. Placement and geometric representation sliding door.

Placement	#23730= IFCLOCALPLACEMENT(#125,#23729);
Geometric representation	#23723= IFCSHAPEREPRESENTATION(#98,'Body','MappedRepresentation',(#23721)); #23725= IFCPRODUCTDEFINITIONSHAPE($,$,(#23723));
Element type	#23731= IFCWINDOW('1wO1DsiDPCVh_lKlIzcJ65',#41,'NLRS_31_WI_Aluminium schuifpui2:31_schuifpui_aluminium:1058185',$,'31_schuifpui_aluminium',#23730,#23725,'1058185',2578.00000000259,2524.00000000262);

Finally, there are other construction activities which need crane utilization; such as lifting scaffolding works, mounting prefabricated roof panels and dormers. However, scaffolding works is often not included in the 3D model and prefabricated roof panels are outsourced to the subcontractor. The self-erecting crane needs to be moved as little as possible, because it takes around thirty minutes to assemble and dismantle the crane. This assemble and dismantle time is based on the measurements during the observations.

5. Tool development

The results of the literature review, interviews and observations are used for the development of a simulation tool. The aim of the tool is to optimize the crane deployment during the preparation of residential construction projects. In section 5.1 of this chapter the simulation tool is explained in general. Section 5.2 explains the data files which are implemented within the tool. Thereafter, the Python code is further elaborated in section 5.3 by using a Flow Chart diagram. The starting point of the simulation tool is explained in section 5.4. Finally, the known limitations of the tool are elaborated in section 5.5.

5.1 Simulation tool

The tool should assist the crane planner during the determination of crane deployment. First, the position of the crane and material storage can be determined by using the three-dimensional Cartesian coordinate system, with origin O and axis lines *X*, *Y* and *Z* (Figure 17). Based on the crane profile and an IFC-model of a residential construction project, the lift duration of the window frames and floors is calculated. The lift duration is based on horizontal, vertical and rotation speed of the crane by using the Cylindrical coordinate system, with origin O and Axis A, and longitudinal axis L (Figure 18). In addition, it is determined whether the window frames and floors can be lifted, based on the weight of each building element, the capacity of the material storage and the capacity of the crane. The crane profile consists of crane dimensions, their ranges, capacity and lift speed in combination with hook and unhook time. The IFC-model is important to determine the (material)name and volume or area per building element, which is further elaborated in section 5.2. In addition, the IFC-model is used for the three-dimensional visualization, in which each element has a pick point. The pick points are located at the top centre of each element, which is visualized in Figure 19. The crane needs these pick points to determine the distances to calculate the total lift duration.
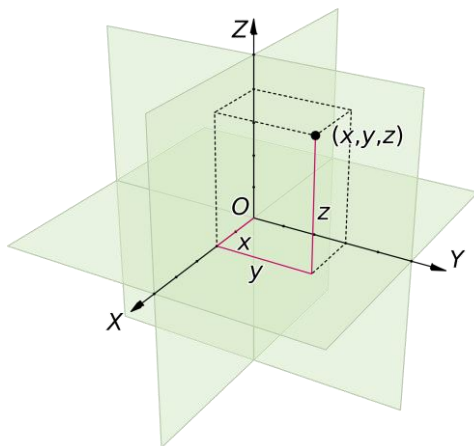
Figure 17. 3D Cartesian coordinate system (Stolfi, 2009).
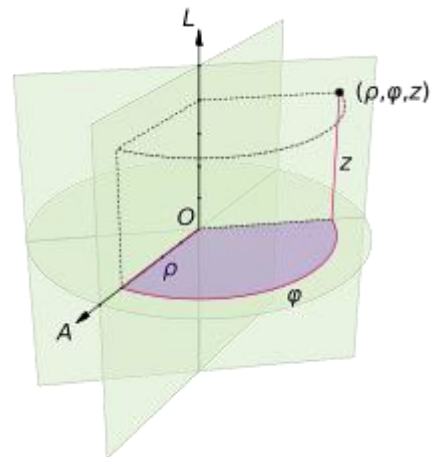
Figure 18. Cylindrical coordinate system (Stolfi, 2009).
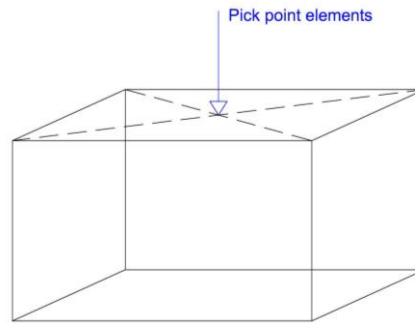
Figure 19. Pick point building elements.

By using the tool, analyses of the window frames and floors are carried out. Simulations are performed for different combinations of the crane location and the material storage location. For example, when there are three possible crane locations and three possible material storage locations, this results in nine different combinations shown in Table 6. For each combination, it is calculated if building elements can be lifted and what their total lift duration is. Finally, the most optimal combination of crane location and material storage location is selected, in which all building elements can be lifted and the total lift duration is as low as possible. This way of analysis is called brute-force analysis, which goes through all possible solutions extensively. This analysis gives the most optimal answer, however it is inefficient when the number of possible combinations increases (Wilson, 2012).

Table 6. Example different combinations.

Location crane	Location material storage	Combination
A	1	A-1
A	2	A-2
A	3	A-3
B	1	B-1
B	2	B-2
B	3	B-3
C	1	C-1
C	2	C-2
C	3	C-3

Finally, the simulation tool represents the amount of window frames (`IfcCurtainWall` and `IfcWindow`) and floors (`IfcSlab`), which can be lifted, are out of range or are too heavy for a specific location of the crane and material storage (Figure 20). In addition, the total lift duration is obtained for the window frames and floors which can be lifted (Figure 21). The walls are not included within Figures 20 and 21, because lifting these elements as whole building elements is not reality based. A three-dimensional model also shows which elements can be lifted, are out of range or are too heavy (Figure 22). Building elements which can be lifted have a green colour, out of range an orange colour and too heavy a red colour. In this three-dimensional visualization, the walls are also visualized. Finally, the lifting of building elements and their lift duration is shown for each building element in Figure A3.1 in Appendix 3. The building elements which are integrated are `IfcCurtainWall` (windows), `IfcWindow` (sliding doors), `IfcSlab` (floors) and `IfcWallStandardCase` (walls).
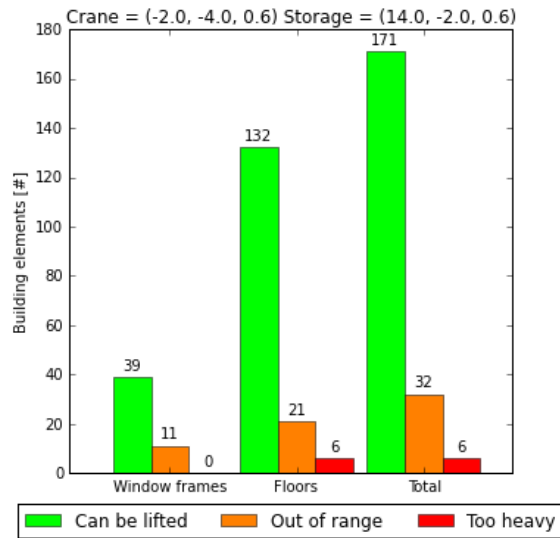
Figure 20. Bar Chart lifted elements.
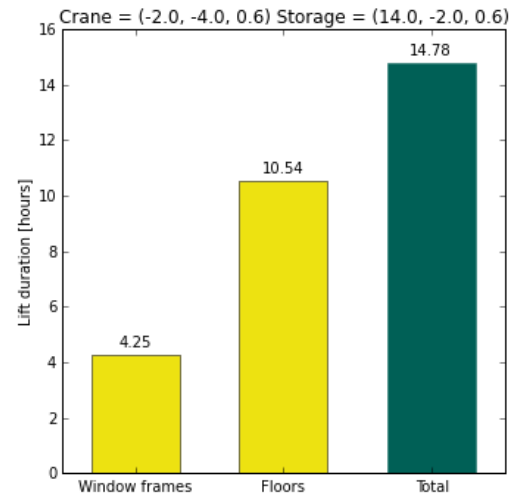
Figure 21. Bar Chart total lift duration.
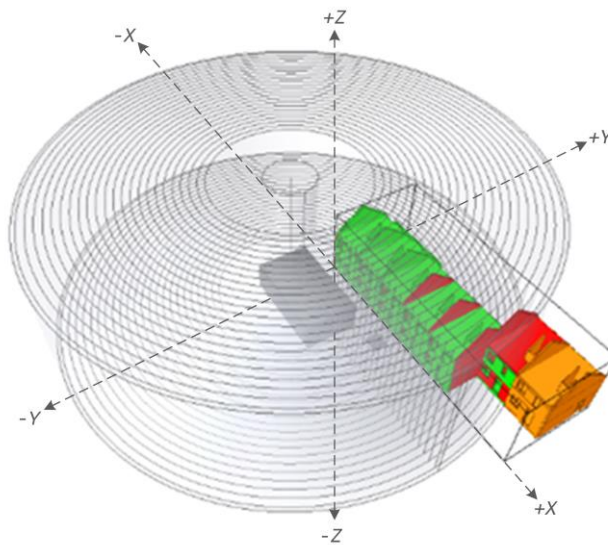
Figure 22. 3D visualization of the tool.

5.2 Data files

Two types of data files are imported within the simulation tool; one IFC2x3 file and five CSV-files. An overview of these imported data files are shown in Table 7. Important parameters which are obtained from the IFC-file are the element type, (material)name and quantity units like area or volume. Table 8 shows an overview of the building elements and their parameters. The material name and the name of each element type are based on the Dutch Revit Standards, which is a uniform set of arrangements for working with Revit (Ham, Riet, Tas, & Wieringa, 2016). Within this Dutch Revit Standards, the NL/Sfb system is included. The NL/SfB system is the Dutch version of the internationally recognized SfB classification, especially aimed as element coding methodology for the construction industry (STABU, 2016). Material name consists of at least NLRS (Netherlands Revit Standards), classification code according to NL/Sfb table 3 (STABU, 2016) and the description of material. For example, the material name for a limestone element is `NLRS_f1_kalkzandsteen`. Description, properties, generic of the manufacturer's name and distributor's name are optional for the material name. The name of each element type consists of at least NLRS, classification code according to NL/Sfb table 2 (STABU, 2016), Revit category and

description. For example, the name of a window frame can be `NLRS_31_CW_Merk`. Some other Revit categories are Floors (FL), Windows (WI) and Curtain Walls (CW). The material name and quantity units can be obtained according to a bottom up principle within the IFC-file. For example, the quantity unit area for a window frame (#2069) can be obtained from `IfcRelDefinesByProperties` (#2484) to `IfcPropertySet` (#2482) and finally `IfcPropertySingleValue` (#2452), which is shown in Appendix 4 in Table A4.1. Table A4.1 until Table A4.7 in Appendix 4 displays the IFC data for a window frame (Table A4.1), sliding door (Table A4.2), concrete hollow-core slab (Table A4.3), waffle slab (Table A4.4), limestone element (Table A4.5), brickwork (Table A4.6) and cellular concrete element (Table A4.7). In addition, the IFC-file contributes to the visualization of the residential construction project.

Table 7. Overview data files.

Type of data file	Name	Provided information
IFC2X3 file	Project_Drunen.ifc	3D model and integrated information
CSV-file	SK377-AT3 dimensions.csv	Length, width, height, length from backside of the crane
CSV-file	SK377-AT3 ranges.csv	Ranges, load capacity per range, lift height of the crane
CSV-file	SK377-AT3 speed.csv	Horizontal, vertical and rotation speed per load capacity of the crane
CSV-file	hook and unhook time.csv	The hook and unhook time per element type
CSV-file	material specifications.csv	Material densities, weight of equipment of the crane, length and width dimensions of the floors

Table 8. Building elements and their parameters.

Building element	Element type	(*Material*)name	Unit
Window frame	`IfcCurtainWall`	NLRS_31_CW_Merk	m²
Sliding door	`IfcWindow`	NLRS_31_WI_Aluminium	m²
Concrete hollow-core slab	`IfcSlab`	NLRS_23_FL_kanaalplaat	m³
Waffle slab	`IfcSlab`	NLRS_23_FL_ribcassettevloer	m³
Limestone element	`IfcWallStandardCase`	*NLRS_f1_kalkzandsteen*	m³
Brickwork	`IfcWallStandardCase`	*NLRS_g2_baksteen*	m³
Cellular concrete element	`IfcWallStandardCase`	*NLRS_f4_cellenbeton*	m³

Five CSV-files are imported within the simulation tool, of which the first file is named "SK377-AT3 dimensions" (Riel, 2013). This file consists of the length, width, height and length from backside of the crane in meters (Table A5.1 in Appendix 5). The second CSV-file "SK377-AT3 ranges" (Riel, 2013) consists of lift ranges of the crane in meters, their load capacity per range in kg and the maximum lift height in meters (Table A5.2 in Appendix 5). The third file is named "SK377-AT3 speed" (Riel, 2013), which consists of a horizontal, vertical and rotation speed per load capacity of the crane (Table A5.3 in Appendix 5). The fourth CSV-file "hook and unhook time" is based on hook and unhook time per element type, which is added to the lift time based on (material)name (Table A5.4 in Appendix 5). The hook and unhook time is based on the measurements of the observations, which is shown in Appendix 2. Finally, the fifth CSV-file "material specifications" consists of weight per m³ or

m² of each element type (Boxtel, 1995) (Belgische Baksteenfederatie, 2008) (NCV, 2016) (Vin, 2016) (VBI, 2016) (Betonson Prefab B.V. , 2016), which is multiplied with the quantity measures of the IFC-file. In addition, this file contains weights of the equipment of the crane (Nemaco Holding B.V., 2016) (Van Eck Verreikerverhuur, 2016) (Riel, 2013), the length and width dimensions (VBI, 2016) (Betonson Prefab B.V. , 2016) of the floors (Table A5.5 in Appendix 5).

5.3 Python code

IPython is used for the development of the simulation tool, which uses IfcOpenShell (http://notebook.ifcopenshell.org/hub/). IfcOpenShell is an open source software library for programming with the IFC file format (Krijnen, 2016). In addition, Open Cascade Technology is used within the Notebook platform. OCCT is an open source software development platform for 3D CAD, computer-aided manufacturing (CAM) and computer-aided Engineering (CAE). The tool is developed by using Python 3.0 programming language (Python Software Foundation , 2016), which is easy to read and to use. With the aid of a Flow Chart diagram in Figure 23, the whole main Python code and its modules is visualized. A module bundles functions into manageable parts and containers. The tool consists of three main processes; the processing of elements, determination if elements can be lifted and the calculation of the total lift duration of each building element (Figure 23).

Based on the processing of elements process, a list is created with information for each `IfcWallStandardCase`, `IfcSlab`, `IfcWindow` and `IfcCurtainWall`. This list contains the following information for each building element: GUID, Element type, Element weight [kg], Flight index, Capacity crane [kg], Capacity material storage [kg], Lifted? and Lift duration [min]. A part of this list is shown in Figure A3.1 in Appendix 3.

The second main process determines if elements can be lifted, by using the weight of each building element, the capacity of the crane and capacity of the material storage. The weights of the building elements are calculated by multiplying the quantity measures of the IFC-file "Project_Drunen.ifc" with the material densities in the file "material specifications". In addition, the weight of crane equipment, which is retrieved from the file "material specifications", is added to the element weight. The capacity of the crane is based on the file "SK377-AT3 ranges". Each range has a different capacity, in which the higher the radius the smaller the capacity. However, it is often the case that the capacity in the first range is 0 kg. The SK377-AT3 self-erecting crane has a capacity of 0 kg in range 1 (0 to 3.5 meters), 7500 kg in range 2 (3.5-10.5 meters), 7030 kg in range 3 (10.5 to 11.5 meters) etc. The capacity of the material storage is dependent on the crane range where it is situated, also based on the file "SK377-AT3 ranges".

Finally, the third main process calculates the total lift duration of each building element for the elements, which can be lifted. The lift duration of each building element is calculated by multiplying the horizontal-, vertical- and rotation distance with the horizontal- vertical- and rotation speed based on the file "SK377-AT3 speed". The distances are obtained based on Open Cascade Technology. In addition, the hook and unhook time, which is retrieved from the file "hook and unhook time", is added to the total lift duration. The whole main code and its modules is shown in Appendix 6 and 7.

Process elements

Start

Import:
Open Cascade modules
IfcOpenShell library
CSV-files
other modules (.py)

open IFC-file project

Create list of building element properties within Python code

Is element type [*elem*] an IfcWallStandardCase, IfcSlab, IfcWindow or IfcCurtainWall?

Is *elem* an IfcCurtainWall and consists of IfcMembers?

Create compound of IfcMembers

Get XYZ-coordinates min/max and create Bounding Box of each *elem*

Is relation *elem* IfcRelDefinesByProperties?

Is name IfcPropertySet "Dimensions"?

Is property in IfcPropertySet an IfcPropertySingleValue?

Is propertyname == "Area" or "Volume"?

Get value "false"

Get density materials [*Den*] and weight crane equipment [*WcE*] from "material specifications.csv"

Is *Mn* in *elem* name?

Get value "true"

Is *Mn* in IfcMaterial?

Get quantity values "Area" and "Volume" [*Quan*]

Contains *elem Mn*? (from "hook and unhook time.csv")

Calculate weight [*Wg*] each *elem*:
(*Quan* * *Den*) + *WcE*

Calculate total hook and unhook time [*HuT*]

Get (material)name [*Mn*] from "material specifications.csv"

Get IfcMaterial

Is relation *elem* IfcRelAssociatesMaterial.RelatingMaterial?

Is *elem* IfcSlab?

Append "GUID", "element type", "element weight", "pickpoint element", "shape element" and "total (un)hook time" to list of building element properties within Python code

Cut floors based on floor width and length from "material specifications.csv"

Get properties "element weight" and "pickpoint element" from cutted floors

More *elem*?

Draw Bounding Box around entire IFC-model

User input:
XYZ coordinates crane location and material storage

Set location crane, ranges and material storage based on user input

Lift duration

add value "Lift duration [min]" in "Output data: Location crane = XYZ Location material storage = XYZ.csv"

More *elem*?

Create a barchart "Lift duration: Location crane = XYZ Location material storage = XYZ.png"

End

Set value "Lift duration [min]" to "None"

Calculate total lift duration each element:
(*Hd* * *Hor*) + (*Vd* * *Ver*) + (*Rd* * *Rs*) + *HuT*

Get horizontal-[*Hor*], vertical-[*Ver*] and rotation speed [*Rs*] from "SK377-AT3 speed.csv"

Get horizontal-[*Hd*], vertical-[*Vd*] and rotation distance [*Rd*], based on Open Cascade

Is capacity crane ranges ≥ *Wg*?

Lifted elements

add value "lifted?" in "Output data: Location crane = XYZ Location material storage = XYZ.csv"

More *elem*?

3D visualization project: show crane, ranges and material storage

Create a barchart "Lifted elements: Location crane = XYZ Location material storage = XYZ.png"

Set color building element to red and value "lifted?" to "too heavy"

Set color building element to orange and value "lifted?" to "out of range"

Set color building element to green and value "lifted?" to "can be lifted"

Is *Wg* > *CbE* or *Wg* > *CmS*?

Is *CbE* "None"?

Capacity building element [*CbE*] is based on "SK377-AT3 ranges.csv"

Capacity building element [*CbE*] = None

Create list of crane flights and their capacities within Python code (based on "SK377-AT3 ranges.csv")

Is location material storage within crane flights?

Capacity material storage [*CmS*] is based on "SK377-AT3 ranges.csv"

Is location building element within crane flights?

Capacity material storage [*CmS*] = 0

Draw crane with ranges based on "SK377-AT3 dimensions.csv" and "SK377-AT3 ranges.csv". In addition, draw material storage.

Create file "Output data: Location crane = XYZ Location material storage = XYZ.csv"

Figure 23. Flow Chart diagram Python code.

5.4 Starting point of the tool

Before the locations of the crane and material storage can be determined, the starting point of the tool should be clear. The *XYZ*-coordinates 0.0, 0.0, 0.0 of the crane and material storage are established, which are based on meters. These starting points are at the corners of both the crane as the material storage and the Bounding Box. Figure 24, 25 and 26 are visualizing the starting points of both the crane (0.0, 0.0, 0.0) and the material storage (0.0, 0.0, 0.0). The dimensions of the crane are determined based on the input of CSV-file "SK377-AT3 dimensions". The material storage is modelled within the main code by using a length and width of 2 meters and a height of 0.001 meters. The ranges of the crane are modelled based on the input of CSV-file "SK377-AT3 ranges".
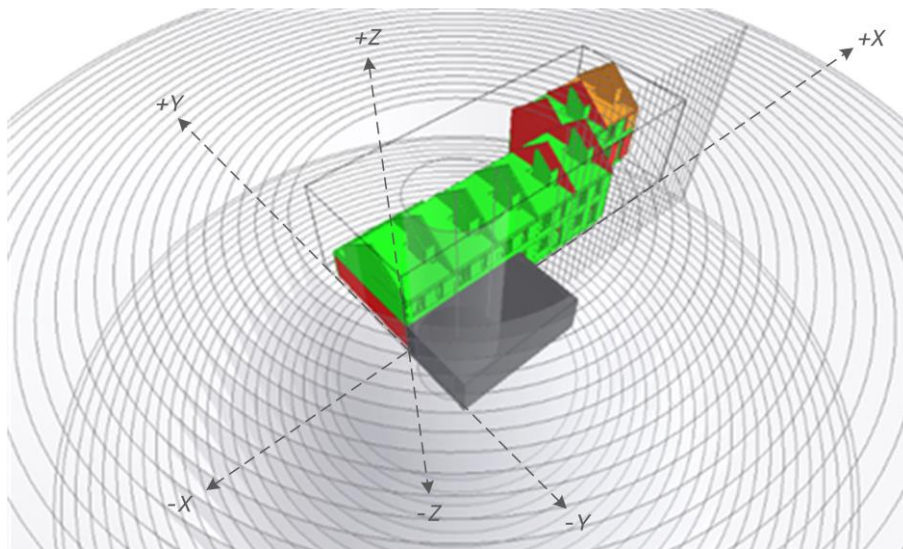
Figure 24. Top view starting points of the tool.
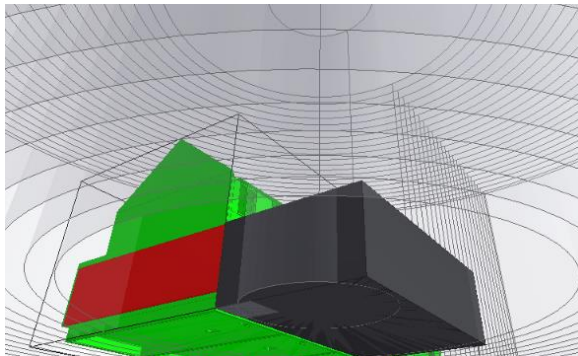
Figure 25. Elevation view starting points of the tool.
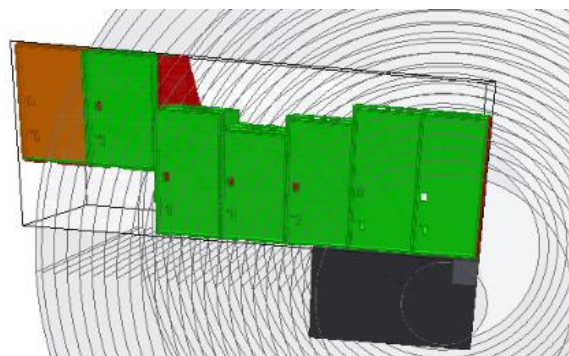
Figure 26. Bottom view starting points of the tool.

In addition, it is important to understand the direction of the *XYZ*-coordinates. Figure 24 shows these directions, in which the *X* and *Y* coordinates determine the horizontal movements, while the *Z* coordinates indicates the vertical movements.

5.5 Known limitations

The developed simulation tool prototype has limitations. As mentioned earlier, the wall building elements (`IfcWallStandardCase`) are not shown in the output graphs, because lifting of these elements as whole building elements is not reality based. These building elements like limestone elements, brickwork and cellular concrete elements are modelled as whole elements, while in reality they are lifted per pallet. From this point of view, more lifts

are needed which have approximately the same weight per lift. The floors within the IFC-model are modelled as whole parts per storey, however in reality they have smaller dimensions. The tool cuts these floors into smaller parts, based on the input of floor dimensions within CSV-file "material specifications". It is recommended to model the floors as LOD400, in which they are accurate in terms of size, shape, location, quantity and orientation with complete fabrication, assembly and detailed information (Spekkink, 2012). In addition, the grooves of the floors have to be filled with concrete by using a crane and a bucket, however these grooves are not modelled. The tool also does not take into account crane deployment for the mounting of prefabricated roof panels and dormers. The crane deployment for these roof panels and dormers are often outsourced to the subcontractor of the roofs and have a low weight. Crane deployment for lifting isolation packages will be neglected, because these elements have a very low weight. These limitations of the tool have much impact on the total lift duration, because the tool is only based on window frames and floors, while in reality there are more construction activities which need crane deployment. In reality, the total lift duration is higher, because there are more crane activities, such as the lifting of limestone elements, brickwork and cellular concrete elements.

The simulation tool does not take into account the environment of the construction site. There can be buildings on the construction site or nearby, or other objects such as trees. In addition, the construction site always has fixed dimensions and some building elements which are already lifted, can be barriers for elements which still needs to be lift. Usually, the construction site consists of scaffolding work, construction fences, site offices and construction roads. Aforementioned objects are not incorporated within the IFC-file, which can be stored under the entity `IfcSite`, however this entity is not widely used. Also stamping of the crane on a stable underground and other safety factors are not incorporated within the tool. In addition, the tool gives no error when the location of the crane and material storage are within the building area or when they are at the same position. It is also not possible to rotate the crane and material storage in the simulation tool. During each simulation of the tool, aforementioned environmental factors should be taken into consideration as much as possible. The lifted building elements and total lift duration per building element may not always be realistic, because not all environmental factors can be taken into account.

The reality based material storage is larger in comparison with the one in the tool and consists of many pick points. However, the implementation of such material storage requires many calculations, making the tool very complex. The tool is based on one type of self-erecting mobile crane, the SK377-AT3 (Riel, 2013). However, other type of self-erecting cranes can be imported by changing the input CSV-files "SK377-AT3 dimensions", "SK377-AT3 ranges" and "SK377-AT3 speed". Within this research only the self-erecting crane SK377-AT3 is taken into consideration, which cannot be rotated. Besides that, each crane has minimal rental hours, however this data is excluded from the tool. The tool suggests that all lifts of each building element type are carried out in sequence, however in reality this is not the case. The simulation tool is based on one location of the crane, in which it is not taken into account the movement of the crane to another location. The crane should be moved as little as possible, because the movement will take time, which costs money. Finally, analyses with the simulation tool are based on brute-force analysis. This type of

analysis is not very effective when many locations for the crane and material storage are possible, which makes it time-consuming.

As shown in this section, there are many parameters which must be taken into account. The developed tool focuses on the determination of the crane location, material storage location and calculates if elements can be lifted and what their total lift duration is.

6. Verification and validation

Within this chapter, the simulation tool is used for a residential construction project. First, the in- and output data of the simulation tool is verified in section 6.1. Within section 6.2 the tool is validated by implement a residential construction project within the tool.

6.1 Verification

As mentioned in section 5.2, one IFC-file and five CSV-files are imported within the simulation tool. The IFC-file of the residential construction project has one big shortcoming. The floors within the IFC-file are modelled as whole parts per storey, while in reality they have smaller dimensions. This problem is solved by cutting the floors in smaller parts within the Python code, based on floor dimensions within the CSV-file "material specifications". A fixed width and length is held for both concrete hollow-core slabs as waffle slabs, which is obtained from the suppliers documentation. The quantity measures area and volume within the IFC-file were compared with the measures within Revit Architecture. It can be concluded that the quantity measures within the IFC-file are correct.

The information of the CSV-files "SK377-AT3 dimensions", "SK377-AT3 ranges" and "SK377-AT3 speed" are obtained from the subcontractor of the crane. The (material)name in the CSV-file "hook and unhook time" is based on the IFC-file and the hook and unhook time is retrieved from the observations. The reliability of the observations can be taken in doubt, because seven lifts of the floors were measured and five lifts of window frames. However, when at least hundred measurements for both the lifting of the floors as the window frames are done, the hook and unhook time can be more reliable. These measurements should be carried out on different construction projects, in which different riggers and crane operators should be observed. Within this research, the hook and unhook times of current observations are implemented within the tool. In the CSV-file "material specifications", the (material)name is also based on the IFC-file. The material specifications within this fifth file (kg/m³, kg/m², length and width floors) are obtained from the supplier or subcontractor of the building elements. Finally, the equipment weights of the crane (e.g. (floor)clamp, forceps) within the "material specifications" file are obtained from the subcontractor of the crane.

During the development of the simulation tool, different tests were carried out by using the results of the quantity measures, weights, distances and speeds to verify the results. As mentioned before, the output table shows results for the element types `IfcCurtainWall`, `IfcWindow`, `IfcSlab` and `IfcWallStandardCase`. However, the results for `IfcWallStandardCase` are incorrect, because these elements are not lifted as whole building elements. Hence, the two output graphs are consisting of the results from `IfcCurtainWall`, `IfcWindow` and `IfcSlab`.

6.2 Validation

The simulation tool is validated by implement the IFC-file "Project_Drunen" within the tool. This residential project has already been built and is located in Drunen, The Netherlands. The project consists of seven terraced dwellings with two storeys each. The site area is 1.590 m² and the building block has a total gross floor area of 1.015 m². The building block has a maximum length of 36.24 meters and a width of 13.9 meters. The self-erecting crane SK377-AT3 was deployed during this project, which is a mobile crane with a boom length of 33

meters and a hook height of 20 meters. Without stamping, this crane has a length of 13.3 meters, a width of 2.6 meters and a height of 4 meters. When the crane is stamped, the width will become 7.5 meters instead of 2.6 meters.

The validation process consists of several parts. First, the as-built location of the crane and material storage is visualized on a construction site plan. In addition, other locations of the crane and material storage are determined and visualized. During the consideration of other locations, the environmental factors should be taken into account as much as possible. The fixed dimensions of the construction site are settled by using construction fences. Around the building block there is scaffolding work of 2 meters width, there are trees and there should be some space for site offices and construction roads. Secondly, the combinations of crane location and material storage location are simulated by using the tool. The results of the simulations are compared with the as-planned and as-built data of this project. The as-planned data shows how crane hours were planned before the project was built. The as-built data visualises the actually incurred hours of the crane. After the results are compared with each other, feedback is obtained from two construction site engineers. Finally, the combinations of crane location and material storage location are simulated again, in which the input data of the hook and unhook time are adjusted.

The project has already been built, whereby the as-built crane location and material storage location are known. Figure 27 and 28 shows the as-built crane location C1 and material storage location S1 of this project. The as-built location of the crane has *XYZ*-coordinates 14.6, -2.3, 0.6 and the as-built material storage location *XYZ*-coordinates 6.7, -5.1, 0.6. These *XYZ*-coordinates are measured in meters from the starting point of the tool (shown in section 5.4) to the upper left corner of each crane and material storage, which is shown by little circles in Figure 27 and 28. The self-erecting crane is stamped, which has a length of 13.3 meters and a width of 7.5 meters. The material storage has a length and width of 2 meters. The *X* and *Y* directions are also visualized in Figure 27 and 28. In addition, Figure 27 and 28 shows the other locations for the crane and material storage. There are two alternative locations for the crane and three for the material storage. Each Z-coordinate of the crane and material storage is 0.6, because the crane and material storage were located at level 0. The building model consists of brickwork under level 0, which results in a Bounding Box under level 0. Figure 27 and 28 also shows the construction fences, scaffolding work of 2 meters width and several trees.
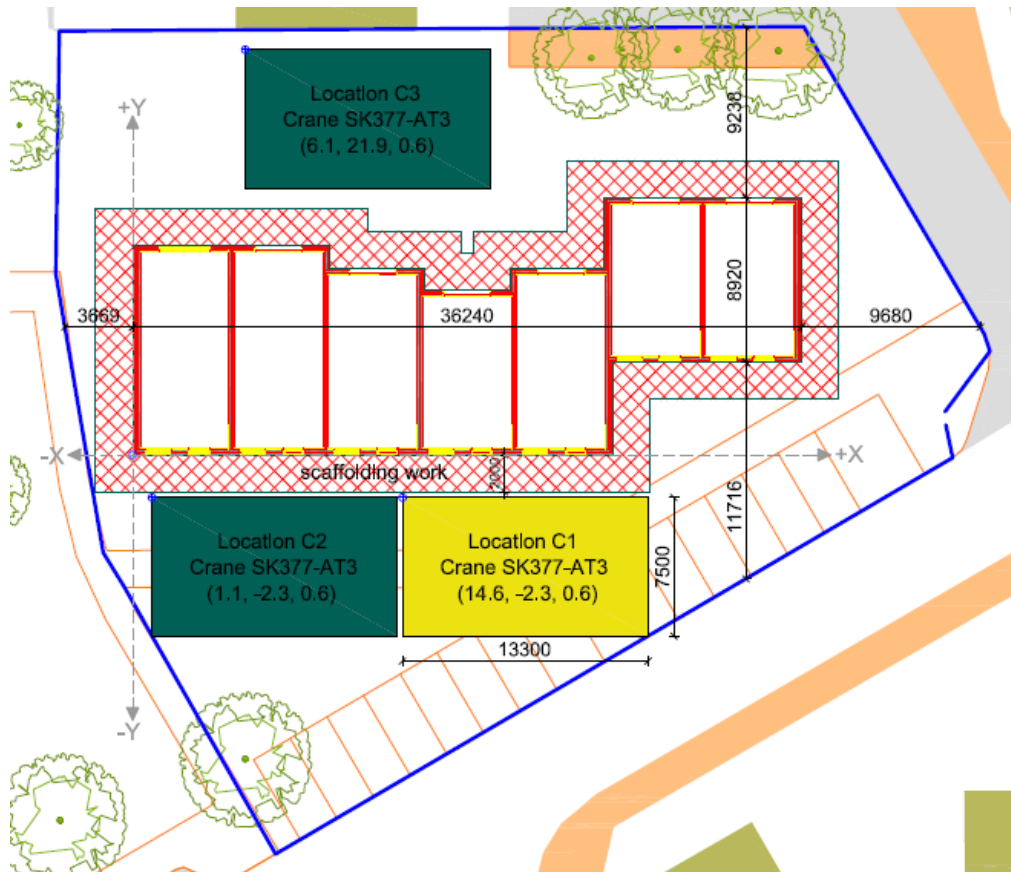
Figure 27. Crane locations.
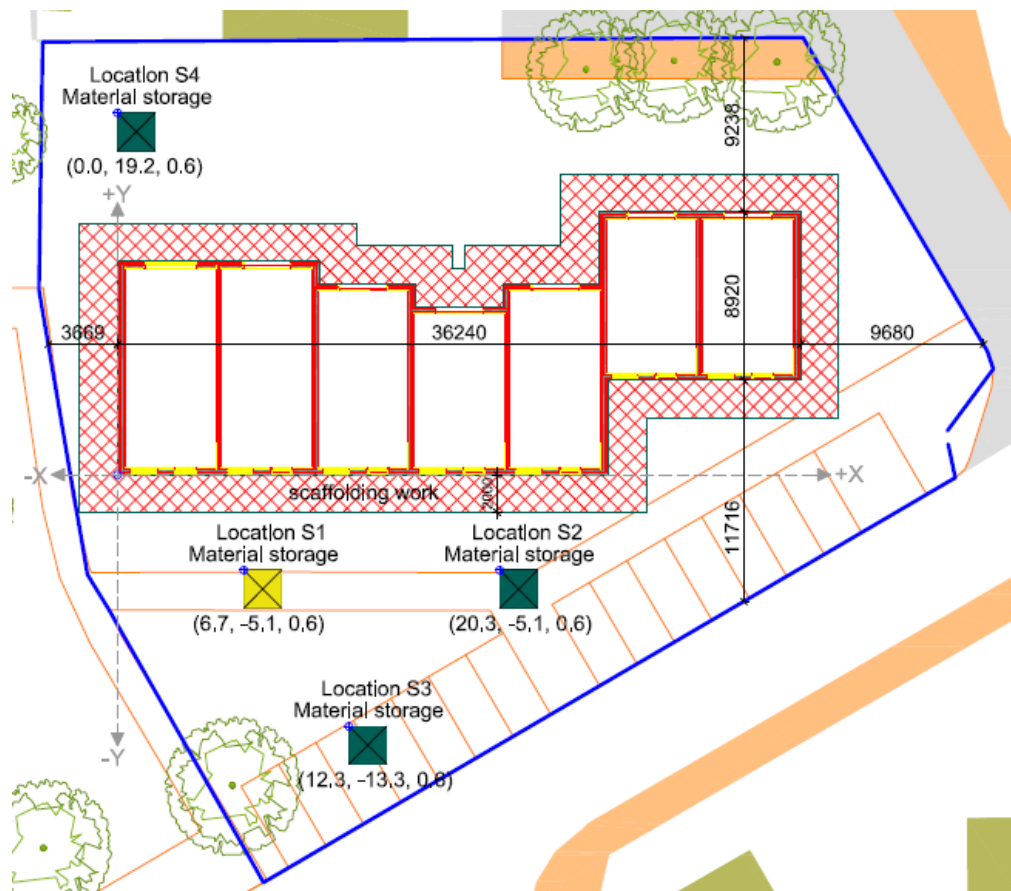
Figure 28. Material storage locations.

Location C1-S1 was chosen by the construction site engineer, because it was located in the middle of the seven dwellings, in which everything should be lifted. In addition, nearby the crane location, parking places had to be built. These parking places need rubble as underground, which can be used as construction road. Finally, there were several trees at the backside of the building block, thus the passageway for the crane can be small.

Table 9 shows the results of the simulations for the combinations between the three crane locations and four material storage locations in Figure 27 and 28. It is highly recommended to opt for a combination of locations, in which all window frames and floors can be lifted (Figure 29). Subsequently, the total lift duration should be as low as possible. Within the as-built crane location C1 and material storage location S1 all window frames and floors can be lifted, and the total lift duration is 12 hours and 47 minutes. The output of the simulation C1-S1 is shown in Figure 30 and 31. There are three other combinations of crane location and material storage location, in which everything can be lifted and where the total lift duration is lower as the as-built locations. Of these three combinations, two combinations have the lowest total lift duration: C3-S1 and C3-S2. The output of the simulation C3-S1 is shown in Figure 32 and 33.

Table 9. Simulation results of combinations crane and material storage (part 1).

Crane location	Material storage location	Can be lifted	Total lift duration [hrs]
C1	S1	100%	12.78
C1	S2	0%	-
C1	S3	100%	14.04
C1	S4	100%	12.89
C2	S1	0%	-
C2	S2	88%	10.67
C2	S3	88%	11.53
C2	S4	88%	10.95
C3	S1	100%	12.00
C3	S2	100%	12.00
C3	S3	100%	12.64
C3	S4	100%	13.98
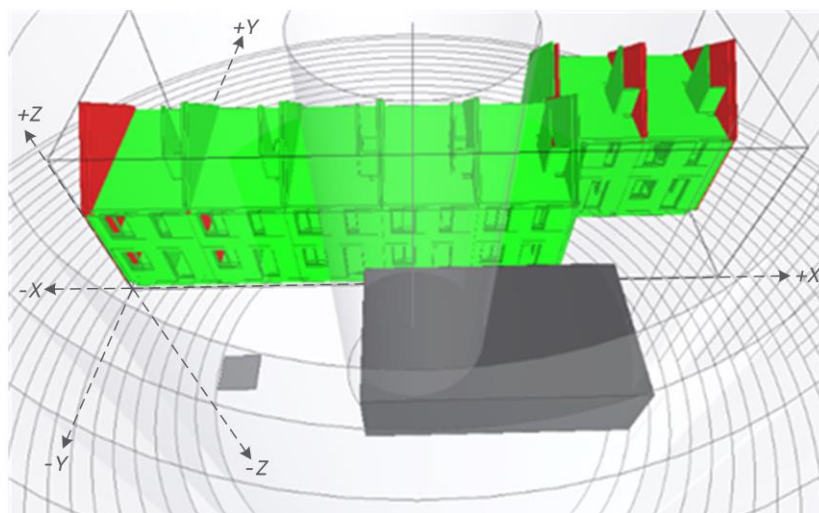
Figure 29. Three-dimensional visualization lifted elements locations C1-S1
(all window frames and floors can be lifted).
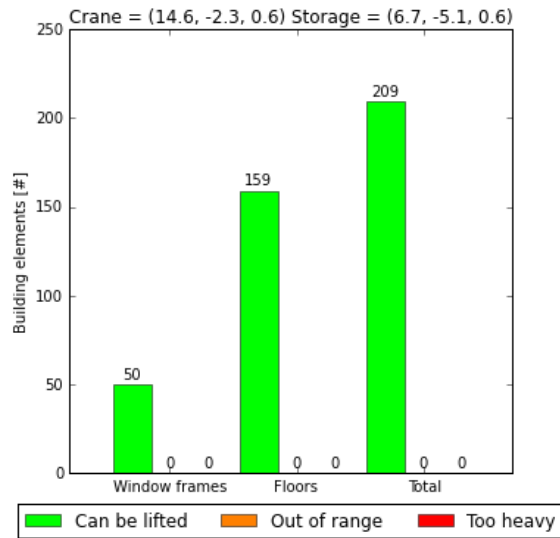
Figure 30. Bar Chart lifted elements (C1-S1).
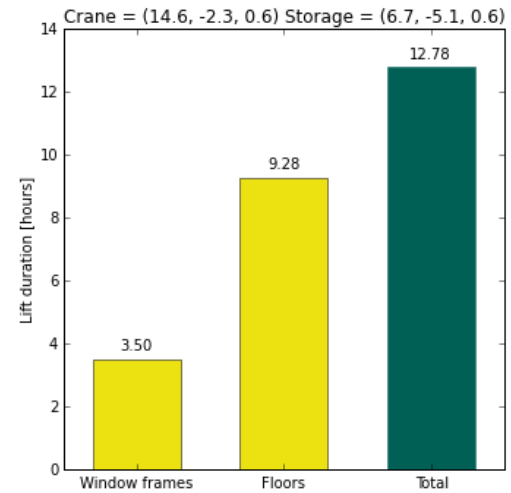
Figure 31. Bar Chart total lift duration (C1-S1).
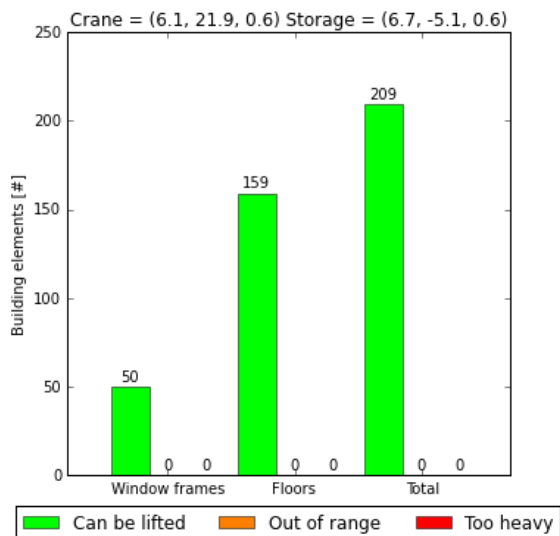
Figure 32. Bar Chart lifted elements (C3-S1).
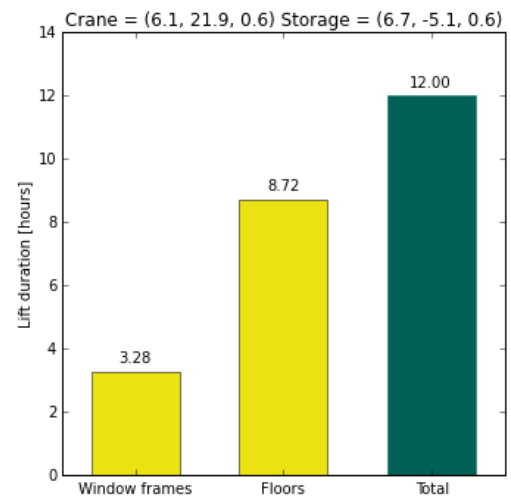
Figure 33. Bar Chart total lift duration (C3-S1).

The results of the first simulations are compared with the as-planned and as-built data (Table 10). In this research the as-planned data is gathered from the Gant chart and the interviews. The as-built data is obtained from invoices of the construction project. Both the as-planned and as-built data is only related to the lifting of window frames and floors. In addition, the as-planned and as-built data is solely based on lifting of the elements, in which assembling and dismantling of the crane is not added.

Table 10. As-planned, as-built and simulation results (part 1).

	As-planned [*hrs*]	As-built [*hrs*]	Simulation tool (C1-S1) [*hrs*]
Window frames	**7.5**	**7**	**3.50**
Waffle slabs (ground floor)	*4.5*	*4.5*	
Concrete-hollow slabs (1st floor)	*7.5*	*8.5*	
Concrete-hollow slabs (2nd floor)	*7.5*	*6.5*	
Floors	**19.5**	**19.5**	**9.27**
Total	**27**	**26.5**	**12.78**

As shown in Table 10 the values (in hours) of the as-planned and as-built data are approximately the same. However, the results of the simulation of the as-built locations of the crane and material storage show large differences with the as-planned and as-built data. The simulation results of the window frames are 50% lower in comparison with the as-built data and of the floors 52%. These big differences can be explained by two factors.

First, the simulation tool only considers the lifting of the window frames and floors, in which other operations of these elements are not included. During the lifting of window frames, the window frame trestles may need to be moved. Lifting of the floors consists also of these additional lifts, such as the lifting of floors at the material storage location. For example, it may be happen that a floor is located at the bottom of a pile at the material storage, causing that other floors should be lifted first. However, stacking of the floors according to the construction sequence already starts in the factory during the manufacturing process, and thereafter during the transport to the construction site. In addition, there are other additional lifts, such as the lifting of steel and scaffolding work. The simulation tool also does not take into account the changing of the equipment of the crane. Secondly, the hook and unhook times from the observations may not be accurate. This hook and unhook time depends on many factors, such as the rigger(s) and crane operator. In order to obtain accurate results, at least hundred measurements concerning hook and unhook time should be carried out in the future.

Based on the observations, one window frame can be lifted within 4 min. 30 sec. and one concrete hollow-core slab within 3 min. 30 sec. Within these lifts, the hook and unhook time for the window frames is both 1 min. 40 sec. The hook time for the floors is 50 sec. and the unhook time 1 min. 55 sec. However, these measurements are based on the lifting of concrete hollow-core slabs instead of waffle slabs. These hook and unhook times are shown in Table 11, on which the first simulations are based. According to the two construction site engineers, a window frame can be lifted within 8 min., a waffle slab within 3 min. 30 sec and a concrete hollow-core slab within 6 min. Within these lifts, the new hook time for window frames is 2 min. and the unhook time 4 min. The new hook and unhook time for waffle slabs are based on the hook and unhook times of the concrete hollow-core slabs before. Finally, the new hook time for concrete hollow-core slabs is 1 min. and the unhook time is 4 min. 15 sec. (Table 11). Especially, the unhook time of each building element is higher in comparison with pre-determined unhook times.

Table 11. Hook and unhook times.

	Hook time tool [min]	Unhook time tool [min]	Hook time new [min]	Unhook time new [min]
Window frames	1:40	1:40	2:00	4:00
Waffle slabs (ground floor)	0:50	1:55	0:50	1:55
Concrete-hollow slabs (1st floor)	0:50	1:55	1:00	4:15
Concrete-hollow slabs (2nd floor)	0:50	1:55	1:00	4:15

The new hook and unhook times within Table 11 are implemented within the input CSV-file "hook and unhook times", which is more reality based. Within these hook and unhook times, the additional lifts of these elements are captured. The adjusted CSV-file "hook and unhook times" is shown in Table A8.1 in Appendix 8. Again, the combinations of crane location and material storage location are simulated. The simulation results of the window frames are 1 hour and 17 minutes (18%) lower in comparison with the as-built data (Table 12). The simulation results of the floors are 5 hours and 53 minutes (30%) lower in comparison with the as-built data. This second part of the simulations shows that the lift durations are closer to the as-built durations of the building elements in comparison with the first simulation part, which makes the tool more realistic. However, the differences between the values could be that the crane does not turn continuously in reality, in which sometimes there is no crane activity.

The crane can be rented per hour, in which each hour costs €83,50 (M.J. van Riel, 2016). According to the as-built lifting hours in Table 12, it costs €2254,50 in total to rent the crane for 27 hours. According to the lifting hours (Table 12) from the simulation tool, it costs €1670,- in total to rent the crane for 20 hours. The difference between these two outcomes is €584,50, which is based on 7 crane rental hours.

Table 12. As-planned, as-built and simulation results (part 2).

	As-planned [hrs]	As-built [hrs]	Simulation tool (C1-S1) [hrs]
Window frames	**7.5**	**7**	**5.72**
Waffle slabs (ground floor)	*4.5*	*4.5*	
Concrete-hollow slabs (1st floor)	*7.5*	*8.5*	
Concrete-hollow slabs (2nd floor)	*7.5*	*6.5*	
Floors	**19.5**	**19.5**	**13.61**
Total	**27**	**26.5**	**19.33**

Table 13 shows the simulation results of the second part. There are three interesting combinations of crane location and material storage location. These combinations and their outputs are shown in Figure 34 until 42. The combination C1 and S1 are the as-built locations of the crane and material storage. Combination C1-S1 has the lowest total lift duration when the crane is located at C1, namely 19 hours and 20 minutes. In addition, all window frames and floors can be lifted (Figure 34, 35 and 36). Combination C2-S2 has the lowest total lift duration when the crane is located at C2, which is 16 hours and 28 minutes. However, only 88% of the building elements can be lifted, causing the crane should be moved once (Figure 37, 38 and 39). Combination C3-S1 has the lowest total lift duration when the crane is location at C3, namely 18 hours and 33 minutes. In addition, all window frames and floors can be lifted (40, 41 and 42). Nearby crane location C1, parking places had to be built. These parking places need rubble as underground, which can be used as construction road. Hence, it is not needed to deposit a lot more rubble when combination C1-S1 is used. Combinations C2-S2 and C3-S1 need more rubble in comparison with combination C1-S1, because at these locations no parking places are built. In addition, a part of the output table of simulation C1-S1 is visualized in Table A3.1 in Appendix 3.

Table 13. Simulation results of combinations crane and material storage (part 2).

Crane location	Material storage location	Can be lifted	Total lift duration [hrs]
C1	S1	100%	19.33
C1	S2	0%	-
C1	S3	100%	20.59
C1	S4	100%	19.44
C2	S1	0%	-
C2	S2	88%	16.46
C2	S3	88%	17.32
C2	S4	88%	16.74
C3	S1	100%	18.55
C3	S2	100%	18.55
C3	S3	100%	19.19
C3	S4	100%	20.53
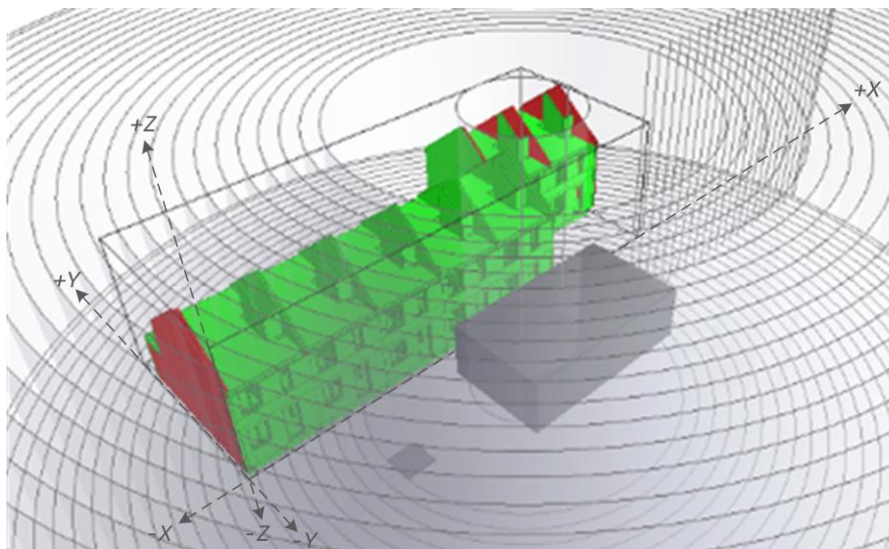
Figure 34. Three-dimensional visualization C1-S1.
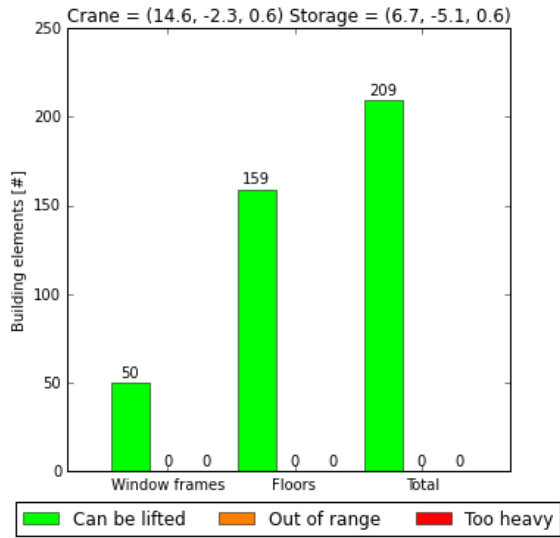
Figure 35. Bar Chart 2 lifted elements (C1-S1).
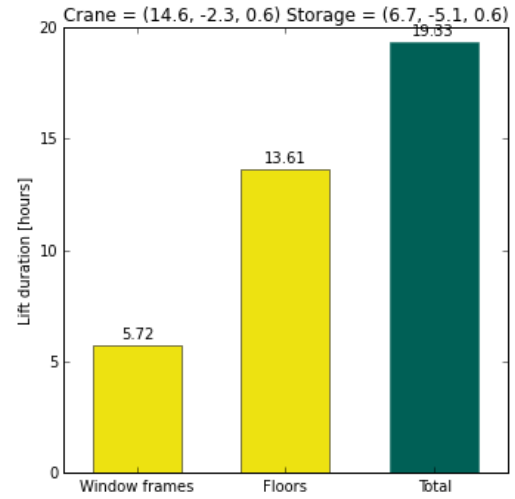
Figure 36. Bar Chart 2 total lift duration (C1-S1).
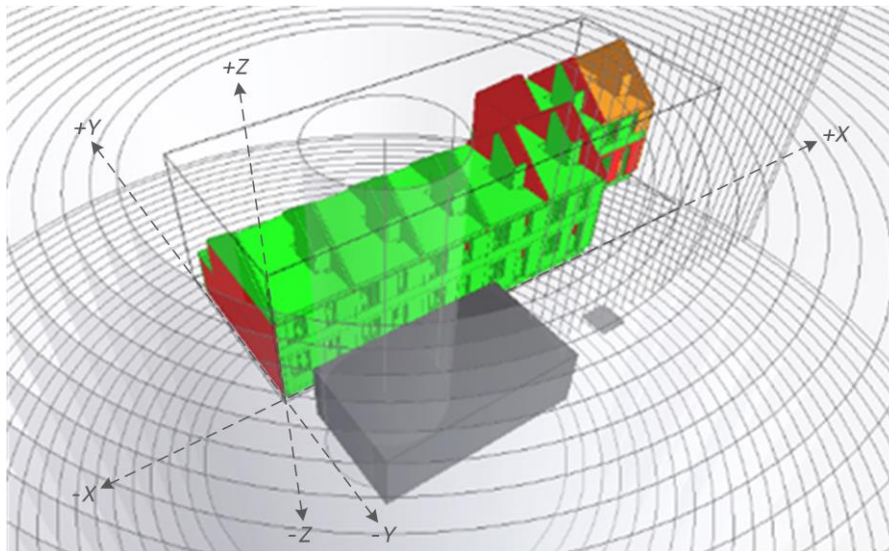
Figure 37. Three-dimensional visualization C2-S2.
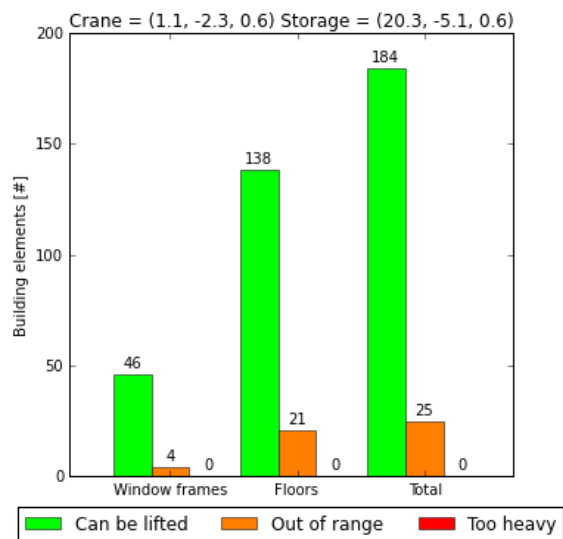
Figure 38. Bar Chart 2 lifted elements (C2-S2).
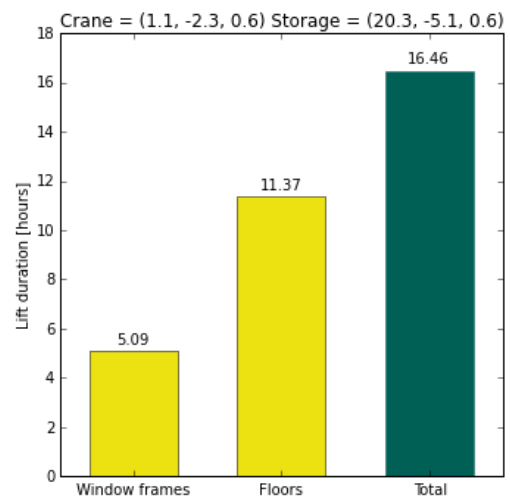
Figure 39. Bar Chart 2 total lift duration (C2-S2).
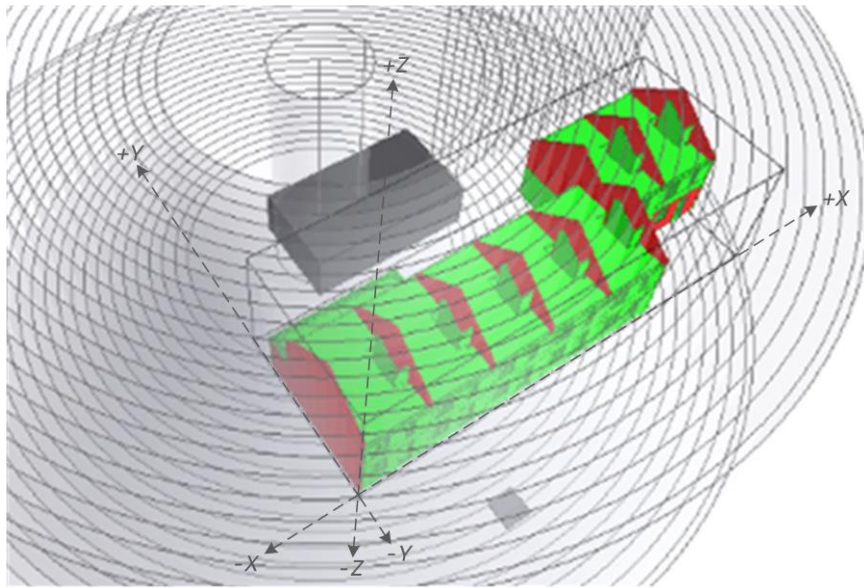
Figure 40. Three-dimensional visualization C3-S1.
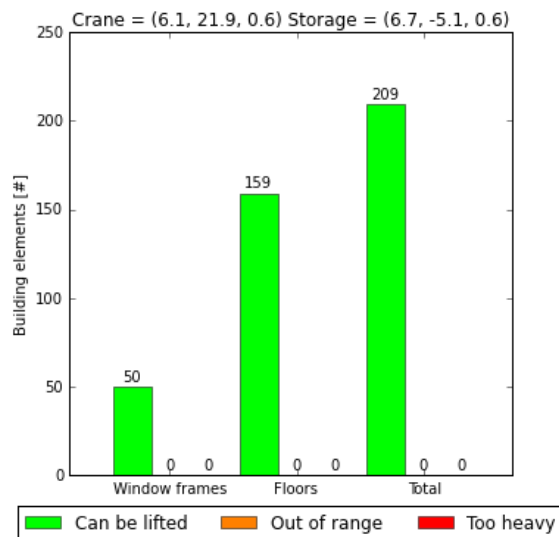
Figure 41. Bar Chart 2 lifted elements (C3-S1).
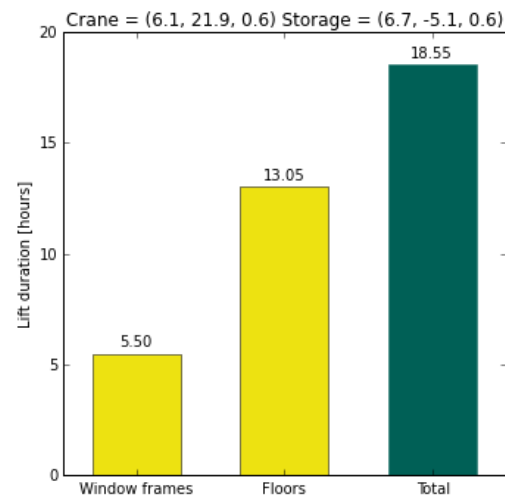
Figure 42. Bar Chart 2 total lift duration (C3-S1).

According to the simulations, there are three interesting combinations of crane and material storage location. An overview of the lifted building elements, their lift duration, crane hours and their costs is shown in Figure 43, 44 and Table 14. Because not everything can be lifted when the combination C2-S2 is applied, the crane should be moved once, which costs one crane hour. The costs are based on the rental price of €83,50 per hour (M.J. van Riel, 2016). In addition, all combinations need rubble for the parking places, which costs €10,59 per m² (Dura Vermeer Divisie Infra, 2015). This rubble for the parking places is 196 m², shown in Figure 45. Combination C1-S1 needs additional rubble of 142 m² for the construction road and crane location. Combination C2-S2 needs additional rubble of 142 m² and 105 m² for the crane location and construction road. Finally, combination C3-S1 needs rubble on the backside of the building block of 207 m² as construction road and for the crane location (Figure 45). As shown in Table 14, the combination of crane location C1 and material storage location S1 is the cheapest and most convenient. Combination C1-S1 is €605,- (10%) cheaper in comparison with C3-S1 and €945,- (15%) compared with C2-S2.
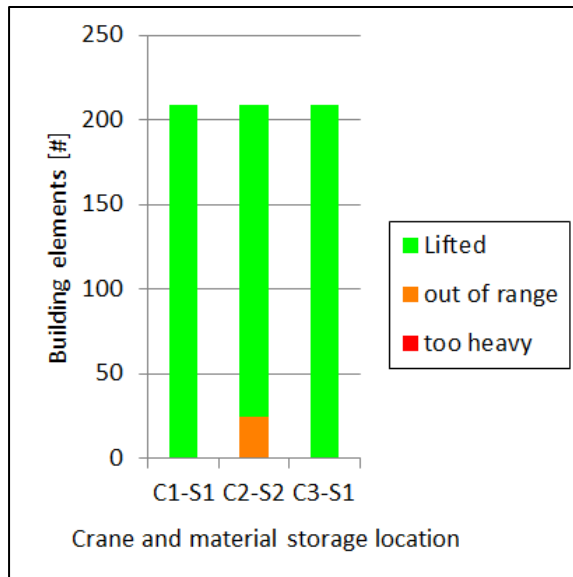
Figure 43. Overview lifted building elements.
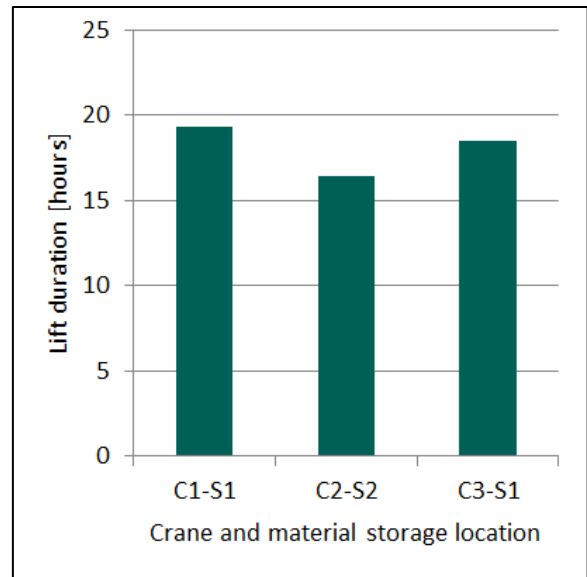
Figure 44. Overview lift duration.

Table 14. Overview crane hours and costs (M.J. van Riel, 2016) (Dura Vermeer Divisie Infra, 2015).

	C1-S1	C2-S2	C3-S1
Crane rental [hrs]	20	17	19
Movement crane [hrs]	-	1	-
Costs Crane rental	€1670,-	€1503,-	€1587,-
Costs rubble parking places	€2076,-	€2076,-	€2076,-
Costs additional rubble	€1504,-	€2616,-	€2192,-
Total	**€5250,-**	**€6195,-**	**€5855,-**
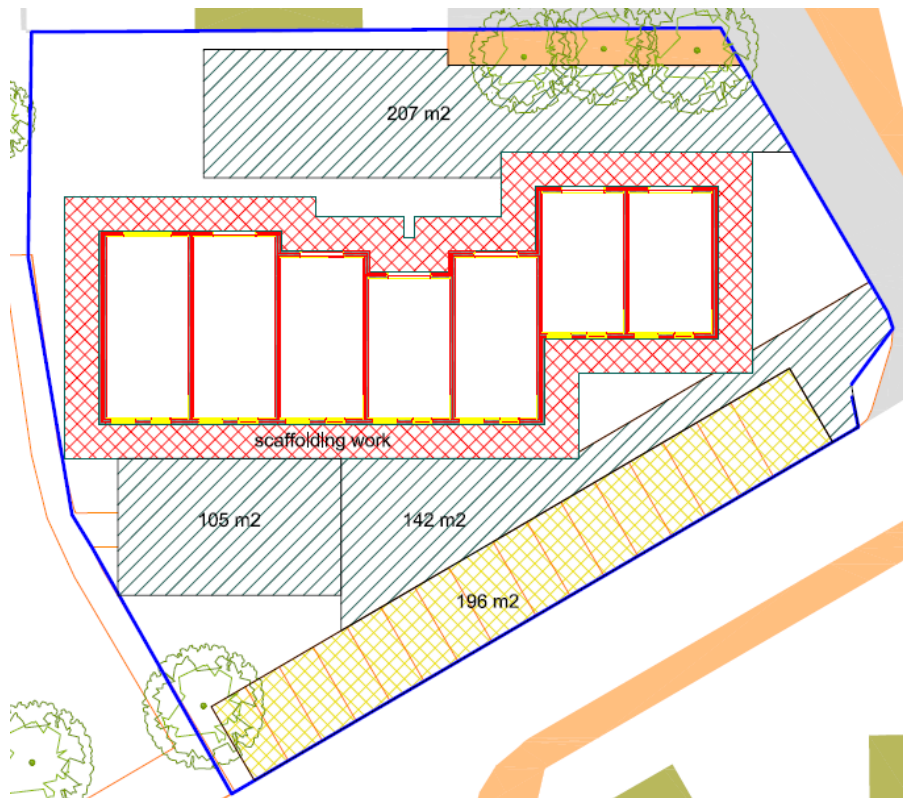
Figure 45. Rubble parking places and additional rubble.

Both construction site engineers said that the tool could be useful, and further development would be very interesting. Especially the BIM Manager of Dura Vermeer Equipment Service in Haaften is completely excited about the simulation tool. According to the two construction site engineers it is useful to implement the capacity and dimensions of the crane within the tool, but the implementation of crane specifications to select the most optimal location is quite convenient.

7. Conclusions

This chapter shows the results of this master thesis and gives answers on the research questions. Construction delays on construction sites are one of the biggest problems within the AEC industry (El-Razek, Bassioni, & Mobarak, 2008) (James, et al., 2014). They are generally caused by poor managerial and technical skills of contractors; such as poor site mobilization, poor subcontractors work and ineffective planning and scheduling (Rao & Culas, 2014). Crane deployment is part of site mobilization and a very important part of the planning process, because many construction activities are highly dependent on it. In order to gain insights in the crane deployment during residential projects, the sub-questions and main question are answered.

SQ1. What are the expected gains to optimize the crane deployment within residential construction projects?

Crane deployment is associated with rental costs, which are based on the total hours a crane is located at a location. The crane and its specifications can be modelled in a three-dimensional environment. This three-dimensional crane model can be implemented within a 3D-model of a residential project. In this three-dimensional environment, the total lift duration of the crane should be as low as possible and as much as possible building elements should be lifted. Through this kind of optimization, a more optimal crane deployment can be determined, which finally results in a reduction of crane expenses.

SQ2. How do these opportunities relate to the current construction industry?

Crane deployment is mainly determined based on the personal experience and knowledge of the crane planner, whereby the crane deployment can greatly differ from each other. Currently, the construction industry focuses more on BIM and IFC data structures. In addition, computer related techniques are increasingly used to assist within the planning and management process. These developments have positive effects to develop a tool, which supports the crane planner during the determination of crane deployment. This tool should support IFC data files, which are becoming increasingly important within the AEC industry.

SQ3. Which parameters concerning construction time are important for the crane deployment within residential construction projects?

An important parameter of crane deployment concerning construction time is the total lift duration per building element. This total lift duration is dependent on several factors. First, the horizontal-, vertical-, and rotation speed within the crane specifications should be taken into account. This speed is dependent on the crane location, material storage location and the final location of each building element. Finally, the hook and unhook time of each building element is very important, because this time is the biggest part of the total lift duration.

SQ4. What are functional requirements for a tool to help in this process within residential construction projects?

The tool should visualize the crane and residential project in a three-dimensional environment. Within this three-dimensional environment it should be clarified which building elements can be lifted, are out of range or are too heavy. In addition, the total lift duration is calculated and visualized for the building elements which can be lifted. The residential project within the simulation tool is based on the IFC data structure, which is becoming increasingly important within the construction industry. Finally, the tool should assist the crane planner during the determination of crane deployment. The crane planner can be for example a construction site engineer.

SQ5. How can the consequences of choices in the planning process concerning crane deployment be communicated during the construction process?

By using the simulation tool, the environmental factors should be taken into account by using a construction site plan including construction site dimensions and other site objects. The results of the simulations of the tool are visualized in graphs, an output table and in a three-dimensional visualization. Based on these results, the crane planner can determine a more optimal crane location and material storage location.

"How can the crane utilization be optimized based on building models, considering the minimization of time?"

In this research, a specific framework is assumed, because crane deployment consists of many parameters. The results within this framework shows that crane utilization can be optimized by using a simulation tool, which takes into consideration a three-dimensional environment and the minimization of time. This kind of optimization is very promising and finally could results in a reduction of crane expenses.

8. Further research

This research shows that the optimization of crane deployment is very promising for the construction industry, in which a three-dimensional environment and the minimization of lift time are taken into consideration.

However, this research focuses only on one type of self-erecting crane, applied within a residential construction project. Further research can be done to the implementation of other types of cranes, such as a crawler crane, telescopic crane, tower crane and other types of self-erecting cranes. This could be very interesting, because crawler cranes and telescopic cranes have other boom movements and a tower crane cannot be moved easily. Additional observations can be done, making the differences between the types of cranes clearer. In addition, other crane systems can be applied, such as a crane on rails. It would be very useful to simulate the deployment of more cranes, taken into consideration their movements, the crane occupation in hours and safety factors, such as ground reinforcement and wind speed. It could be the case that the general construction site costs are high; causing lifting from the street can be cheaper.

In addition, it can also be interesting to optimize the crane deployment for one or more utility construction projects. When the crane deployment for more construction projects can be determined, it is possible to plan in months instead of weeks. Further research can also be done to the optimization of crane deployment for different construction methods, such as prefabricated, timer-framed and pouring work. Finally, the ultimate goal is to gather the optimal crane hours from an optimization tool and to automatic schedule the most optimal hours within the construction planning (4D).

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Appendices

Appendix 1 – Results semi-structured interviews

Interview Wout Somers

Date:	March 23, 2016
Time:	08:45h
Place:	Stationsplein 1, Rosmalen

Participants:	Wout Somers	BIM Coordinator	WS
	Rob Simons	Graduate student TU/e	RS

❖ **Introduction**

My name is Rob Simons and I am studying the master Construction Management and Engineering at the Technical University at Eindhoven. At 1 February 2016 I started with graduation within Dura Vermeer Bouw Rosmalen.

By using this interview, I would like to identify which tools are currently used to create and coordinate construction schedules. In addition, I want to discover which functional requirements are desirable for a respective software application. The interview consists of 16 semi-structured questions, which is expected to last approximately one hour. Would you agree if I record the interview? Let us start.

❖ **Personal information**

RS: What is your age and which studies you have completed?
WS: I am 33 years old, and I studied the master Architecture Building Planning (ABP) at the Technical University Eindhoven. My graduation specialization was architecture urban design.

RS: How long have you worked within the construction industry? And within Dura Vermeer?
WS: I worked within the construction industry since 2010 and within Dura Vermeer Bouw Rosmalen since 1 October 2015.

RS: What is your function within Dura Vermeer?
WS: I am BIM coordinator, so I am responsible to implement BIM software and BIM work methods within Dura Vermeer Bouw Rosmalen. I work in close collaboration with Bart Simmelink (BIM manager Dura Vermeer Bouw Rosmalen), who is responsible on strategic level. In addition, I work in close collaboration with other BIM coordinators of other Dura Vermeer locations. Applying BIM innovations and the training of personnel (training courses, workshops, face-to-face explanations) are also part of my function.

RS: On which type of construction projects are you currently active?
WS: I am active as BIM coordinator at residential projects, such as the construction of 36 terraced dwellings "De Weverij" in Geldrop. I am also active as modeller at 4 patio dwellings "Tholen" in Zeeland, which is kind of experiment to model more often in the future. In addition, I am active at the construction of 85 apartments "De Kyker" in Breda, in which I collaborate a lot with the architect.

RS: How many hours do you work at the office vs. at the construction site?

WS: I work 40 hours at office and 0 hours on the construction site. I would like to go more often to the construction site, to discover what is going on. At this moment, I am active from design to performance model / early production model. I am not active at the construction phase of projects.

❖ **Create / Coordinate construction schedules**

RS: What type of construction schedules you are using within projects?

WS: I hardly use construction schedules within projects; however different construction schedules can be distinguished. We use the joint planning session in the preliminary phase. In the production/engineering phase the engineering schedule is used, in which production time and delivery time is included for the biggest parties (walls, windows, floors, installations).

RS: Do you create these construction schedules themselves?

WS: No, I always create construction schedules in the preliminary stage. In addition, I create modelling schedules to determine when which model parts should be provided.

RS: If yes, what indicators or data do you use?

WS: We use often existing schedules of specific/similar construction projects.

RS: What is important that is included within a construction schedule on-site?

WS: I think environmental factors onsite are very important, both onsite as around the construction site. In addition, construction sequences are very important, which can be influenced by environmental factors. It also needs to be decided whether workable days should or should not be taken along in the construction schedule. Dura Vermeer Bouw Rosmalen does not integrate the critical path within construction schedules.

RS: Which tools (software, techniques) do you use to create construction schedules and to coordinate them?

WS: We use Asta Powerproject and Excel to create construction schedules. When the construction schedule is created, the progress is monitored mainly on paper. All construction schedules use the Gantt Chart technique, other planning techniques are not introduced within Dura Vermeer (for example network diagrams). When the building project is wind- and waterproof, more tasks can be executed, which is seen as an important milestone during construction projects.

RS: Do you often face delays within construction projects?

WS: In the design phase continuously. There are always project stakeholders, which cannot deliver or process the data in the design phase.

RS: If yes, what are most common delays and how they are caused?

WS: A decision should be taken and the relevant person to take the decision is unknown or is not up to date what is happening. In other words, it is not clear who is the responsible person for a specific problem or task. Autodesk BIM 360 Glue should stimulate, accelerate and clarify this process, in which all project stakeholders should be active on the software

platform. Autodesk BIM 360 Glue is used during the design and engineering process, while Autodesk 360 Field can be used during the construction phase. The government can also cause delays in the design phase, for example when permits are requested or possible modifications are submitted. Delays can also occur in the sales process, mainly when the sales value has not exceeded 70%, after which construction of the project starts. Purchaser options can also cause delays, because each client has different needs. Delays can also occur during the production process, often caused by the modelling knowledge of subcontractors. Not all subcontractors work in a proper way with BIM, in which they draw the 3D geometric model and connect incorrect information to the 3D model. This modelling knowledge of subcontractors can be improved by making use of training programs. However, how do you educate the subcontractors? And do you create some time to educate them? The aim of this training programs should be to collaborate with the same subcontractors, because the contractor has invested in them.

RS: How do you make delays visible during the design phase of projects?
WS: On basis of a printout of Excel or Asta Powerproject, a status line will be drawn on the printout. Thereafter, there can be determined where accelerations are possible. Reasons of the delays are often not discussed.

RS: How do you communicate these delays to (sub)contractor(s)?
WS: Delays during the design phase are often communicated internally.

❖ **Software Application**

RS: Do you think that a software application can help to detect future delays of construction projects?
WS: Yes.

RS: How can a software application contribute to that?
WS: Within a contractor, it is possible to keep track the status of the delivery of materials by subcontractors. You can ask to yourself: Are materials delivered on time? Is the subcontractor accurate? (quality control on delivery). How do construction products/materials arrive on the construction site? (quality of product/material). Are the delivered products/materials the correct ones? (correct material, measurements, etc.). Is the product/material implemented according the drawing/3D model? Aforementioned points can be used to test the subcontractors' quality and to give them feedback.

❖ **Closure**

This was the end of the interview. Thank you for your cooperation and for taking your time! I will send the elaborated interviews to you by mail within a week.

Interview Rob van Kuijk

Date:	March 30, 2016
Time:	09:15h
Place:	Stationsplein 1, Rosmalen

| **Participants:** | Rob van Kuijk | BIM Engineer | RvK |
| | Rob Simons | Graduate student TU/e | RS |

❖ **Introduction**

My name is Rob Simons and I am studying the master Construction Management and Engineering at the Technical University at Eindhoven. At 1 February 2016 I started with graduation within Dura Vermeer Bouw Rosmalen.

By using this interview, I would like to identify which tools are currently used to create and coordinate construction schedules. In addition, I want to discover which functional requirements are desirable for a respective software application. The interview consists of 16 semi-structured questions, which is expected to last approximately one hour. Would you agree if I record the interview? Let us start.

❖ **Personal information**

RS: What is your age and which studies you have completed?

RvK: I am 26 years old. First, I studied 4 years at Built Environment at MBO and thereafter I studied 3 years Built Environment at the Avans Hogeschool. For Built Environment at the Avans Hogeschool, I graduated together with Tim van Lith at Dura Vermeer and our subject was "Waste Management".

RS: How long have you worked within the construction industry? And within Dura Vermeer?

RvK: After graduation within Dura Vermeer, I started a 2-years traineeship within Dura Vermeer Bouw Rosmalen. During this traineeship, I worked in the work preparation of the construction of 133 residential dwellings "Breda Vooruit" phase 1.

RS: What is your function within Dura Vermeer?

RvK: Since August 2015 I am BIM Engineer.

RS: On which type of construction projects are you currently active?

RvK: I am active as BIM Engineer at both residential projects as utility construction projects. At this moment, I work on the residential project of 20 dwellings "Rietpark" in 's-Hertogenbosch. In addition, I work on the utility construction project "Breda Vooruit".

RS: How many hours do you work at the office vs. at the construction site?

RvK: I work 40 hours at office and 0 hours on the construction site, however sometimes I visit the construction site. During my traineeship at project "Breda Vooruit" I worked 40 hours a day on the construction site, because it was a big and complex project.

❖ **Create / Coordinate construction schedules**

RS: What type of construction schedules you are using within projects?

RvK: First, a general construction planning is provided by department project bureau of Dura Vermeer. In addition, a purchase scheme / planning and engineering planning are important. Two times during the construction of a residential project (according to PCS) a joint planning session between the contractor and subcontractors (GPS) is planned. Pre Choice System (PCS) is a housing project system to build all dwellings from one baseline, such as a standard to draw details and calculate units. This GPS is planned once for the structural work and

once for the finishing work. This GPS ensures that the contractor and subcontractors can build according to schedule and meet deadlines. The GPS is kind of execution planning, because this schedule is very detailed on parcel level.

RS: Do you create these construction schedules themselves?
RvK: Usually, Harm Wingens (project leader) and Frankwin Ceelen (construction site engineer) are creating the construction schedules. Frankwin Ceelen has most knowledge according to the amount of work which can be performed within a day and the relationships between different activities. The construction schedule can be checked in collaboration. However, there is always contact with sub-contractors, for example to understand pace of work and the total man-hours available.

RS: If yes, what indicators or data do you use?
RvK: The department project bureau uses planning indicators from reference projects, but they have little value. Most functional indicators are from the sub-contractors. However, the creating of construction schedules is most dependent on the knowledge of Harm Wingens and Frankwin Ceelen and the gained knowledge from sub-contractors. Finally, planning indicators are often based on needed and available man-hours.

RS: What is important that is included within a construction schedule on-site?
RvK: Crane deployment and scaffolding are very important, which can ensure that activities shift. It is economically advantageous to deploy a crane for a whole day, instead of a portion of a day. In addition, delivery moments of components are very important in the preparation of a project, this ensures that components are available when they are constructed.

RS: Which tools (software, techniques) do you use to create construction schedules and to coordinate them?
RvK: Software programmes Asta Powerpoject (not much for residential projects) and Excel are used to create construction schedules. Excel is very easy to understand for anyone within the project. We use the Gantt Chart technique, however in Asta Powerproject no relation to building blocks can be created. The construction will be coordinated by using a state line, to show the status of all activities. A lot of people on the construction site are struggling to understand the construction schedule (Gantt Chart). Therefore, we created a 3D and 2D drawing to visualize the planning activities within the project "Breda Vooruit".

RS: Do you often face delays within construction projects?
RvK: Yes.

RS: If yes, what are most common delays and how they are caused?
RvK:
- Subcontractors fail to meet production, which depends on the available capacity.
- The product / project information of the contractor is incorrect or incomplete.
- Unforeseen delays; when materials should have been delivered, however nothing or the wrong material is delivered or the material is damaged.
- Complaint from local residents in the neighbourhood.
- Unworkable weather.
- Polluted soil (e.g. asbestos).

RS: How do you make delays visible during the design phase of projects?

RvK: Each day there is a start, where every foreman of the subcontractor looks at the construction schedule, and shows their progress. There can be determined to work one or more days on another project, or the resume the activities at the project.

RS: How do you communicate these delays to (sub)contractor(s)?

RvK: The construction site engineer will communicate with the foreman of each sub-contractor. It should be clear what are the delays and how to resume the construction project.

❖ **Software Application**

RS: Do you think that a software application can help to detect future delays of construction projects?

RvK: Yes, 100%. On a flat planning, you cannot see how a building is constructed.

RS: How can a software application contribute to that?

RvK: In the preparation phase, it has little advantage. However, on the construction site this is very useful. It is mainly useful for the construction site engineer, because it is clear what everyone should construct in a day and relations between activities are becoming clear.

❖ **Closure**

This was the end of the interview. Thank you for your cooperation and for taking your time! I will send the elaborated interviews to you by mail within a week.

Interview Harm Wingens

Date:	April 1, 2016
Time:	15:45h
Place:	Stationsplein 1, Rosmalen

Participants:	Harm Wingens	Project Leader	HW
	Rob Simons	Graduate student TU/e	RS

❖ **Introduction**

My name is Rob Simons and I am studying the master Construction Management and Engineering at the Technical University at Eindhoven. At 1 February 2016 I started with graduation within Dura Vermeer Bouw Rosmalen.

By using this interview, I would like to identify which tools are currently used to create and coordinate construction schedules. In addition, I want to discover which functional requirements are desirable for a respective software application. The interview consists of 16 semi-structured questions, which is expected to last approximately one hour. Would you agree if I record the interview? Let us start.

❖ **Personal information**

RS: What is your age and which studies you have completed?

HW: I am 35 years old. First, I completed VWO and thereafter I studied Civil Engineering at HBO at the Avans Hogeschool. I graduated at concrete and hydraulic engineering. In addition, I studied different training courses.

RS: How long have you worked within the construction industry? And within Dura Vermeer?

HW: 12,5 years within Dura Vermeer. First, I worked 1,5 years at the construction department concrete and hydraulic engineering of Dura Vermeer. Thereafter, I worked 11 years at built environment of Dura Vermeer, both residential- as utility construction projects.

RS: What is your function within Dura Vermeer?

HW: Project Leader. I am engaged within residential projects, from development to handover of a project. Work preparation and execution of the project are also part of the construction process. My responsibilities are to manage the BIM engineers (work preparation) and construction site engineer (execution).

RS: On which type of construction projects are you currently active?

HW: Currently, I am active as Project Leader at all residential projects.
- Under development: Uden (8 dwellings) and Veghel (72).
- Work preparation: Eindhoven (42), Dongen (46), Vught (14), Geldrop (36).
- Execution: Drunen (7), Hank (9), Haaften (8), Son (22), Rosmalen (20), Tholen (8).

RS: How many hours do you work at the office vs. at the construction site?

HW: I work 36 hours at office and 4 hours on the construction site.

❖ **Create / Coordinate construction schedules**

RS: What type of construction schedules you are using within projects?

HW: Currently, we use "Gezamelijke Planning Sessie" schedules (GPS), also called a joint planning session. GPS is used in close collaboration between the contractor and sub-contractors. We schedule on a daily basis, in which the building numbers are shown in the planning. Each day from 08:45 until 09:00h there is a day start, in which the as-planned and as-built status of the project will be discussed. When deviations are detected, the schedule needs to be adjusted within 1-2 days.

RS: Do you create these construction schedules themselves?

HW: Usually, the project leader (me) and the construction site engineer are creating the construction schedules in close collaboration. The base schedule is created, whereafter a GPS is planned with people of work preparation, the cion onstrusite engineer, project leader and sub-contractors. The construction site engineer is the chairman during this GPS and makes appointments with the sub-contractors.

RS: If yes, what indicators or data do you use?

HW: We use fixed intervals for the construction of residential projects (constructed with limestone elements). 2, 6 and 9 weeks are these fixed intervals. 2 weeks is from the foundation phase until the ground floor. 6 weeks is from the ground floor until the start of

finishing work. Finally, the finishing work is 9 weeks until the handover of the first 7 dwellings. The construction speed for the handover of terraced dwellings is 7 dwellings per week and for semi-detached dwellings 5 dwellings per week.

RS: What is important that is included within a construction schedule on-site?

HW: All sub-contractors should be included and all tasks should be integrated in the schedule, where you think in teams. For example, when the roofer will stick the roof covering for an extension, this task will be summarized in one rule. Subtasks (foil, insulation, first and second layer) can be excluded in the schedule and summarized in one task. This rule may look like "the extension of dwellings 1 and 2" on that day, which ensures good overview. Sequences within a schedule are also very important; the big tasks (foundation, ground floor, intermediate floors and roof) are marked in red colour. This ensures that you will see the intervals, the start of the finishing work and the tasks for crane deployment.

RS: Which tools (software, techniques) do you use to create construction schedules and to coordinate them?

HW: We use Excel to create the construction schedules. A big advantage of Excel is that you will see the building numbers in the schedule. However, Excel is no planning software and it lacks sequences between tasks. Therefore, you should determine and see the sequences by yourself. In addition, we use pictures of 3D models from dwellings and the construction site plan for better/easy communication. Previously, we also worked with Asta Powerproject for utility construction- and residential projects. However, we discovered that Excel is much clearer in comparison with Asta Powerproject, when you plan on building number. Excel is user-friendly for all project team members, including the construction site engineer and sub-contractors. The planning data on-site should be displayed on a manner that is readable in one specific way. During each day start, the construction schedule and a picture of the 3D model are printed and shown to all project team members. It would be ideal to visualize the 4D model (3D model including planning) on a flat screen in the site office of a project. This is especially interesting for structural work, the façade and roof phase. It is also possible to visualize it for the finishing work, however this is less clear.

RS: Do you often face delays within construction projects?

HW: Not often, but sometimes it will happen that a sub-contractor cannot meet his appointments. The pressure increases within the construction industry, whereby sub-contractors struggling to meet the as-planned deliveries.

RS: If yes, what are most common delays and how they are caused?

HW: Most delays occur by the elements floors, roofs and stairs. Currently, there is a big demand for these elements, however there are too little sub-contractors for these elements.

RS: How do you make delays visible during the construction phase of projects?

HW: First, you will try to meet your as-planned schedule. When a delay occurs, you will select a part of the schedule and move it forwards for a few days. However, the goal is to meet the schedule and to fulfil agreements with sub-contractors. When you do not fulfil agreements, you will lose the credibility with sub-contractors.

RS: How do you communicate these delays to (sub)contractor(s)?

HW: We use a customized schedule, which we send by email to the sub-contractors and we will call them.

❖ **Software Application**

RS: Do you think that a software application can help to detect future delays of construction projects?

HW: Yes, of course.

RS: How can a software application contribute to that?

HW: It would be ideal if the site engineer could see (on an iPad) the as-built project status of that day and automatically compare it with the as-planned schedule. The deployment of cranes are visualized in red and the scaffolding are shown in grey colour in the Excel schedule. The deployment of cranes and the scaffolding may also be included in the software application.

❖ **Closure**

This was the end of the interview. Thank you for your cooperation and for taking your time! I will send the elaborated interviews to you by mail within a week.

Interview Tim van Lith

Date:	April 8, 2016
Time:	09:00h
Place:	Stationsplein 1, Rosmalen

Participants:	Tim van Lith	BIM Engineer	TvL
	Rob Simons	Graduate student TU/e	RS

❖ **Introduction**

My name is Rob Simons and I am studying the master Construction Management and Engineering at the Technical University at Eindhoven. At 1 February 2016 I started with graduation within Dura Vermeer Bouw Rosmalen.

By using this interview, I would like to identify which tools are currently used to create and coordinate construction schedules. In addition, I want to discover which functional requirements are desirable for a respective software application. The interview consists of 16 semi-structured questions, which is expected to last approximately one hour. Would you agree if I record the interview? Let us start.

❖ **Personal information**

RS: What is your age and which studies you have completed?

TvL: I am 27 years old. First, I studied MBO Built Environment Architecture at the Koning Willem I College in Den Bosch. Thereafter, I studied HBO Built Environment at the Avans Hogeschool in Den Bosch. For Built Environment at the Avans Hogeschool, I graduated together with Rob van Kuijk at Dura Vermeer and our subject was "Waste Management".

RS: How long have you worked within the construction industry? And within Dura Vermeer?

TvL: After graduation within Dura Vermeer, I started a 1,5-years traineeship within Dura Vermeer Bouw Rosmalen. At this moment, I have a contract within Dura Vermeer Rosmalen since one year.

RS: What is your function within Dura Vermeer?

TvL: I am BIM Engineer, which is the new way of work preparation. I am responsible for the procurement of materials from subcontractors, the creation and monitoring of construction schedules, checking drawings with each other by using BIM models and finally creating the order confirmations.

RS: On which type of construction projects are you currently active?

TvL: I am active as BIM Engineer at residential projects. At this moment, I work on the project of 8 dwellings in Haaften, which is completed in May. In addition, I work on the preparation (e.g. permit requests) of the residential projects 46 dwellings in Dongen and 14 dwellings in Vught.

RS: How many hours do you work at the office vs. at the construction site?

TvL: I work 36 hours at the office and 4 hours on the construction site. I am at the construction site to check what the progress is and if appointments are met. In addition, procurement conversations are held on the construction site, so it is easier to see the construction progress in real life.

❖ **Create / Coordinate construction schedules**

RS: What type of construction schedules you are using within projects?

TvL: I use preparation schedules, which are used in the preliminary phase when permit documents must be submitted. The construction schedules we use are joint planning sessions between the contractor and subcontractors (GPS), which is used for the structural and finishing work. In addition, we use an engineering planning. An engineering planning consists of due dates to hand in 3D models/drawings by subcontractors, checking of 3D models/drawings by Dura Vermeer, manufacturing time, delivery dates onsite and the duration of installation elements.

RS: Do you create these construction schedules themselves?

TvL: Previously, I created the construction schedules together with the project leader or construction site engineer. Latest projects I created the schedules as far as possible by myself (including the GPS schedule) and checked it together with the project leader and construction site engineer. During the construction of small projects, we create the schedule and project team members may react by email or telephone. When bigger and more complex projects are built, we meet up with project team members to optimize the construction schedule of the structural and finishing work.

RS: If yes, what indicators or data do you use?

TvL: We use fixed intervals for the construction of residential projects (constructed with limestone elements). 2, 5 and 9 weeks are these fixed intervals. 2 weeks is from the foundation phase until the ground floor. 5 weeks is from the ground floor until the start of finishing work. Finally, the finishing work is 9 weeks until the handover. The brickwork runs

between these intervals and may continue when the finishing work is already started. We also use specific construction sequences. For example, one day after the construction of the roof the stairs are placed and the finishing work starts. In addition, after the construction of the first floor the brickwork starts. Schedules of similar projects can also be used as template for new construction projects. For example, I pick the part "foundation" of a similar project schedule and use it for the new project. However, I always create the schedules from a blank schedule template to prevent mistakes.

RS: What is important that is included within a construction schedule on-site?

TvL: Almost all parts: especially the connection of gas/water/electricity (after which the finishing work starts), scaffolding work, crane deployment (milestones). In addition, the responsibility of tasks is very important, which can be the contractor or a specific sub-contractor.

RS: Which tools (software, techniques) do you use to create construction schedules and to coordinate them?

TvL: We use Excel to create schedules and currently we want to use Asta Powerproject for a construction project to test the software. Excel is very useful to visualize the building numbers within a construction schedule. The construction will be coordinated to draw a state line on a printed schedule, to show the status of all activities. However, the coordination of construction schedules is the responsibility of the construction site engineer. We use the Gantt Chart technique to create schedules. In addition, sometimes we use scale models or pictures of 3D models from dwellings and the construction site for better/easy communication.

RS: Do you often face delays within construction projects?

TvL: Not very often, but sometimes it happens.

RS: If yes, what are most common delays and how they are caused?

TvL: The biggest delays occur due to the supply of filling pieces of stair gaps and roofs. The filling pieces of stair gaps are produced by a prefab concrete factory and supplied by another sub-contractor. Currently, there are too much orders, which causes delays in the production process and finally in a delayed delivery. There is also a big demand for the roofs, however; there are too little sub-contractors for these elements. Sometimes bricklayers cause delays, which may be caused by unworkable weather.

RS: How do you make delays visible during the design phase of projects?

TvL: Generally, the schedule is being adapted and will be sent to the sub-contractor(s). In addition, the construction site engineer warns the BIM engineers and other project team members.

RS: How do you communicate these delays to (sub)contractor(s)?

TvL: The construction site engineer will send the adapted schedule (e-mail) to the sub-contractor(s) and calls them when needed. When the delay has no major impact, we try to communicate in a proper way with the subcontractors, because we work frequently with some of these sub-contractors. When the delay and communication are dramatic, internal letters will be sent to the different project team members.

❖ Software Application

RS: Do you think that a software application can help to detect future delays of construction projects?

TvL: Yes, I think this is possible in the future.

RS: How can a software application contribute to that?

TvL: I think the construction schedule can be connected to the 3D model, in which the construction progress can be visualized within the 3D model. Software applications, such as Autodesk BIM 360 Field and Glue can contribute to this improvement on the construction site.

❖ Closure

This was the end of the interview. Thank you for your cooperation and for taking your time! I will send the elaborated interviews to you by mail within a week.

Interview Frankwin Ceelen

Date:	April 18, 2016
Time:	15:30h
Place:	Stationsplein 1, Rosmalen

| **Participants:** | Frankwin Ceelen | Construction site engineer | FC |
| | Rob Simons | Graduate student TU/e | RS |

❖ Introduction

My name is Rob Simons and I am studying the master Construction Management and Engineering at the Technical University at Eindhoven. At 1 February 2016 I started with graduation within Dura Vermeer Bouw Rosmalen.

By using this interview, I would like to identify which tools are currently used to create and coordinate construction schedules. In addition, I want to discover which functional requirements are desirable for a respective software application. The interview consists of 16 semi-structured questions, which is expected to last approximately one hour. Would you agree if I record the interview? Let us start.

❖ Personal information

RS: What is your age and which studies you have completed?

FC: I am 35 years old. I studied Built Environment at MBO, where my graduation process was quite theoretical.

RS: How long have you worked within the construction industry? And within Dura Vermeer?

FC: 17 years within Dura Vermeer. First, I worked 1 year as carpenter within Advin (part of Dura Vermeer), thereafter I worked 16 years as (assistant) construction site engineer.

RS: What is your function within Dura Vermeer?

FC: Construction site engineer.

RS: On which type of construction projects are you currently active?

FC: Since one year, I am active at residential projects. Previously, I was active on different type of projects; company halls, schools, apartment blocks and facility centres.

RS: How many hours do you work at the office vs. at the construction site?

FC: I work approximately 10 hours at office and 35 hours on the construction site. However, I prefer to work more on the construction site and less at the office.

❖ **Create / Coordinate construction schedules**

RS: What type of construction schedules you are using within projects?

FC: Currently, we use "Gezamelijke Planning Sessie" schedules (GPS), also called a joint planning session. GPS is used in close collaboration between the contractor and fixed sub-contractors, which is discussed during one or more meetings for bigger/complex residential projects.

RS: Do you create these construction schedules themselves?

FC: The BIM Engineer (work planner) creates a first schedule of the construction project; thereafter I will check and adjust the schedule in collaboration with the BIM Engineer.

RS: If yes, what indicators or data do you use?

FC: Mainly, I use my planning experience from previous projects. The schedules are always created from a blank schedule template to prevent mistakes. In addition, we use fixed intervals for the construction of residential projects (constructed with limestone elements). 2, 5 and 9 weeks are these fixed intervals. 2 weeks is from the foundation phase until the ground floor. 5 weeks is from the ground floor until the start of finishing work. Finally, the finishing work is 9 weeks until the handover of the first 7 dwellings.

RS: What is important that is included within a construction schedule on-site?

FC: I think it is mainly important to include all elements/tasks in the schedule, so the schedule is as detailed as possible. By using a detailed schedule, fewer errors are made concerning the execution of tasks. In addition, it is important to include all free days and building numbers in the schedule. I think it is also convenient to add a small 2D construction site plan, which includes the route how to execute the project from start until the end.

RS: Which tools (software, techniques) do you use to create construction schedules and to coordinate them?

FC: We use Excel to create the construction schedules. Previously, we also worked with Asta Powerproject for utility construction- and residential projects. However, we discovered that Excel is much easier in comparison with Asta Powerproject. Within Dura Vermeer, the Gantt chart technique is used to create the schedules. We do not have software to coordinate the construction schedules. When delays are discovered, the schedule is customized in Excel and printed. I think coordination software may contribute to discover and display the state of the construction schedule much easier.

RS: Do you often face delays within construction projects?

FC: Sometimes delays occur.

RS: If yes, what are most common delays and how they are caused?

FC: Unworkable weather may cause delays, such as rain during the placing of limestone elements or wind when the roof is being placed. It can also occur that the water well will flood during the groundworks, caused by the high groundwater level. In addition, a delayed supply of elements from sub-contractors may also causes delays in the project. Finally, a lack of availability of personnel (e.g. bricklayers) can also cause delays.

RS: How do you make delays visible during the construction phase of projects?

FC: On basis of a printout Excel or Asta Powerproject, a status line will be drawn on the printed schedule. Thereafter, there can be determined who is ahead or behind of schedule. In a GPS schedule, the status should be updated from day to day.

RS: How do you communicate these delays to (sub)contractor(s)?

FC: I always call the sub-contractor(s), because you do not know when they read their email. When delays are enormous, there will also be sent an email with costs caused by the delay.

❖ **Software Application**

RS: Do you think that a software application can help to detect future delays of construction projects?

FC: I think it works great and it is a good idea, however it is difficult to discover future delays. It is possible to change the as-built schedule when a delay is discovered and compare it with the as-planned schedule.

RS: How can a software application contribute to that?

FC: It would be ideal if the construction site engineer could see the as-built project status of that day and automatically compare it with the as-planned schedule. The project status should also be visualized in a table, to show the tasks in the construction schedule with corresponding colours. The deployment of cranes may also be included in the software application, because there is a lot of money involved.

❖ **Closure**

This was the end of the interview. Thank you for your cooperation and for taking your time! I will send the elaborated interviews to you by mail within a week.

Interview René van Alten

Date:	April 25, 2016
Time:	13:00h
Place:	Stationsplein 1, Rosmalen

| **Participants:** | René van Alten | Coordinator operations office | RvA |
| | Rob Simons | Graduate student TU/e | RS |

❖ **Introduction**

My name is Rob Simons and I am studying the master Construction Management and Engineering at the Technical University at Eindhoven. At 1 February 2016 I started with

graduation within Dura Vermeer Bouw Rosmalen. Previous interviews showed that crane deployment is essential for the construction process, also taken into consideration the high costs involved with it. I would like to develop a tool, which connects the 3D model and crane deployment data to analyse and optimize the crane deployment of residential projects.

By using this interview, I would like to identify how at this moment an optimal crane deployment for various construction projects is achieved. In addition, I want to discover which functional requirements are desirable for a software application to optimize crane deployment. The interview consists of 16 semi-structured questions, which is expected to last approximately one hour. Would you agree if I record the interview? Let us start.

❖ **Personal information**

RS: What is your age and which studies you have completed?

RvA: I am 45 years old. First, I studied at LTS (lower technical school), thereafter building technique and built environment at MTS (middle technical school) and finally building technique at HTS (higher technical school). My graduation subject was about the construction of a building and its requirements in order to meet.

RS: How long have you worked within the construction industry? And within Dura Vermeer?

RvA: After my studies, I worked 20 years for a local constructor in Tilburg, which was part of the road construction group. Currently, I work almost a year within Dura Vermeer. The first five months I was temporarily hired for a specific project as project manager.

RS: What is your function within Dura Vermeer?

RvA: Coordinator operations office. During the calculation phase, I define all parts of the direct costs; such as planning, construction site organizations, logistics, staff capacity and safety.

RS: On which type of construction projects are you currently active?

RvA: I am mainly active on utility construction projects, however also on residential projects. The residential projects are constructed according to the Pre Choice System (PCS), which is a system to build all dwellings from one baseline, such as a standard to draw details and calculate units. Residential construction projects are often built according to this standard, which results in less coordination for the parts, such as crane deployment.

RS: How many hours do you work at the office vs. at the construction site?

RvA: I work 36 hours at office and 4 hours on the construction site. However, I prefer to work 32 hours at the office and 8 hours on the construction site.

❖ **Crane deployment**

RS: Which types of construction cranes will be used for which activities (elements)?

RvA: This depends a lot on the specific project. Most common used cranes are the crawler crane, self-erecting crane, telescopic crane and tower crane. Residential PCS projects are constructed by using mobile cranes; usually the self-erecting crane and sometimes telescopic cranes. Crawler cranes will be used when the residential project has a prefabricated frame. Within residential projects, mobile cranes are usually located within a

range to place the floor elements for 4 till 5 dwellings. It takes about half an hour to move a mobile crane to another location on the construction site.

RS: What are the main activities (elements) concerning crane deployment for residential projects?
RvA: The heaviest is perhaps the concrete bucket and thereafter the concrete hollow-core slabs. In addition, the prefabricated foundation beams are important elements concerning crane deployment. Prefabricated roofs are less important, because they are not heavy (consisting of around 90% fibreglass). In principle, all elements that are heavier than 25kg have to be lifted.

RS: Which parameters are important to determine the amount and type of cranes?
RvA: First, the weight of the lifted elements is important. Second, the location(s) of the crane(s) are important (can I locate there? and is this correct?). The jack distances and dimensions of the crane are also significant factors for the location. Finally, the radius of the crane is important (how far the element has to be lifted?). The radius is depending on the mounting location of the element and unloading the elements from the truck to the storage on the construction site. It is also possible to reverse the whole process, to determine the crane type and investigate if the elements, location and lift distances can be adjusted.

RS: How are these parameters obtained?
RvA: The location of the crane can be determined by using construction site plans. The crane specifications are obtained from the sub-contractor who provides the cranes. These specifications are standard documentations, which mainly consists of tables.

RS: Is there for each construction project a crane deployment schedule created?
RvA: For residential projects, I have never done it within Dura Vermeer. However, when the project has an inconvenient location for the crane(s), something needs to be adjusted and scheduled for crane deployment. For utility construction projects, crane deployment schedules are created, in which the lift time for specific elements is determined by using standards. The lift time is often decisive for the construction time of a project, which is also dependent on the crane operator and the site staff.

RS: If yes, who creates the schedule and which software is used?
RvA: Timetables are created in Microsoft Excel and crane quantity states are shown in the calculation software IBIS-TRAD.
RS: Are there other tools (software) used to determine the crane deployment?
RvA: I use Autodesk AutoCAD as drawing software for the construction site plan, in order to draw/measure distances, building heights and sections. In addition, I visit the construction locations and take pictures as backup. Own knowledge is also very important, in which you should know where are your limits. When there are doubts concerning crane deployment, I ask an expert of the sub-contractor to give me advice about crane deployment.

RS: Has Dura Vermeer construction cranes under own management?
RvA: Yes, Dura Vermeer Equipment Service in Haaften, who manages tower cranes. Dura Vermeer Equipment Service has no mobile cranes in management.

RS: Are there also cranes hired from sub-contractors?
RvA: Yes; the crawler cranes, self-erecting cranes and telescopic cranes.

❖ **Software Application**

RS: Do you think that a software application can help to analyse the crane deployment of construction projects?
RvA: Yes, of course.

RS: How can a software application contribute to that?
RvA: I think it saves a lot of money, when all elements are lifted once and placed on the right mounting location. In other words, the lift moments should be deployed more efficiently. However, the sub-contractor of the mobile crane(s) asks for load- and unloads costs when it takes over an hour. In addition, the manufacturing process of the elements is also crucial, because each sub-contractor has its own system to produce and deliver elements.

❖ **Closure**

This was the end of the interview. Thank you for your cooperation and for taking your time! I will send the elaborated interviews to you by mail within a week.

Interview Frankwin Ceelen (2)

Date: May 17, 2016
Time: 15:00h
Place: Stationsplein 1, Rosmalen

Participants: Frankwin Ceelen   Construction site engineer   FC
                        Rob Simons   Graduate student TU/e   RS

❖ **Introduction**

My name is Rob Simons and I am studying the master Construction Management and Engineering at the Technical University at Eindhoven. At 1 February 2016 I started with graduation within Dura Vermeer Bouw Rosmalen. Previous interviews showed that crane deployment is essential for the construction process, also taken into consideration the high costs involved with it. I would like to develop a tool, which connects the 3D model and crane deployment data to analyse and optimize the crane deployment of residential projects.

By using this interview, I would like to identify how the crane deployment during the construction project of 7 dwellings in Drunen is determined. The interview consists of 11 semi-structured questions, which is expected to last approximately one hour. Would you agree if I record the interview? Let us start.

❖ **Crane deployment**

RS: Which type of construction cranes have been deployed during the project of 7 dwellings in Drunen?
FC: Four different cranes have been deployed: two types of self-erecting cranes (SK377-AT3 and SK498-AT4) and two types of telescopic cranes (KA040 and KA050). The SK377-AT3 self-

erecting crane have been deployed for around 80% of the crane hours during the project in Drunen.

RS: How is the choice concerning type of construction cranes determined?
FC: First, the rental price and quality of the construction crane are important. Secondly, the maximum lift range and maximum load capacity are crucial. By using a telescopic crane, activities on the ground floor can be lifted. When the lift height is higher, a self-erecting crane is more interesting. The KT044, SK498-AT4 self-erecting crane has been deployed for cleaning activities during the project in Drunen, where there was little space to place the crane.

RS: Is there a construction site map of the project 7 dwellings in Drunen available?
FC: Yes, I created this by myself on 2D. I will send it to you by mail.

RS: Are there any minimum hours (days) to rent a construction crane type?
FC: Yes, you can rent the SK377-AT3 self-erecting crane for a minimum of 3 hours. The telescopic cranes (KA040 and KA050) you can rent for a minimum of two hours. The minimum rental time of the KT044, SK498-AT4 self-erecting crane is four hours. Our sub-contractor defines these minimum rental hours.

RS: For which type of activities (elements) were these construction cranes deployed and can you show them in the calculation/construction schedule?
FC: The telescopic crane KA050 was deployed for pour concrete. The telescopic crane KA040 was used for some scaffolding works. The KT044, SK498-AT4 self-erecting crane has been deployed for cleaning activities at the end of the project, when there was little space to place the crane. For all other crane deployment activities, the SK377-AT3 self-erecting crane was used. These activities included:
-   Lifting brickwork at level zero
-   Placing the ground floor and filling grooves
-   Lifting limestone elements at the ground floor
-   Lifting scaffolding work between the ground floor and first floor
-   Placing concrete hollow-core slabs at the first floor
-   Fill the grooves of the concrete hollow-core slabs at the first floor
-   Lifting limestone elements and cellular concrete elements at the first floor
-   Lifting scaffolding work between the first- and second floor
-   Placing concrete hollow-core slabs at the first- and second floor
-   Fill the grooves of the concrete hollow-core slabs at first- and second floor
-   Lifting limestone elements for the tops
-   Lifting scaffolding work for the tops
-   Placing window frames at the ground floor
-   Lifting brickwork at the ground floor
-   Placing window frames at the first floor
-   Lifting brickwork at the first floor
-   Dismounting scaffolding works
-   Mounting wall plates
-   Mounting prefabricated roof panels and dormers

The brick chimneys are mounted by the sub-contractor (this is included in the price). Lintels and sills sometimes need crane deployment when they are heavier than 25 kg; however, in practice no crane is being used.

RS: How many elements can be processed per day or daypart?
FC: The storey floors of 7 dwellings can be placed in one day (8 hours). The limestone elements of one floor can be lifted for 14-15 dwellings in one day (8 hours). The grooves of the floors can be filled for 15-20 dwellings in one day (8 hours). All window frames of one storey for 7 dwellings can be placed within 4 hours.

RS: How long it will take to build a construction crane, to move the crane and to put the elements on the final location?
FC: The SK377-AT3 self-erecting crane is assembled within half an hour and moved in three quarters. The time to get the element on the final location depends on the sight of the crane operator, the location of the crane and the lifted elements (safety net, other lift equipment).

RS: Which safety factors must be taken into account regarding crane deployment?
FC: General safety measures (helmet, construction shoes, safety glasses) and stamping on a stable underground. In addition, rotation range must be shielded to the public (discuss with the crane operator), the crane operator should have an expertise certificate, the rigger should have a certificate concerning lifting equipment (how to pick elements and which equipment is needed for which elements) and wearing a walkie-talkie is required when the crane rotates out of sight.

RS: How many and which type of cranes have been deployed during other "PCS Groene Stroom" projects?
FC: Usually the SK377-AT3 self-erecting crane. This type of crane is moved in a short time, rotates quickly and the rental price is not that high.

RS: Are there often problems and delays caused by inefficient crane deployment?
FC: Yes, an optimal crane deployment is most important, because the rental of cranes will costs money.

RS: If yes, what are most common problems/delays and how they are caused?
FC: Delays may occur when a crane is located on a wrong place, so the crane should be moved. For example, the crane is located at the transport road or the crane cannot lift the elements concerning range/load capacity. The load capacity of a telescopic crane is always calculated without lift equipment. When a telescopic crane can lift 8000 kg and the lift equipment weight is 400 kg, then the lift capacity is 7600 kg. The load capacity of a self-erecting crane is also calculated without lift equipment; however, most important is the weight of the floor clamp (500-600 kg).

❖ **Closure**
This was the end of the interview. Thank you for your cooperation and for taking your time! I will send the elaborated interviews to you by mail within a week.

Interview Harry Brokken

Date: May 25, 2016
Time: 09:00h
Place: Bijenlaan, Son en Breugel

Participants:	Harry Brokken	Construction site engineer	HB
	Rob Simons	Graduate student TU/e	RS

❖ **Introduction**

My name is Rob Simons and I am studying the master Construction Management and Engineering at the Technical University at Eindhoven. At 1 February 2016 I started with graduation within Dura Vermeer Bouw Rosmalen. Previous interviews showed that crane deployment is essential for the construction process, also taken into consideration the high costs involved with it. I would like to develop a tool, which connects the 3D model and crane deployment data to analyse and optimize the crane deployment of residential projects.

By using this interview, I would like to identify how the crane deployment during different residential projects is determined. The interview consists of 16 semi-structured questions, which is expected to last approximately one hour. Would you agree if I record the interview? Let us start.

❖ **Personal information**

RS: What is your age and which studies you have completed?
HB: I am 51 years old. I studied the training program for (assistant) construction site engineer all-round. In addition, I did some training courses, such as working with AutoCAD and Solibri. Currently, I am learning BIM 360 Field.

RS: How long have you worked within the construction industry? And within Dura Vermeer?
HB: First, I worked 19 years as carpenter within P.K. van Eijkenlenburg, which was acquired by Dura Vermeer between 1996 and 1997. Nowadays, I am construction site engineer for 15 years within Dura Vermeer Bouw Rosmalen.

RS: What is your function within Dura Vermeer?
HB: Construction site engineer.

RS: On which type of construction projects are you currently active?
HB: I am active at residential PCS projects for 5 years. Previously, I was active on different type of projects; such as industrial projects, the construction of a school and other utility construction projects.

RS: How many hours do you work at the office vs. at the construction site?
HB: I work approximately 50 hours on the construction site. I prefer to work at the construction site, because a construction site engineer should regulate and control everything on the site.

❖ **Crane deployment**

RS: Which types of construction cranes will be used for which activities (elements) during "PCS Groene Stroom" projects?

HB: I use the KA050 (55 tons) telescopic crane up to and including the first floor. This type of crane is easy to move and is very strong. The activities for this crane include:
- Foundation works
- Placing the ground floor and filling grooves
- Lifting limestone elements
- Lifting scaffolding works
- Placing concrete hollow-core slabs at the first floor
- Fill the grooves of the concrete hollow-core slabs at the first floor

In addition, this type is cheaper than a self-erecting crane. After the first floor is placed and the grooves are filled, I use a self-erecting crane for the additional activities.

RS: Which parameters are important to determine the amount and type of cranes?

HB: The lift range of the crane, load capacity and the project implementation are important for the crane deployment. For example, mounting the prefabricated roof panels is outsourced to the sub-contractor of the roofs (the crane is included).

RS: How are these parameters obtained?

HB: These parameters are obtained from crane specifications, which are implemented intuitively and on experience.

RS: Do you create a construction site plan during projects, which consists of the crane position, storage location and construction site dimensions?

HB: No, I do not create these drawings for the PCS residential projects. The crane deployment for these residential projects is solely based on intuition and experience.

RS: Which other tools (software) can be used to determine the crane deployment?

HB: Nothing, I use specifications from the cranes and my experience. When heavier elements are lifted, I calculate the height * length * load, in order to know which crane I need.

RS: Are there any minimum hours (days) to rent a construction crane type?

HB: Yes, you can rent the telescopic cranes (KA040 and KA050) for a minimum of two hours. You can rent the SK377-AT3 self-erecting crane for a minimum of three hours. The minimum rental time of the KT044, SK498-AT4 self-erecting crane is four hours. Our sub-contractor defines these minimum rental hours, which are defined on a sheet.

RS: How many elements can be processed per day or daypart?

HB: The storey floors of 7 dwellings can be placed in one day (8 hours), in which one storey consists of ten concrete hollow-core slabs. All limestone elements can be lifted for 7 dwellings in one day (8 hours). The window frames of 7 dwellings can be placed within 8 hours.

RS: How long it will take to build a construction crane, to move the crane?

HB: A telescopic crane is assembled and dismantled within fifteen minutes. A self-erecting crane is assembled and dismantled within forty minutes.

RS: Which safety factors must be taken into account regarding crane deployment?

HB: Within the range of the crane, a helmet is required! Safety measures must be taken when crane operations are deployed. Chains are required when concrete hollow-core slabs are lifted. Putting forward brickwork needs that the bricks are covered with foil. When limestones are lifted, it is required to use safety equipment. When a pallet hook is used, a safety belt on the hook is mandatory. In addition, the crane operator must be certified and should have a driver's license.

RS: Are there often problems and delays caused by inefficient crane deployment?

HB: Not often, but sometimes it will happen.

RS: If yes, what are most common problems/delays and how they are caused?

HB: Delays may occur, when the crane operator does not fulfil the instructions of the construction site engineer. The crane operator must be on the correct location, which is determined by the construction site engineer. Other factors, which cause delays, are the transport of material and environmental factors, such as parking within the lift range of the crane. It is important to solve these issues in advance. Me (Harry) and Frankwin Ceelen (construction site engineer) have a different view on crane deployment. Frankwin uses the SK377-AT3 self-erecting crane for almost all construction activities, because this crane rotates the easiest. I use telescopic cranes up to and including the first floor. These types of cranes are cheaper in comparison with the self-erecting cranes, however they do not rotate as fast as the self-erecting cranes. I make this choice from a financial perspective, while Frankwin considers that the usability is more important.

❖ **Closure**

This was the end of the interview. Thank you for your cooperation and for taking your time! I will send the elaborated interviews to you by mail within a week.

Appendix 2 – Measurements observations

Table A2.1. Observation limestone elements.

Lift	Hooking	Flight	Unhooking	Flight	Total
1	0:40	0:19	0:31	0:16	1:46
2	0:32	0:17	0:29	0:46	2:04
3	0:20	0:18	0:28	0:14	1:20
4	0:27	0:19	0:29	0:16	1:31
5	0:23	0:17	0:30	0:17	1:27
6	0:26	0:21	0:21	0:26	1:34
7	0:38	0:20	0:32	0:19	1:49
8	0:29	0:21	0:36	0:18	1:44
9	0:22	0:18	0:25	0:21	1:26
10	0:41	0:19	0:34	0:29	2:03
11	0:30	0:23	0:32	0:18	1:43
12	0:25	0:20	0:29	0:15	1:29
13	0:31	0:18	0:26	0:18	1:33
14	0:20	0:23	0:31	0:22	1:36
15	0:25	0:19	0:29	0:18	1:31
16	0:33	0:19	0:24	0:22	1:38
17	0:22	0:17	0:31	0:18	1:28
18	0:24	0:18	0:29	0:14	1:25
19	0:32	0:21	0:35	0:22	1:50
20	0:27	0:18	0:28	0:23	1:36
21	0:35	0:15	0:33	0:32	1:55
22	0:26	0:20	0:26	0:28	1:40
23	0:23	0:15	0:31	0:25	1:34
24	0:38	0:24	0:21	0:23	1:46
25	0:21	0:18	0:35	0:20	1:34
26	0:27	0:19	0:30	0:18	1:34
27	0:33	0:18	0:27	0:22	1:40
28	0:41	0:18	0:24	0:22	1:45
29	0:23	0:17	0:24	0:27	1:31
30	0:37	0:24	0:35	0:23	1:59
Average	**0:30**	**0:19**	**0:29**	**0:21**	**1:39**

Table A2.2. Observation brickwork.

Lift	Hooking	Flight	Unhooking	Flight	Total
1	0:20	0:35	1:33	0:32	3:00
2	0:24	0:21	1:39	0:15	2:39
3	0:30	0:16	2:25	0:19	3:30
4	0:28	0:18	1:51	0:26	3:03
5	0:29	0:22	2:18	0:18	3:27
6	0:19	0:17	1:32	0:21	2:29
7	0:24	0:25	1:22	0:18	2:29
8	0:27	0:21	2:11	0:31	3:30
9	0:21	0:22	2:03	0:15	3:01

10	0:23	0:18	2:20	0:30	3:31
11	0:31	0:23	2:27	0:27	3:48
12	0:28	0:29	2:11	0:21	3:29
13	0:24	0:18	2:28	0:17	3:27
14	0:27	0:21	1:31	0:22	2:41
15	0:28	0:20	1:56	0:22	3:06
16	0:19	0:18	2:05	0:15	2:57
17	0:25	0:17	1:38	0:17	2:37
18	0:27	0:22	1:44	0:17	2:50
19	0:30	0:24	1:55	0:19	3:08
20	0:31	0:18	1:50	0:16	2:55
Average	**0:25**	**0:21**	**1:56**	**0:20**	**3:02**

Table A2.3. Observation cellular concrete elements.

Lift	Hooking	Flight	Unhooking	Flight	Total
1	0:31	0:30	0:42	0:17	2:00
2	0:28	0:13	0:31	0:22	1:34
3	0:33	0:18	0:32	0:27	1:50
4	0:22	0:21	0:43	0:17	1:43
5	0:24	0:15	0:26	0:19	1:24
6	0:21	0:17	0:33	0:22	1:33
7	0:45	0:18	0:34	0:19	1:56
8	0:30	0:23	0:37	0:26	1:56
9	0:30	0:15	0:31	0:27	1:43
10	0:41	0:26	0:39	0:23	2:09
11	0:37	0:15	0:25	0:18	1:35
12	0:37	0:14	0:28	0:24	1:43
13	0:22	0:22	0:31	0:26	1:41
14	0:27	0:19	0:41	0:18	1:45
15	0:50	0:18	0:30	0:26	2:04
16	0:32	0:24	0:22	0:25	1:43
17	0:23	0:22	0:21	0:19	1:25
18	0:39	0:19	0:33	0:23	1:54
19	0:28	0:23	0:28	0:18	1:37
20	0:31	0:24	0:19	0:20	1:34
Average	**0:31**	**0:19**	**0:30**	**0:20**	**1:40**

Table A2.4. Observation concrete hollow-core slabs.

Lift	Hooking	Flight	Unhooking	Flight	Total
1	0:23	0:21	1:16	0:24	2:24
2	0:17	0:20	1:41	0:26	2:44
3	0:19	0:21	1:39	0:28	2:47
4	1:46	0:41	1:36	0:26	4:29
5	1:24	0:30	2:54	0:16	5:04
6	0:48	0:22	2:13	0:17	3:40
7	0:56	0:20	2:01	0:16	3:33
Average	**0:50**	**0:25**	**1:54**	**0:21**	**3:30**

Table A2.5. Observation window frames.

Lift	Hooking	Flight	Unhooking	Flight	Total
1	2:35	0:42	1:50	0:25	5:32
2	1:00	0:38	1:23	0:33	3:34
3	1:38	0:45	1:41	0:30	4:34
4	1:55	0:40	1:38	0:42	4:55
5	1:21	0:33	1:45	0:28	4:07
Average	**1:41**	**0:39**	**1:39**	**0:31**	**4:30**

Appendix 3 – Part of the output CSV-file

Table A3.1. Output CSV-file (location C1-S1).

GUID	Element type	Element weight [kg]	Flight index	Capacity crane [kg]	Capacity material storage [kg]	Lifted?	Lift duration [min]
00rpqOXJTEIf SD2ORXlo2q	IfcWallStandardCase	5683.04	7	4490	7500	too heavy	
00rpqOXJTEIf SD2ORXlo3L	IfcSlab	1937.612866	5	1975	7500	can be lifted	5.867348642
38qvkIOZDB1 xtnLVLnvhfF	IfcCurtainWall	144.4436	6	1900	7500	can be lifted	6.366807708
1wO1DsiDPC Vh_lKlIzcLtr	IfcWindow	163.1271723	17	1900	7500	can be lifted	7.27424588

Appendix 4 – Tables IFC data building elements

Table A4.1. IFC data window frame.

Element type	#2069= IFCCURTAINWALL('0k4qeubkXBwOb$RolzGIUp',#41,'Curtain Wall:NLRS_31_CW_Merk A:979906',$,'Curtain Wall:NLRS_31_CW_Merk A:986175',#2068,$,'979906');
Unit	#2452= IFCPROPERTYSINGLEVALUE('Area',$,IFCAREAMEASURE(2.88887200000001),$); #2482= IFCPROPERTYSET('0k4qeubkXBwOb$QIdzGIUp',#41,'Dimensions',$,(#2452,#2453)); #2484= IFCRELDEFINESBYPROPERTIES('0k4qeubkXBwOb$Q2dzGIUp',#41,$,$,(#2069),#2482);

Table A4.2. IFC data sliding door.

Element type	#23731= IFCWINDOW('1wO1DsiDPCVh_lKlIzcJ65',#41,'NLRS_31_WI_Aluminium schuifpui2:31_schuifpui_aluminium:1058185',$,'31_schuifpui_aluminium',#23730,#23725,'1058185',2578.00000000259,2524.00000000262);
Unit	#23755= IFCPROPERTYSINGLEVALUE('Area',$,IFCAREAMEASURE(3.26254344636161),$); #23791= IFCPROPERTYSET('1wO1DsiDPCVh_lLFQzcJ65',#41,'Dimensions',$,(#23755,#23756,#23757,#23758,#23759)); #23793= IFCRELDEFINESBYPROPERTIES('1wO1DsiDPCVh_lLVQzcJ65',#41,$,$,(#23731),#23791);

Table A4.3. IFC data concrete hollow-core slab.

Element type	#7881= IFCSLAB('38qvkIOZDB1xtnLVLnvhjj',#41,'Floor:NLRS_23_FL_kanaalplaat 200_gen:1045667',$,'Floor:NLRS_23_FL_kanaalplaat 200_gen',#7828,#7879,'1045667',.FLOOR.);
Unit	#7942= IFCPROPERTYSINGLEVALUE('Volume',$,IFCVOLUMEMEASURE(7.74076945828633),$); #7948= IFCPROPERTYSET('38qvkIOZDB1xtnK$Tnvhjj',#41,'Dimensions',$,(#7935,#7936,#7937,#7938,#7939,#7940,#7941,#7942)); #7950= IFCRELDEFINESBYPROPERTIES('38qvkIOZDB1xtnKlTnvhjj',#41,$,$,(#7881),#7948);
Material	#1220= IFCMATERIAL('NLRS_f2_beton_prefab'); #1234= IFCMATERIALLAYER(#1220,200.,$); #1235= IFCMATERIALLAYERSET((#1234),'Floor:NLRS_23_FL_kanaalplaat 200_gen'); #7912= IFCMATERIALLAYERSETUSAGE(#1235,.AXIS3.,.POSITIVE.,0.); #61372= IFCRELASSOCIATESMATERIAL('2X3o313M9C9RpfWw6ZBJjz',#41,$,$,(#7881),#7912);

Table A4.4. IFC data waffle slab.

Element type	#21233= IFCSLAB('1wO1DsiDPCVh_lKlIzcJVp',#41,'Floor:NLRS_23_FL_ribcassettevloer 350mm_gen:1057791',$,'Floor:NLRS_23_FL_ribcassettevloer 350mm_gen',#21212,#21231,'1057791',.FLOOR.);
Unit	#21551= IFCPROPERTYSINGLEVALUE('Volume',$,IFCVOLUMEMEASURE(16.6741224999997),$); #21570= IFCPROPERTYSET('1wO1DsiDPCVh_lLFQzcJVp',#41,'Dimensions',$,(#21544,#21545,#21546,#21547,#21548,#21549,#21550,#21551)); #21572= IFCRELDEFINESBYPROPERTIES('1wO1DsiDPCVh_lLVQzcJVp',#41,$,$,(#21233),#21570);
Material	#1220= IFCMATERIAL('NLRS_f2_beton_prefab'); #21491= IFCMATERIAL('NLRS_n7_isolatie'); #21505= IFCMATERIALLAYER(#1220,200.,$); #21506= IFCMATERIALLAYER(#21491,150.,$); #21507= IFCMATERIALLAYERSET((#21505,#21506),'Floor:NLRS_23_FL_ribcassettevloer 350mm_gen'); #21511= IFCMATERIALLAYERSETUSAGE(#21507,.AXIS3.,.POSITIVE.,0.); #61538= IFCRELASSOCIATESMATERIAL('077ao6aWLDnP7PtDKo$SYX',#41,$,$,(#21233),#21511);

Table A4.5. IFC data limestone element.

Element type	#192= IFCWALLSTANDARDCASE('00rpqOXJTEIfSD2ORXlo2p',#41,'Basic Wall:NLRS_22_WA_kzs element dragend woningscheidend 120 CS12_gen:835755',$,'Basic Wall:NLRS_22_WA_kzs element dragend woningscheidend 120 CS12_gen:755007',#161,#188,'835755');
Unit	#258= IFCPROPERTYSINGLEVALUE('Volume',$,IFCVOLUMEMEASURE(2.71152),$); #287= IFCPROPERTYSET('00rpqOXJTEIfSD3uJXlo2p',#41,'Dimensions',$,(#256,#257,#258)); #289= IFCRELDEFINESBYPROPERTIES('00rpqOXJTEIfSD3eJXlo2p',#41,$,$,(#192),#287);
Material	#216= IFCMATERIAL('NLRS_f1_kalkzandsteen_dragend'); #229= IFCMATERIALLAYER(#216,120.,$); #231= IFCMATERIALLAYERSET((#229),'Basic Wall:NLRS_22_WA_kzs element dragend woningscheidend 120 CS12_gen'); #234= IFCMATERIALLAYERSETUSAGE(#231,.AXIS2.,.POSITIVE.,-60.); #61258= IFCRELASSOCIATESMATERIAL('1tiHlpNxP6GxqrhvEjYtQT',#41,$,$,(#192),#234);

Table A4.6. IFC data brickwork.

Element type	#1516= IFCWALLSTANDARDCASE('3DBlji4inEYAvYqo63lFzj',#41,'Basic Wall:NLRS_21_WA_mw rood 100_gen:849171',$,'Basic Wall:NLRS_21_WA_mw rood 100_gen:30899',#1490,#1514,'849171');
Unit	#1586= IFCPROPERTYSINGLEVALUE('Volume',$,IFCVOLUMEMEASURE(1.0555562),$); #1605= IFCPROPERTYSET('3DBlji4inEYAvYrIE3lFzj',#41,'Dimensions',$,(#1584,#1585,#1586)); #1607= IFCRELDEFINESBYPROPERTIES('3DBlji4inEYAvYr2E3lFzj',#41,$,$,(#1516),#1605);
Material	#1563= IFCMATERIAL('NLRS_g2_baksteen_wf_210x100x50_10mm_voeg_halfsteens_rood_genuanceerd'); #1573= IFCMATERIALLAYER(#1563,100.,$); #1574= IFCMATERIALLAYERSET((#1573),'Basic Wall:NLRS_21_WA_mw rood 100_gen'); #1577= IFCMATERIALLAYERSETUSAGE(#1574,.AXIS2.,.NEGATIVE.,50.); #61290= IFCRELASSOCIATESMATERIAL('3ZQFlMNGP28Bc5LFDK8CXt',#41,$,$,(#1516),#1577);

Table A4.7. IFC data cellular concrete element.

Element type	#5349= IFCWALLSTANDARDCASE('3LGFC514D1BQr6nAzKKojq',#41,'Basic Wall:NLRS_22_WA_Ytong 100_gen:1018792',$,'Basic Wall:NLRS_22_WA_Ytong 100_gen:758362',#5323,#5347,'1018792');
Unit	#5385= IFCPROPERTYSINGLEVALUE('Volume',$,IFCVOLUMEMEASURE(0.58079999999995),$); #5407= IFCPROPERTYSET('3LGFC514D1BQr6mgrKKojq',#41,'Dimensions',$,(#5383,#5384,#5385)); #5409= IFCRELDEFINESBYPROPERTIES('3LGFC514D1BQr6mwrKKojq',#41,$,$,(#5349),#5407);
Material	#5364= IFCMATERIAL('NLRS_f4_cellenbeton_panelen_900_wit_generiek'); #5374= IFCMATERIALLAYER(#5364,100.,$); #5375= IFCMATERIALLAYERSET((#5374),'Basic Wall:NLRS_22_WA_Ytong 100_gen'); #5378= IFCMATERIALLAYERSETUSAGE(#5375,.AXIS2.,.POSITIVE.,-50.); #61308= IFCRELASSOCIATESMATERIAL('398zkjiDzE3vHs0hnc6PtO',#41,$,$,(#5349),#5378);

Appendix 5 – Tables CSV-files

Table A5.1. CSV-file "SK377-AT3 dimensions" (Riel, 2013).

Length [m]	Width [m]	Height [m]	Length from backside [m]
13.3	7.5	4	2.45

Table A5.2. CSV-file "SK377-AT3 ranges" (Riel, 2013).

Lift range [m]	Load capacity [kg]	Max lift height [m]
0-3.5	0	20
3.5-10.5	7500	20
10.5-11.5	7030	20
11.5-12.5	6325	20
12.5-13.5	5745	20
13.5-14.5	5260	20
14.5-15.5	4845	20
15.5-16.5	4490	20
16.5-17.5	4175	20
17.5-18.5	3905	20
18.5-19.5	3665	20
19.5-20.5	3450	20
20.5-21.5	3255	20
21.5-22.5	3080	20
22.5-23.5	2925	20
23.5-24.5	2780	20
24.5-25.5	2650	20
25.5-26.5	2530	20
26.5-27.5	2420	20
27.5-28.5	2315	20
28.5-29.5	2220	20
29.5-30.5	2130	20
30.5-31.5	2050	20
31.5-32.5	1975	20
32.5-33	1900	20

Table A5.3. CSV-file "SK377-AT3 speed" (Riel, 2013).

Load capacity [kg]	Lift speed horizontal [m/min]	Lift speed vertical [m/min]	Rotation speed [rotation/min]
0	70	60	1
1900	70	36	1
1975	70	36	1
2050	70	35	1
2130	70	35	1
2220	70	34	1
2315	70	33	1
2420	70	33	1
2530	70	32	1
2650	70	31	1

2780	70	31	1
2925	70	30	1
3080	70	29	1
3255	70	28	1
3450	70	28	1
3665	70	27	1
3905	70	26	1
4175	70	25	1
4490	70	24	1
4845	70	23	1
5260	70	22	1
5745	70	21	1
6325	70	20	1
7030	70	19	1
7500	70	18	1

Table A5.4. CSV-file "hook and unhook time".

Material_name	hook_time [min]	unhook_time [min]
NLRS_f1_kalkzandsteen	0.5	0.5
NLRS_g2_baksteen	0.42	1.92
NLRS_f4_cellenbeton	0.5	0.5
NLRS_31_CW_Merk	1.67	1.67
NLRS_31_WI_Aluminium	1.67	1.67
NLRS_23_FL_kanaalplaat	0.83	1.92
NLRS_23_FL_ribcassettevloer	0.83	1.92

Table A5.5. CSV-file "material specifications" (Boxtel, 1995) (Belgische Baksteenfederatie, 2008) (Riel, 2013) (NCV, 2016) (Vin, 2016) (VBI, 2016) (Betonson Prefab B.V. , 2016) (Nemaco Holding B.V., 2016) (Van Eck Verreikerverhuur, 2016) (Betonson Prefab B.V. , 2016).

Material_name	weight1 [kg_m3]	weight2 [kg_m2]	max_length [m]	max_width [m]	equipment_crane [kg]
NLRS_f1_kalkzandsteen	2000				260
NLRS_g2_baksteen	2100				170
NLRS_f4_cellenbeton	800				
NLRS_31_CW_Merk		50			
NLRS_31_WI_Aluminium		50			
NLRS_23_FL_kanaalplaat	1540		7.6	1.2	480
NLRS_23_FL_ribcassettevloer	646		6.5	1.2	480

Appendix 6 – Main Python code

```python
import OCC.gp
import OCC.Bnd
import OCC.BRepPrimAPI
import OCC.BRepAlgoAPI
import OCC.BRepBndLib
import OCC.BRepPrimAPI
import OCC.BRepClass3d
import OCC.GProp
from OCC.BRepGProp import brepgprop_VolumeProperties

import ifcopenshell
import ifcopenshell.geom

from viewer import viewer
from collections import namedtuple

import crane_dimensions
import crane_ranges
import material_specifications
import crane_speed
import hook_time
import user_input

from get_property import get_property
from make_hollow_cylinder import make_hollow_cylinder
from materialname import contains_materialname

import math
import csv

def get_volume(shp):
    p = OCC.GProp.GProp_GProps()
    brepgprop_VolumeProperties(shp, p)
    return p.Mass()

f = ifcopenshell.open('models/Project_Drunen.ifc')

s = ifcopenshell.geom.settings()
s.set(s.USE_PYTHON_OPENCASCADE, True)

v = viewer()

colors = [
    ('IfcSite', (0.75, 0.8, 0.65)),
    ('IfcSlab', (0.4 , 0.4, 0.4)),
    ('IfcWall', (0.8, 0.8, 0.8)),
    ('IfcWindow', (0.75, 0.8, 0.75, 0.1)),
    ('IfcDoor', (0.55, 0.3, 0.15))
]

# A bounding box for the entire model
bbox = OCC.Bnd.Bnd_Box()

elements = []
```

```python
elem_props = namedtuple("elem_props", ("ifc_product", "ifc_type", "weight", "center_point", "shape",
"hook_time"))

for p in f.by_type('IfcProduct'):

    if p.is_a() not in {'IfcWallStandardCase', 'IfcSlab', 'IfcWindow', 'IfcCurtainWall'}: continue

    if p.Representation:
        shp = ifcopenshell.geom.create_shape(s, p).geometry
        OCC.BRepBndLib.brepbndlib_Add(shp, bbox)
        clr = None
        for ty, c in colors:
            if p.is_a(ty):
                clr = c
                break

        bbox_element = OCC.Bnd.Bnd_Box()
        OCC.BRepBndLib.brepbndlib_Add(shp, bbox_element)
        xmin, ymin, zmin, xmax, ymax, zmax = bbox_element.Get()

    elif p.is_a("IfcCurtainWall") and p.IsDecomposedBy:

        bbox_element = OCC.Bnd.Bnd_Box()

        shp = OCC.TopoDS.TopoDS_Compound()
        builder = OCC.BRep.BRep_Builder()
        builder.MakeCompound(shp)

        for rel in p.IsDecomposedBy:
            for el in rel.RelatedObjects:
                if el.Representation:
                    sub_shp = ifcopenshell.geom.create_shape(s, el).geometry
                    builder.Add(shp, sub_shp)
                    OCC.BRepBndLib.brepbndlib_Add(sub_shp, bbox_element)

        xmin, ymin, zmin, xmax, ymax, zmax = bbox_element.Get()

    area = get_property("Area", p)
    volume = get_property("Volume", p)

    weight = None
    max_width = None
    max_length = None

    for mat_name, kgm3, kgm2, ml, mw, kgm in material_specifications.material_specs():
        if contains_materialname(p, mat_name) or mat_name in p.Name:
            if kgm3 is not None:
                weight = (volume * kgm3)
            else:
                weight = (area * kgm2)

            if kgm is not None:
                weight = weight + kgm

            max_width = mw
            max_length = ml
```

```
        hook_time_crane = None

    for mat_name, hook_time1, unhook_time1 in hook_time.hook_time():
        if contains_materialname(p, mat_name) or mat_name in p.Name:
            hook_time_crane = hook_time1 + unhook_time1

    element_length = xmax - xmin
    element_width = ymax - ymin

    if (max_length is not None and max_width is not None) and (element_width > max_width or element_length
> max_length):

        x1 = xmin
        y1 = ymin

        shp = ifcopenshell.geom.create_shape(s, p).geometry

        bbox_element = OCC.Bnd.Bnd_Box()
        OCC.BRepBndLib.brepbndlib_Add(shp, bbox_element)
        xmin, ymin, zmin, xmax, ymax, zmax = bbox_element.Get()

        element_length = xmax - xmin
        element_width = ymax - ymin

        y1 = ymin - 0.00001

        while y1 < ymax:

            y2 = y1 + max_width
            x1 = xmin - 0.00001

            while x1 < xmax:

                x2 = x1 + max_length

                box = OCC.BRepPrimAPI.BRepPrimAPI_MakeBox(OCC.gp.gp_Pnt(x1, y1, zmin - 1), OCC.gp.gp_Pnt(x2,
y2, zmax + 1)).Shape()
                cut_shape = OCC.BRepAlgoAPI.BRepAlgoAPI_Common(shp, box).Shape()

                try:
                    xmin2, ymin2, zmin2, xmax2, ymax2, zmax2 = bbox_element.Get()
                except:
                    x1 = x2
                    continue

                v0 = get_volume(shp)
                v1 = get_volume(cut_shape)
                element_weight = weight / v0 * v1

                if element_weight < 0.1:
                    x1 = x2
                    continue

                elements.append(elem_props(
                    p.GlobalId,
                    p.is_a(),
                    element_weight,
```

```python
                OCC.gp.gp_Pnt((xmin2+xmax2) / 2., (ymin2+ymax2) / 2., zmax2),
                shp,
                hook_time_crane
            ))

            x1 = x2

        y1 = y2

    else:
        elements.append(elem_props(
            p.GlobalId,
            p.is_a(),
            weight,
            OCC.gp.gp_Pnt((xmin+xmax) / 2., (ymin+ymax) / 2., zmax),
            shp,
            hook_time_crane
        ))

# Get the
xmin, ymin, zmin, xmax, ymax, zmax = bbox.Get()

# Draw the entire model bounding box
v.display(OCC.BRepPrimAPI.BRepPrimAPI_MakeBox(
    OCC.gp.gp_Pnt(xmin, ymin, zmin),
    OCC.gp.gp_Pnt(xmax, ymax, zmax)
    ).Shape(), color=(0,0,0,0))

user_coords = user_input.determine_coordinates()
print('Location crane = (%1.1f, %1.1f, %1.1f) Location material storage = (%1.1f, %1.1f, %1.1f)' %
tuple(user_coords))

output_filename = "Output data: Location crane = (%1.1f, %1.1f, %1.1f) Location material storage = (%1.1f,
%1.1f, %1.1f).csv" % tuple(user_coords)
output_file = open(output_filename, 'w', newline='')
output_data = csv.writer(output_file)

output_data.writerow(["GUID", "Element type", "Element weight [kg]", "Flight index", "Capacity crane [kg]",
"Capacity material storage [kg]", "Lifted?", "Lift duration [min]"])

CRANE_LOCATION = OCC.gp.gp_Pnt(user_coords[0] + xmin + crane_dimensions.length_from_backside(),
user_coords[1] + ymin - crane_dimensions.width()/2, user_coords[2] + zmin)
CRANE_RADIUS = OCC.gp.gp_Ax2(CRANE_LOCATION, OCC.gp.gp_Dir(0,0,1))
STORAGE_LOCATION = OCC.gp.gp_Pnt(user_coords[3] + xmin, user_coords[4] + ymin, user_coords[5] + zmin)

# Draw the crane
v.display(OCC.BRepPrimAPI.BRepPrimAPI_MakeBox(
    OCC.gp.gp_Pnt(CRANE_LOCATION.X() - crane_dimensions.length_from_backside(), CRANE_LOCATION.Y() -
crane_dimensions.width() / 2, CRANE_LOCATION.Z()),
    crane_dimensions.length(),crane_dimensions.width(),crane_dimensions.height() # < Dimensions of crane,
to update based on csv files
    ).Shape(), color=(0.2,0.2,0.2))

crane_flights = []

for inner_radius, outer_radius, height in crane_ranges.radius():
    c = make_hollow_cylinder(CRANE_RADIUS, inner_radius, outer_radius, height)
```

```
    crane_flights.append(c)
    v.display(c, color=(0.8,0.8,0.8,0.1))

# Draw storage location
v.display(OCC.BRepPrimAPI.BRepPrimAPI_MakeBox(
    OCC.gp.gp_Pnt(STORAGE_LOCATION.X(), STORAGE_LOCATION.Y() - 2, STORAGE_LOCATION.Z()),
    2,2,0.001
    ).Shape(), color=(0.4,0.4,0.4))

# for flight in crane_flights:
flight_capacities = []
for f in crane_ranges.crane_flights():
    flight_capacities.append(f[2])

flight_index = 0
storage_flight = None
for inner_radius, outer_radius, height in crane_ranges.radius():
    distance = OCC.gp.gp_Pnt(CRANE_LOCATION.X(), CRANE_LOCATION.Y(),
0).Distance(OCC.gp.gp_Pnt(STORAGE_LOCATION.X(), STORAGE_LOCATION.Y(), 0))
    contained_in_flight = (distance >= inner_radius and distance < outer_radius) and (CRANE_LOCATION.Z() +
height > STORAGE_LOCATION.Z())

    if contained_in_flight:
        storage_flight = flight_index
    flight_index = flight_index + 1

if storage_flight is None:
    storage_flight_capacity = 0.
else:
    storage_flight_capacity = flight_capacities[storage_flight]

for elem in elements:

    flight_index = 0
    for inner_radius, outer_radius, height in crane_ranges.radius():
        distance = OCC.gp.gp_Pnt(CRANE_LOCATION.X(), CRANE_LOCATION.Y(),
0).Distance(OCC.gp.gp_Pnt(elem.center_point.X(), elem.center_point.Y(), 0))
        contained_in_flight = (distance >= inner_radius and distance < outer_radius) and (CRANE_LOCATION.Z() +
height > elem.center_point.Z())

        if contained_in_flight:
            break
        flight_index = flight_index + 1

    if flight_index == len(flight_capacities):
        flight_index = None
        capacity = None
    else:
        capacity = flight_capacities[flight_index]

    if (capacity is None):
        v.display(elem.shape, color=(1, 0.5, 0))
        lifted = "out of range"

    elif (capacity is not None) and (elem.weight > capacity or elem.weight > storage_flight_capacity):
        v.display(elem.shape, color=(1, 0, 0))
        lifted = "too heavy"
```

```python
        else:
            v.display(elem.shape, color=(0, 1, 0))
            lifted = "can be lifted"

    # Lift duration of the crane
    distance_hor = abs((OCC.gp.gp_Pnt(CRANE_LOCATION.X(), CRANE_LOCATION.Y(),
0)).Distance(OCC.gp.gp_Pnt(STORAGE_LOCATION.X(), STORAGE_LOCATION.Y(), 0)) -
(OCC.gp.gp_Pnt(CRANE_LOCATION.X(), CRANE_LOCATION.Y(),
0)).Distance(OCC.gp.gp_Pnt(elem.center_point.X(), elem.center_point.Y(), 0)))
    distance_vert = abs((OCC.gp.gp_Pnt(0, 0, STORAGE_LOCATION.Z())).Distance(OCC.gp.gp_Pnt(0, 0,
elem.center_point.Z())))
    storage_direction = OCC.gp.gp_Dir(STORAGE_LOCATION.X() - CRANE_LOCATION.X(), STORAGE_LOCATION.Y()
- CRANE_LOCATION.Y(), 0)
    element_direction = OCC.gp.gp_Dir(elem.center_point.X() - CRANE_LOCATION.X(), elem.center_point.Y() -
CRANE_LOCATION.Y(), 0)
    angle_rotation = storage_direction.Angle(element_direction) / (2 * math.pi)

    total_duration = None

    if lifted == "can be lifted":
        capacity_0, horizontal_speed_0, vertical_speed_0, rotation_speed_0 = crane_speed.crane_speed()[0]
        for capacity, horizontal_speed, vertical_speed, rotation_speed in crane_speed.crane_speed():
            if capacity >= elem.weight:
                duration_hor = (distance_hor / horizontal_speed) + (distance_hor / horizontal_speed_0)
                duration_vert = (distance_vert / vertical_speed) + (distance_vert / vertical_speed_0)
                duration_rotat = (angle_rotation / rotation_speed) + (angle_rotation / rotation_speed_0)
                total_duration = duration_hor + duration_vert + duration_rotat + elem.hook_time
                break

    output_data.writerow([elem.ifc_product, elem.ifc_type, elem.weight, flight_index, capacity,
storage_flight_capacity, lifted, total_duration])

output_file.close()

total_window_duration = 0
total_floor_duration = 0

with open(output_filename) as f:
    reader = csv.reader(f)

    for i, (guid, element_type, element_weight, flight_index, cap_crane, cap_storage, lifted, lift_duration) in
enumerate(reader):
        if i == 0: continue
        if lift_duration == '': continue
        if element_type == "IfcWindow" or element_type == "IfcCurtainWall":
            total_window_duration = (total_window_duration + float(lift_duration))
        if element_type == "IfcSlab":
            total_floor_duration = (total_floor_duration + float(lift_duration))

        total = total_window_duration + total_floor_duration

total_window_duration_hours = total_window_duration/60
total_floor_duration_hours = total_floor_duration/60
total = total_window_duration_hours + total_floor_duration_hours

import numpy as np
```

```
import matplotlib.pyplot as plt

bu_elements = ('Window frames', 'Floors', 'Total')
values = [total_window_duration_hours, total_floor_duration_hours, total]

index = np.arange(len(bu_elements))
width = 0.6

widthscale = len(bu_elements)*1.8
heightscale = len(values)*1.8
fig, ax = plt.subplots(figsize=(widthscale, heightscale))
bar1 = ax.bar(index, values, align='center', width=width, linewidth=0.5, color='#EDE211')
bar1[2].set_color('#006056')

# add some text for labels, title and axes ticks
ax.set_ylabel('Lift duration [hours]')
ax.set_title('Crane = (%1.1f, %1.1f, %1.1f) Storage = (%1.1f, %1.1f, %1.1f)' % tuple(user_coords))
ax.set_xticks(index)
ax.set_xticklabels(bu_elements)

def autolabel(bars):
    # attach some text labels
    for bar in bars:
        height = bar.get_height()
        ax.text(bar.get_x() + bar.get_width()/2., height + 0.2, '%1.2f' %height, ha='center', va='bottom')

autolabel(bar1)

plt.savefig("Lift duration: Location crane = (%1.1f, %1.1f, %1.1f) Location material storage = (%1.1f, %1.1f,
%1.1f).png" % tuple(user_coords))
plt.show()

can_be_lifted_win = 0
out_of_range_win = 0
too_heavy_win = 0
can_be_lifted_slab = 0
out_of_range_slab = 0
too_heavy_slab = 0

with open(output_filename) as f:
    reader = csv.reader(f)

    for i, (guid, element_type, element_weight, flight_index, cap_crane, cap_storage, lifted, lift_duration) in
enumerate(reader):
        if i == 0: continue
        if element_type == "IfcWindow" or element_type == "IfcCurtainWall":
            can_be_lifted_win = can_be_lifted_win + lifted.count("can be lifted")
            out_of_range_win = out_of_range_win + lifted.count("out of range")
            too_heavy_win = too_heavy_win + lifted.count("too heavy")
        if element_type == "IfcSlab":
            can_be_lifted_slab = can_be_lifted_slab + lifted.count("can be lifted")
            out_of_range_slab = out_of_range_slab + lifted.count("out of range")
            too_heavy_slab = too_heavy_slab + lifted.count("too heavy")

        total_can_be_lifted = can_be_lifted_win + can_be_lifted_slab
        total_out_of_range = out_of_range_win + out_of_range_slab
        total_too_heavy = too_heavy_win + too_heavy_slab
```

```python
bu_elements = ('Window frames', 'Floors', 'Total')
can_be_lifted = (can_be_lifted_win, can_be_lifted_slab, total_can_be_lifted)
out_of_range = (out_of_range_win, out_of_range_slab, total_out_of_range)
too_heavy = (too_heavy_win, too_heavy_slab, total_too_heavy)

index = np.arange(len(bu_elements))
width = 0.3

values = [can_be_lifted, out_of_range, too_heavy]

widthscale = len(bu_elements)*1.8
heightscale = len(values)*1.8
fig, ax = plt.subplots(figsize=(widthscale, heightscale))

bar1 = ax.bar(index, can_be_lifted, align='center', width=width, linewidth=0.5, color=(0, 1, 0))
bar2 = ax.bar(index+width, out_of_range, align='center', width=width, linewidth=0.5, color=(1, 0.5, 0))
bar3 = ax.bar(index+width*2, too_heavy, align='center', width=width, linewidth=0.5, color=(1, 0, 0))

# add some text for labels, title and axes ticks
ax.set_ylabel('Building elements [#]')
ax.set_title('Crane = (%1.1f, %1.1f, %1.1f) Storage = (%1.1f, %1.1f, %1.1f)' % tuple(user_coords))
ax.set_xticks(index+width)
ax.set_xticklabels(bu_elements)
ax.legend((bar1[0], bar2[0], bar3[0]), ('Can be lifted', 'Out of range', 'Too heavy'), loc='upper center',
bbox_to_anchor=[0.5, -0.05], ncol=widthscale)

def autolabel(bars):
    # attach some text labels
    for bar in bars:
        height = bar.get_height()
        ax.text(bar.get_x() + bar.get_width()/2., height + 2, '%d' % int(height), ha='center', va='bottom')

autolabel(bar1)
autolabel(bar2)
autolabel(bar3)

plt.savefig("Lifted elements: Location crane = (%1.1f, %1.1f, %1.1f) Location material storage = (%1.1f, %1.1f,
%1.1f).png" % tuple(user_coords))
plt.show()

v
```

Appendix 7 – Modules (.py)

crane_dimensions.py

```python
import csv
from collections import defaultdict

columns = defaultdict(list) # each value in each column is appended to a list

with open('information files/SK377-AT3 dimensions.csv') as f:
    reader = csv.DictReader(f) # read rows into a dictionary format
    for row in reader: # read a row as {column1: value1, column2: value2,...}
        for (k,v) in row.items(): # go over each column name and value
            columns[k].append(v) # append the value into the appropriate list
                        # based on column name k

def length():
    return float(columns['Length [m]'][0])

def width():
    return float(columns['Width [m]'][0])

def height():
    return float(columns['Height [m]'][0])

def length_from_backside():
    return float(columns['Length from backside [m]'][0])
```

crane_ranges.py

```python
import csv
from collections import defaultdict

columns = defaultdict(list) # each value in each column is appended to a list

with open('information files/SK377-AT3 ranges.csv') as f:
    reader = csv.DictReader(f) # read rows into a dictionary format
    for row in reader: # read a row as {column1: value1, column2: value2,...}
        for (k,v) in row.items(): # go over each column name and value
            columns[k].append(v) # append the value into the appropriate list
                        # based on column name k

def radius():
    return_value = []
    for radius, height in zip(columns['Lift range [m]'], columns['Max lift height [m]']):
        r1, r2 = radius.split("-")
        return_value.append([float(r1), float(r2), float(height)])
    return return_value

def crane_flights():
    crane_flights = []
    for radius, capacity, height in zip(columns['Lift range [m]'], columns['Load capacity [kg]'], columns['Max lift
height [m]']):
        r1, r2 = radius.split("-")
```

```
        crane_flights.append([float(r1), float(r2), float(capacity), float(height)])
    return crane_flights
```

material_specifications.py

```python
import csv
from collections import defaultdict

columns = defaultdict(list) # each value in each column is appended to a list

with open('information files/material specifications.csv') as f:
    reader = csv.DictReader(f) # read rows into a dictionary format
    for row in reader: # read a row as {column1: value1, column2: value2,...}
        for (k,v) in row.items(): # go over each column name and value
            columns[k].append(v) # append the value into the appropriate list
                    # based on column name k

def material_specs():
    material_specs = []
    for name, weight_kg_m3, weight_kg_m2, max_length, max_width, equipment_crane in
zip(columns['Material_name'], columns['weight1 [kg_m3]'],
        columns['weight2 [kg_m2]'], columns['max_length [m]'], columns['max_width [m]'],
columns['equipment_crane [kg]']):
        try: weight_kg_m3_float = float(weight_kg_m3)
        except: weight_kg_m3_float = None
        try: weight_kg_m2_float = float(weight_kg_m2)
        except: weight_kg_m2_float = None
        try: max_length_float = float(max_length)
        except: max_length_float = None
        try: max_width_float = float(max_width)
        except: max_width_float = None
        try: equipment_crane_float = float(equipment_crane)
        except: equipment_crane_float = None
        finally:
            material_specs.append([str(name), (weight_kg_m3_float), (weight_kg_m2_float), (max_length_float),
                    (max_width_float), (equipment_crane_float)])
    return material_specs
```

crane_speed.py

```python
import csv
from collections import defaultdict

columns = defaultdict(list) # each value in each column is appended to a list

with open('information files/SK377-AT3 speed.csv') as f:
    reader = csv.DictReader(f) # read rows into a dictionary format
    for row in reader: # read a row as {column1: value1, column2: value2,...}
        for (k,v) in row.items(): # go over each column name and value
            columns[k].append(v) # append the value into the appropriate list
                    # based on column name k

def crane_speed():
```

```
    crane_speed = []
    for capacity, horizontal_speed, vertical_speed, rotation_speed in zip(columns['Load capacity [kg]'],
columns['Lift speed horizontal [m/min]'], columns['Lift speed vertical [m/min]'], columns['Rotation speed
[rotation/min]']):
        crane_speed.append([float(capacity), float(horizontal_speed), float(vertical_speed),
float(rotation_speed)])
    return crane_speed
```

hook_time.py

```
import csv
from collections import defaultdict

columns = defaultdict(list) # each value in each column is appended to a list

with open('information files/hook and unhook time.csv') as f:
    reader = csv.DictReader(f) # read rows into a dictionary format
    for row in reader: # read a row as {column1: value1, column2: value2,...}
        for (k,v) in row.items(): # go over each column name and value
            columns[k].append(v) # append the value into the appropriate list
                        # based on column name k

def hook_time():
    hook_time = []
    for name, hook_time1, unhook_time1 in zip(columns['Material_name'], columns['hook_time [min]'],
columns['unhook_time [min]']):
        try: hook_time1_float = float(hook_time1)
        except: hook_time1_float = None
        try: unhook_time1_float = float(unhook_time1)
        except: unhook_time1_float = None
        finally:
            hook_time.append([str(name), (hook_time1_float), (unhook_time1_float)])
    return hook_time

#print(hook_time())
```

user_input.py

```
def determine_coordinates():
    user_coords = [0,0,0,0,0,0]
    coords_names = ["X-coordinate crane ", "Y-coordinate crane ", "Z-coordinate crane ",
            "X-coordinate material storage ", "Y-coordinate material storage ", "Z-coordinate material storage
"]

    for i in range(6):
        while True:
            input_str = input(coords_names[i])
            try:
                user_coords[i] = float(input_str)
                break
            except ValueError:
                print('Please enter a number ')
    return user_coords
```

get_property.py

```python
def get_property(name, element):
    for rel in element.IsDefinedBy:
        if rel.is_a("IfcRelDefinesByProperties"):
            propset = rel.RelatingPropertyDefinition
            if propset.Name == 'Dimensions':
                for prop in propset.HasProperties:
                    if prop.is_a("IfcPropertySingleValue"):
                        if prop.Name == name:
                            return prop.NominalValue.wrappedValue
```

make_hollow_cylinder.py

```python
import OCC.Geom
import OCC.BRepBuilderAPI
import OCC.BRepPrimAPI

def make_hollow_cylinder(ax2, inner_radius, outer_radius, height):
    c1 = OCC.Geom.Geom_Circle(ax2, outer_radius).GetHandle()
    c2 = OCC.Geom.Geom_Circle(ax2, inner_radius).GetHandle()
    w1 =
OCC.BRepBuilderAPI.BRepBuilderAPI_MakeWire(OCC.BRepBuilderAPI.BRepBuilderAPI_MakeEdge(c1).Edge()).
Wire()
    w2 =
OCC.BRepBuilderAPI.BRepBuilderAPI_MakeWire(OCC.BRepBuilderAPI.BRepBuilderAPI_MakeEdge(c2).Edge()).
Wire()
    mf = OCC.BRepBuilderAPI.BRepBuilderAPI_MakeFace(w1)
    mf.Add(w2)
    f = mf.Face()
    return OCC.BRepPrimAPI.BRepPrimAPI_MakePrism(f, OCC.gp.gp_Vec(0, 0, height)).Shape()
```

materialname.py

```python
def contains_materialname(element, requested_name):
    for rel in element.HasAssociations:
        if rel.is_a("IfcRelAssociatesMaterial"):
            layersetusage = rel.RelatingMaterial
            for layer in layersetusage.ForLayerSet.MaterialLayers:
                element_material_name = layer.Material.Name
                if requested_name in element_material_name:
                    return True
    return False
```

Appendix 8 – Adjusted CSV-file "hook and unhook time"

Table A8.1. Adjusted CSV-file "hook and unhook time".

Material_name	hook_time [min]	unhook_time [min]
NLRS_f1_kalkzandsteen	0.5	0.5
NLRS_g2_baksteen	0.42	1.92
NLRS_f4_cellenbeton	0.5	0.5
NLRS_31_CW_Merk	2	4
NLRS_31_WI_Aluminium	2	4
NLRS_23_FL_kanaalplaat	1	4.25
NLRS_23_FL_ribcassettevloer	0.83	1.92