Improving the Productivity of Cranes in the Construction Industry

Master Thesis IEM

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Management Summary

Three years ago, construction company Dura Vermeer Bouw Hengelo (DVBH) started to increase their focus on their logistics processes by hiring a logistics manager. This manager started with investigating and improving the supply logistics of the construction sites of DVBH. This research focusses on the next step by investigating the site logistics and the connection with the supply logistics. The crane on the site often determines the speed of the building process, but this resource is also observed idle. Therefore, the goal of this research is to improve the net productivity of the cranes on the construction site, which can be determined by the ratio between the required working time and the time the crane is rented. The research question is:

How can the net productivity of the cranes used in a construction project be improved?

Current situation

There are employees from different departments of DVBH involved in creating the overall planning, selecting the resources and setting the budget. The three most involved functions are:

- *Project organisers*, during the preparation phase they determine the resources needed and create a weekly planning for the full construction of the project.
- *Construction managers*, during the construction phase they create the daily planning usually a week beforehand and set the arrival date and time of the trucks.
- *Logistics managers,* they support the project organisers and construction managers with tools to predict and improve the material flow to and on the construction site. Currently, there is no tool to improve the management of the processes involving the use of a crane.

Most of the decisions made by the employees are based on experience from previous projects. Literature mentions that the processes on site are not aligned in the construction industry. In this research we will create a dashboard in which a scheduling problem is solved to make more data-driven decisions about the cranes and to align multiple processes on site. On the sites of DVBH the activities of a crane are influenced by the arrival reliability of trucks, the material flow and the site characteristics such as the waiting area, the unloading area and the storage capacity.

Proposed problem formulation and solving method

The scheduling problem can be formulated by using mixed integer linear programming. In literature, linear programming is not often used to solve scheduling problems of the construction industry. We give an example of how linear programming can be used to create a schedule for resources used in the construction industry. In our proposed problem formulation, we optimize the net productivity of the cranes, by varying the scheduled arrival time of the trucks, in which we account for the reliability of the arrival of trucks.

The research solves the scheduling problem by using problem-specific constructive and improvement heuristics since exact methods have a too high computational time for this problem. The constructive heuristics are formulated based on how trucks are currently scheduled by construction managers. The best performing constructive heuristic is based on the movement time of cranes while considering the type of truck. These results were improved with a tabu search algorithm. The neighborhood to evaluate is defined as the solutions which have the same arrival time for all of the trucks except for one which differs 0.5 period.

Results

The dashboard is tested with the input of a finished project of DVBH. The results of the dashboard are compared to the actual crane rental of the project. This comparison showed that the total estimated number of needed crane hours is 99 while there are 186 crane hours rented. Figure i Shows per week

how many hours are needed according the created dashboard and how many hours were actually rented.

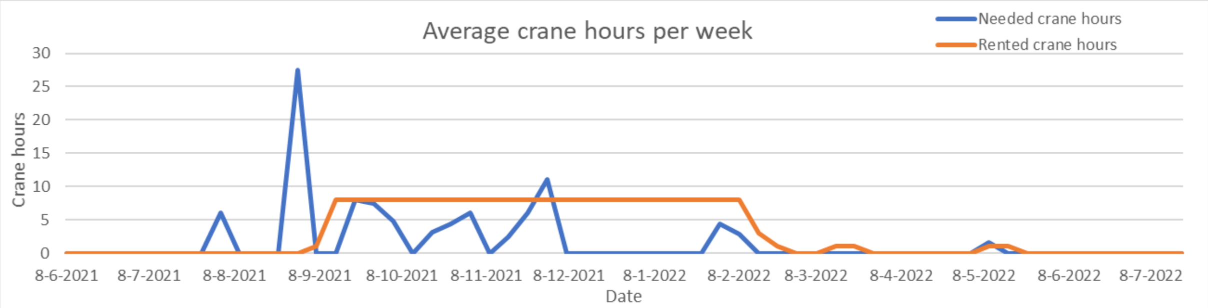


Figure i Comparison crane hours which shows where less crane hours were needed

We also performed a sensitivity analysis on the influence of the input parameters. This analysis showed that the movement time of cranes should be chosen with care since this has a big influence on the results. There is no clear relation between a change in the movement time and the resulting productivity. The constraints for the storage capacity, the unloading areas and the waiting areas are non-binding constraints for this project. By varying the number of these areas, the dashboard can show the minimum number of needed areas.

The final dashboard is developed in Excel. This file contains input and output for the following functions:

- *Project organizers*, they need to give input about the weekly planning and the site characteristics. Their output forms contain the estimated needed number of crane hours and the corresponding productivity.
- *Construction managers*, they need to give information about the daily planning. Their output forms contain the needed number of cranes, the corresponding productivity and the day schedule.
- *Logistics managers*, they need to give information about the supplier reliability. In their output form they can see the influence of the input parameters.

Conclusion and discussion

The created dashboard is a first tool to predict and optimize the productivity of cranes and is based on several assumptions. Therefore, the dashboard cannot yet be used for all construction projects of DVBH. In future research the dashboard can be updated such that several assumptions can be disregarded. This will improve the generalizability of the dashboard. Additionally, it is important to keep evaluating the results of the dashboard and update the dashboard accordingly. This can be done by letting the logistics managers test the dashboard first on several projects. In order to improve the user-friendliness of the dashboard the input can be automatically extracted from other software programs of DVBH.

The current dashboard shows which decisions are proposed for the construction site and the number of arriving trucks to improve the productivity of the cranes. Additionally, the dashboard shows when the trucks should be scheduled to create an efficient schedule for the cranes. By visualizing the results, the weeks during which the productivity is low can easily be defined and the number of rented cranes or crane hours can be lowered in these weeks. This will improve the productivity of the cranes during the entire construction project.

Preface

Dear Reader,

In front of you lies my master thesis which I have written to complete my master at the University of Twente. I am very proud to show you what I have been working on in the past months. This assignment was the perfect combination between my two masters, Industrial Engineering and Management and Construction Management and Engineering and I am happy that I can continue with this topic in my second master thesis.

I am very thankful that I was able to complete this assignment at Dura Vermeer. I especially would like to thank my supervisor, Bouwe, for all the help and feedback. I learned a lot about the logistics challenges in the construction industry and it was great to talk about this with someone who does not have a background in the construction industry, just like myself. I am looking forward to continue working together for my second thesis.

I would also like to thank my supervisors at the university, Wouter and Gréanne. I always received very useful and clear feedback. Their comments about the content have greatly improved the quality of this thesis. They even took the time to correct all my spelling and grammar mistakes.

Hope you enjoy reading,

Wieneke Jansma,

September 2022

List of Abbreviations

DVBH	Dura Vermeer Bouw Hengelo
BIM	Building Information Models
AI	Artificial Intelligence
JIT	Just-In-Time
RFID	Radio-Frequency Identification
LP	Linear Programming
ILP	Integer Linear Programming
MILP	Mixed Integer Linear Programming
GA	Genetic Algorithm
SA	Simulated Annealing
TS	Tabu Search
KPI	Key Performance Indicator
VBA	Visual Basic for Applications

Table of Contents

1. Introduction

This chapter gives an overview of the background information of the research. Section 1.1. describes the company and department at which this research is performed. Section 1.2. gives the motivation of the research and Section 1.3. describes the problems faced by the company, the relation between these problems and the core problem. After this, Section 1.4. gives the research objective and scope. Lastly, Section 1.5. describes the research questions and approach.

1.1. Dura Vermeer Bouw Hengelo

Dura Vermeer Hengelo Bouw (DVHB) is a suborganisation of Dura Vermeer. Dura Vermeer is one of the ten largest construction companies in the Netherlands. They have projects in housing, utility and infrastructure. Dura Vermeer consists of more than 20 suborganisations of which DVBH is one. This organization has around 230 employees and focusses on housing and utility projects. Three years ago, the company hired a logistics manager. This manager focusses on creating a standard for the logistics processes on the construction sites of Dura Vermeer. Since the number of tasks of this manager are growing, a second logistics manager was hired this year. Dura Vermeer is one of the first construction companies in the Netherlands that looks more into what logistics processes they have and how they can further improve these processes.

The management of logistics is relatively new at DVBH. The logistics manager focusses on the material flows to and on the construction site and on the needed resources on the construction site. There is still a lot unknown about how the company can improve the logistics processes. Therefore, the logistics manager started gathering data about the current performances of the logistics processes by measuring for example the time a crane is productive and the reliability of the arrival of trucks. Improving the logistics processes at the construction site will decrease the number of hours a crane is rented or reduce the timeframe in which the project can be built. By increasing the productivity of a crane, the total number of hours cranes are rented can be decreased. So, creating a good logistics schedule can be very valuable for the company.

Dura Vermeer has both public and private clients. Public clients are for example municipalities and private clients are companies. Each client has its own wishes for the project which results in project specific requirements. This makes every project unique. The construction projects are done in close cooperation with other construction companies. Dura Vermeer is in this cooperation the main contractor and hires other subcontractors. Together with these companies Dura Vermeer can do the design, construction and maintenance of the projects. For every project it is different how much the client is involved and in which phases Dura Vermeer is involved. Figure 1 shows the phases of a construction project. The client determines in which phase(s) a contractor will be involved. The subcontractors can be involved in different phases as well, they can add knowledge to the design phase or deliver specific elements of the building in the construction phase. Therefore, on the construction site there are multiple companies present. The main contractor is responsible for most of the logistics processes, but a well-organized logistics process can be beneficial for multiple involved organisations. The preparation of the logistics on the construction site starts already during the design phase.

Figure 1 Phases construction project

1.2. Research Motivation

In the construction industry multiple contractors bid on a tender. With this bid, contractors show that they are willing to work on the project, for which price they are willing to complete it for and in how much time they can perform the task. Therefore, it is important for a construction company to lower their operation costs, so they can lower their bid price without lowering their profit margin and win more tenders. Dura Vermeer wants to decrease the costs of construction projects by improving their logistics processes on the construction site. In construction, the management of logistics involves the strategic storage, handling, transportation and distribution of resources. Also, the planning of the construction site layout and its evolution during the development of the construction project can be included in logistics management (Whitlock, Aband, M.B., Pettang, & Nkeng, 2018).

Several studies showed that the logistics costs represent a substantial part of the total costs in the construction industry. So, a lot of benefit can be gained by optimizing the logistics processes. Nevertheless, in the past years this has never been a focus of construction companies (Sundquist, Gadde, & Hulthén, 2018). By hiring logistics managers Dura Vermeer wants to change this. Currently, they are implementing new software for the supply logistics, but they have not explored the next step of material transport, the site logistics. In order to improve the efficiency and effectiveness of a construction project it is important to also investigate the integration of these two processes.

In the construction industry, materials are either directly ordered from suppliers by the contractors, or the material delivery is organized by subcontractors. These other parties make sure the materials are transported to the construction site. Cranes need to move the materials from the trucks to the site. The material can either be immediately used in the project or temporary placed on a storage place. The company noticed that the crane often slows down the construction process on site. So, the company wants to know how they can decrease the time a crane is idle. A preceding study investigated how much time a crane needs to move different materials (Schonewille, 2021). This new data was used to change the way of calculating the number of arriving trucks and the needed capacity of the present cranes. Additionally, the company is currently working on implementing software which gives the supplier a time in which it needs to arrive. The next step is to investigate which factors influence the productivity of a crane. This can for example be influenced by the presence of storage places or the number of prefabricated objects. This research will focus on aligning the factors which influence the productivity of a crane.

1.3. Problem Identification

Since the logistics department is still very new at Dura Vermeer, there is a lot unknown about the logistics processes. They experience that the cranes at the site often slow down the whole construction process while being repeatedly idle. Figure 2 shows this problem and the causes of the problem. The crane is idle when the weather conditions do not allow material movement. For example, when the wind force is higher than 7, the crane is not allowed to move material. However, this is a problem that is hard to influence and generally not the main problem according to the company. Additionally, a crane is idle when there are no trucks available to empty. This problem can have two causes. First, the trucks can have a delay and thus deviate from the scheduled arrival time. Only 44% of the scheduled trucks arrive within ±30 minutes of their allocated time. So, the arrival of trucks is not reliable. However, this is also a problem that is hard to influence. The transport of the materials is organised by the suppliers and therefore this is a problem they must solve. Negotiations can help in this case, but the result is very dependent on the supplier. The second cause of having no trucks to empty is that the total number cranes available is more than is needed because the total hours a crane is rented is not based on a calculation of the number of hours it is needed, but on an estimation by the employees. So, some days there are more cranes on a construction site than necessary. Therefore, either more trucks could have arrived that day or fewer cranes could have been on site. Employees make an estimation of the number of hours a crane is needed because there are no exact numbers for the movement time of a crane and because resource allocation is not considered when planning the project. The movement time can differ because of a lack of standardisation in the movement process such as hook-up failures. This is very dependent on the employees working on the construction site. This standardisation of moving materials is also hard to influence. As resource allocation is not considered during the creation of the planning of the construction projects is a problem that can be influenced, we consider this problem as the core problem. So, the core problem is that the planning does not take the allocation of cranes into account.

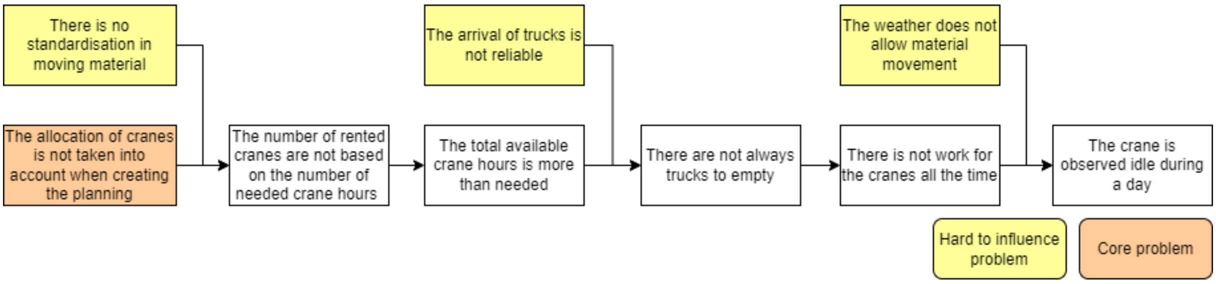


Figure 2 Problem cluster

1.4. Research objective and scope

Based on the core problem, this section defines the corresponding research goal, scope and assumptions. Recall that the core problem of this research is that the allocation of cranes is not considered when the planning is created. The costs and timeframe of the construction project could have been improved when the used cranes are constantly working. So, the goal of the research is:

To improve the net productivity of the cranes used in a construction project

The productivity is the ratio between the number of hours a crane is rented and the number of hours it is working. This is called the gross productivity. It is also possible that a crane is unnecessarily working because of a lack of standardisation. This is for example the case when a hook-up fails multiple times. The ratio between the number of hours a crane is rented and the number of hours in which the performed task could have been done in a perfect situation, is called the net productivity. The focus of this research will be on the net productivity and will be referred to as productivity in the remainder of this report.

A construction project generally uses multiple crane types, but this research will focus on cranes in general. This is possible because previous research showed that the movement time of materials of the crane is the same for every type (Schonewille, 2021). Only material movement which includes a crane is considered during this research. So, material which is for example moved by hand is not taken into account. These materials are usually much smaller and therefore have less influence on the total process. Trucks usually have a deviation from their actual arrival time. The distribution of these deviations is assumed to be given. So, the reasons of unreliability are not considered, and arrival punctuality distributions are considered to be known. Since the weather generally does not cause a problem according to the company, this is not taken into account.

1.5. Research questions and approach

Based on the research goal and core problem, the main research question is formulated:

How can the net productivity of the cranes used in a construction project be improved?

This research question is split into several sub questions. Each phase of this research has its own sub questions and research approach.

1.5.1. Phase 1: Analysing the current situation

The first step is to analyse the current situation of the logistics processes of the company. In this step the process of creating a planning and the used calculations is analysed. Additionally, the known reliability of the delivery of the materials on the construction site is analysed. Therefore, this phase has the following research questions:

1.1. How is the current planning of a construction project created?
1.2. How is the number of needed crane hours of a construction project calculated?
1.3. What type of cranes are present at construction sites and what influences their productivity?
1.4. What is the reliability of the delivery of materials on site?

To answer these questions, small interviews will be conducted with employees of the company after the organisation structure is analysed. Based on this structure the employees to interview are determined. Since, the number of needed crane hours is determined during the design phase and reassessed during the construction phase, it is important to interview at least one employee working in these two construction phases. For this research phase also the information already gathered during the previous project on crane capacity at DVBH will be used.

1.5.2. Phase 2: Identifying known possible solution approaches in literature

When the elements of the current situation are known, a solution approach for the previously defined problem needs to be found. During phase 2, the general construction industry is further analysed in literature. It is important to know how this industry handles its logistics processes and how it organizes its material flow. Additionally, the literature will be analysed for factors influencing the productivity of a crane. After this, possible scheduling methods and corresponding solving methods are analysed. The schedule will be used during the preparation phase of construction projects. In the preparation phase, a weekly schedule is created of the construction tasks. Since this is a weekly planning, the schedule will be used on a tactical level. This scheduling method will be reused during the construction phase when the planning is detailed enough to determine the tasks performed daily. Therefore, the method used needs to be able to create both a tactical and an operational schedule. The tactical schedule should help project organisers to estimate how many cranes are needed during the construction phase and what budget should be set. The operational schedule should help the construction managers during the construction phase to plan the arrival of trucks and to determine the number of needed cranes per hour. This is important because mobile cranes can be rented per hour. In the last part of phase 2, a literature review will be performed about how a dashboard can be made to both visualise the results of the schedules for the project organisers and construction managers and to help the logistics manager to look for new opportunities to improve the logistics processes on site. This step will answer the following research questions:

2.1. How does the worldwide construction industry organise its logistics processes?
2.2. What factors influence the productivity of a crane?
2.3. What scheduling methods can be used to create both a tactical and an operational schedule which maximise the productivity of a crane?
2.5. How can a dashboard be made for multiple employees involved in creating a schedule for the cranes?

During this phase a literature review will be performed which will answer the research questions.

1.5.3. Phase 3: Applying the scheduling method

When suitable scheduling methods are found, the most suitable method for the case of this research needs to be determined. This will be done during phase 3. First, the problem needs to be formulated such that it can create schedules on both a tactical and operational level which is applicable to the process of DVBH. The first schedule will show how many hours a crane is needed for the complete construction phase. The second schedule will show how many cranes are needed per day and what a suitable arrival time of the trucks is. After a scheduling problem is formulated, a solving method will be chosen to solve the formulated problem. Lastly, the resulting productivity of the schedules will be shown on a dashboard. This dashboard will also show what the influence of the input parameters such as the reliability of the truck arrival is and how a change of the input parameters will influence the output of the dashboard. The research questions of this phase are:

3.1. How can the scheduling problem for the construction phase on both a tactical and an operational level be formulated such that it is usable for DVBH?
3.2. How can the scheduling problem be solved within reasonable time?
3.2. How can the calculated productivity and the influence of the input parameters be visualised on a dashboard?

Most of the calculations of the company are done in Excel. Therefore, the implementation of this research will also be done in Excel. This will make the result of the assignment more usable for the company. In Excel both the problem formulation for the schedule and a solving algorithm will be created. The results will be visualised on a dashboard in Excel. This phase will be based on the results of the literature review.

1.5.4. Phase 4: Analysing the solution

In the last phase, a dashboard will be made based on the problem formulation and solving method created in phase 3. In phase 4 the input data from an existing project will be used to create results. The resulting number of cranes will be compared to the actual used number of cranes. Since the value of several input parameters of the dashboard is an estimation, a sensitivity analysis will be performed. Additionally, it is important to know what the limitations of the dashboard are. The dashboard can become very theoretical and in order to implement it correctly the company needs to know what the difference is between the results of the dashboard and the reality. The corresponding research questions of this phase are:

4.1. What is the difference between the results of the created dashboard and the decisions made in previous construction projects of DVBH concerning the needed number of cranes?
4.2. What is the sensitivity of the input parameters of the dashboard on the productivity of the cranes?
4.3. What are the limitations of the dashboard?

During this phase experiments will be done with the dashboard created in Excel in the previous step to analyse the performance and the sensitivity. The experiments will be done by varying the values of the input parameters. These values will be discussed with the company to make the results more realistic. The dashboard will also be applied to a completed project of DVBH. This way the results can be compared to the actual results without the new dashboard. The dashboard will be shown to the employees interviewed in the first phase. When testing the dashboard, they can also give their opinion about the limitations and what effect it can have on the performance of the dashboard.

2. Current Situation

This chapter describes the current situation of the company. It describes the different functions of the employees and who makes what decisions. The information given in this chapter is gained from interviews with employees. Section 2.1. first describes the overall organisation structure of DVBH. Next, Section 2.2. describes the function of project organiser, Section 2.3. of the project preparer, Section 2.4. of the logistics manager, Section 2.5 of the supply chain manager and Section 2.6. of the construction manager. Lastly, Section 2.7. gives the conclusions of this chapter.

2.1. Organization

DVBH works with multifunctional teams with employees from different departments. Each team stays together from the tender phase until the handover of a project. This means that the manager of the construction phase is also part of the team. In this way he can evaluate what went well and what went wrong during the construction and directly give this as feedback to the team. Figure 3 shows the different departments which are part of the team. The teams are split between housing projects and utility projects. This research mainly focusses on the preparation department, but also on the link with the construction department. Projects of both housing and utility are considered. Within the preparation department there are different functions like, project organiser, project preparer, logistics manager and supply chain manager. These are further explained in the next sections. Additionally, Section 2.6. describes the function of construction manager which is part of the construction department.

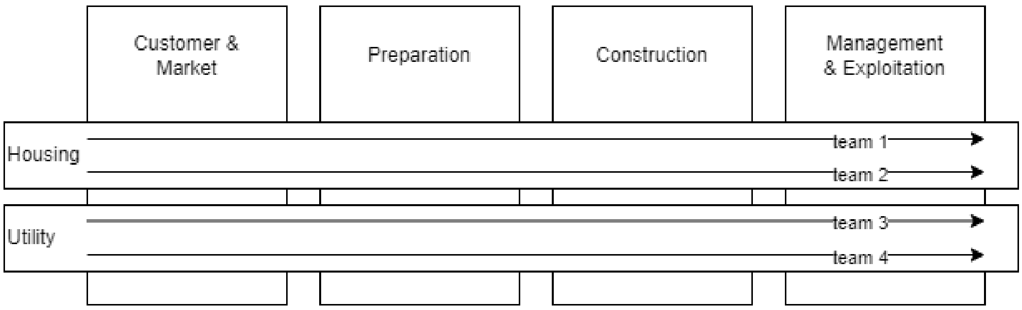


Figure 3 Organisation structure DVBH (DVBH)

2.2. Project Organiser

The project organisers determine at the beginning of a project what the timeframe, building methods and site layout will be. Determining the timeframe is about creating a planning. The design phase consists of different stages. In every stage the design becomes more detailed. For every step a new more detailed planning is made. The planning is based on the surface of the project, the weight and number of materials and the knowledge gained from previous projects. When needed, more knowledge is gained by speaking to construction managers of similar projects. This planning is used to determine a budget of the project. Project organisers mainly determine the costs of the building site. So, the costs of the materials are determined by another department while project organisers focus on the costs of the facilities on site and the costs of employees. The costs of employees are mainly based on the total number of employees and the total revenue of the company. This way the average revenue an employee creates can be calculated. By looking at the expected revenue, the number of needed employees can be calculated. The task of defining the building methods involves determining what materials will be used and what methods will be used. A project organiser can for example determine if prefabrication will be used or if the objects will be built on site. This decision is based on among others, the available space, the requirements of the design and the costs. There is no data about the influence of the building method on the construction time, this is based on the experience of the project organiser. The site lay-out involves determining the needed facilities. This is further explained in Section 2.2.1. Project organisers transfer all their created documents to the project preparers and construction managers. In this transition period a lot of input is asked about how and why decisions are made. After this period, the only way to get feedback about the made decisions is by actively asking for it. Because of time limitations this is often not done. Three aspects of a project which the project organiser determines are important for this research. These are further explained in Sections 2.2.1., 2.2.2. and 2.2.3.

2.2.1. Site lay-out

The lay-out of every construction project is very different. The lay-out is for example very dependent on whether a project is in the middle of a city center or in a meadow. The first step in creating the site lay-out is determining the position of a crane. This is dependent on the type of crane which is used. Next, the routes of the trucks are determined to control the material flow. When a site is large enough, a truck can drive on a site when delivering materials and it is possible to have multiple gates to enter the construction site. The place of these gates is determined by the surrounding of the project and the possible routes for the arriving trucks. These two steps determine a large part of the construction site. After this, the smaller facilities like storage place of tools and materials are determined. Therefore, these can also vary per project. The storage space is generally not based on what is needed, but on what is left of the space. If the space around a project is not large enough for the main facilities, extra space is needed which comes with a certain cost. Therefore, the project only has the storage space that is left after this and does not investigate the option of buying more. The site lay-out is thus mainly determined by what is available instead of what is needed.

2.2.2. Crane types

The type of used cranes on a project is very dependent on the project. A mobile crane is the cheapest option. Therefore, it is first investigated if this is possible. When the materials are too heavy or the building is too tall, a tower crane needs to be used. The tower cranes are only rented for longer periods because of the set-up and break-down costs and need to be reserved several weeks before the start of the project. The mobile cranes can be rented a few days before they are needed and can be rented for only a part of the day if needed. Therefore, this estimation is less precise during the preparation phase. The costs of a crane do not only depend on the duration, but also on the set-up, the (dis)assembly, and the operator. Dura Vermeer mostly uses these two types of cranes. The material facility of Dura Vermeer manages all the cranes and gives advice on which cranes to use. The movement time of the two types of cranes is considered to be the same. The number of tower cranes are determined by the reach of a crane, the total surface of the project and the timeframe. In most cases, if tower cranes are needed, there are one or two tower cranes present on site. These tower cranes are complemented by 1 or 2 mobile cranes dependent on the desired timeframe. The time of a crane can be divided in three different states, moving materials, clearing the construction site and being idle. In this case clearing the construction site means moving materials that are in the way or moving them closer to the project. Figures 4 and 5 show the division of these states as was calculated in a project in Utrecht and Hilversum in a previous project (Schonewille, 2021). These figures show that the division between the states can be very different per project.

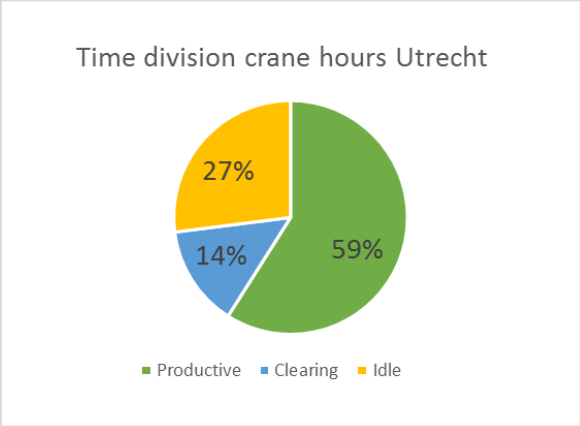


Figure 4 Time division crane project Utrecht (Schonewille, 2021)

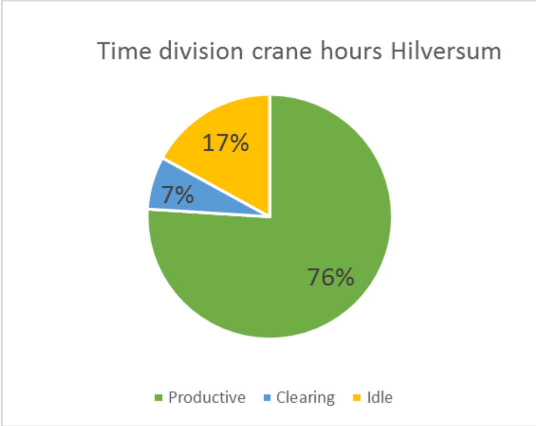


Figure 5 Time division crane project Hilversum (Schonewille, 2021)

2.2.3. Planning

Two years ago, a new function was created in a different suborganisation of Dura Vermeer, a project planner. This employee focusses on making the planning ready for the construction manager after the project organisers are done. He is involved during this transfer period, so on average three months. When more is known, the planning becomes more detailed. One of the most important things he does is assigning hours to the tasks. This can be hours of an engineer or of a crane. The number of hours needed per task is based on a norm of movement time and experience. By doing this, the total hours a crane is needed on a day can be calculated. Figure 6 shows how this total is shown in the planning software used. If possible, the planner will move a task to spread the hours of the crane more. When the maximum hours of a tower crane is reached, a mobile crane will be used. The red line shows the regular hours available on a day which is 8 in this case. The planner considers it acceptable to have 2 hours of overwork. This figure is only used to investigate different options when a crane is needed too much on a day. When a crane is used less than its capacity, this is not considered a problem. Since hours need to be assigned to every task manually, it is easy to make mistakes. Some tasks can for example be forgotten or assigned to multiple cranes. This employee makes a more extensive estimation of the needed crane hours compared to other project organisers, but this requires more effort and is very sensitive for mistakes because of the manual work.

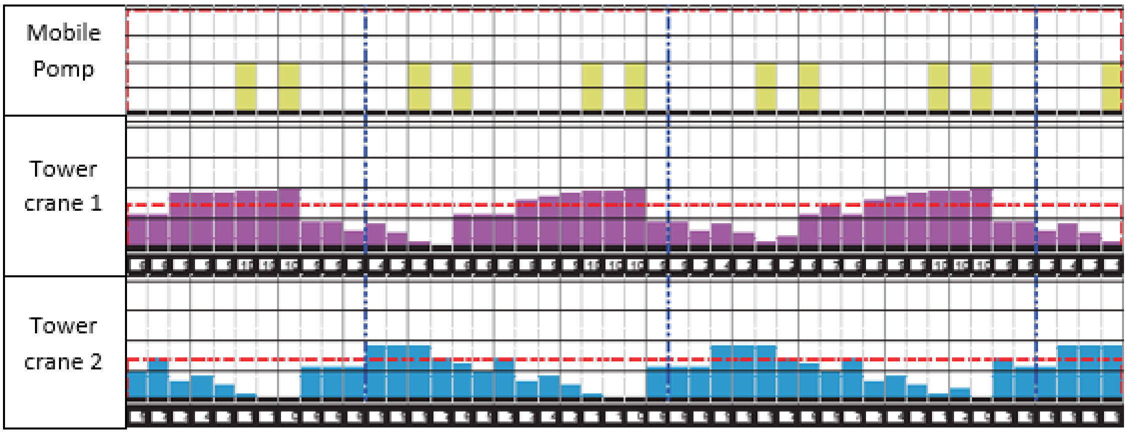


Figure 6 Crane hours needed per day (DVBMW, project planner, 2022)

2.3. Project Preparer

The main task of a project preparer is to manage all the material flows on the site. They contact the suppliers and agree on the delivery amounts and timeframe. After this, the construction manager manages the flow from the truck to the site and the exact delivery time. The project preparer also takes over the planning made by the project organisers and adjusts it when needed. A project preparer becomes involved in a project when there is a more detailed design and stays involved until all the material flows are controlled.

2.4. Logistics Manager

The logistics managers work in close cooperation with the project organisers. The function logistics manager is still rather new, but the tasks of a logistics manager are growing. The logistics manager makes for every project a logistics plan. This plan includes the surrounding of a project and the possible routes to the construction site. The logistics manager determines the important aspects of the area like a school or a viaduct with a maximum height. The logistics plan also includes the volumes of the materials that need to be delivered and how many trucks are expected to arrive. This document will be used as input for the site-layout. The logistics managers have introduced two new systems which are currently being implemented. The first system is ILips, a transport management system and the second system is a volume calculating model. The systems are explained in Sections 2.4.1. and 2.4.2.

2.4.1. ILips

In ILips every arriving truck gets a ticket which specifies the arriving time. When the truck arrives on site, a QR code on the ticket will be scanned to document the actual arrival time. This system gives more insight in the delivery performance of a truck. More and more projects are now using this new system and therefore the logistics manager gains more tasks. With this system the reliability of the arriving trucks can be kept track of. Figure 7 shows how often a truck is on time. We consider a truck to arrive on time if it arrives within ± 30 minutes of the agreed arrival time. Figure 7 also shows the percentage of trucks that arrive within ± 60 minutes, trucks that arrive earlier/later than an hour, and trucks that do not arrive on the agreed day. Lastly, there are also trucks which arrive without being scheduled.

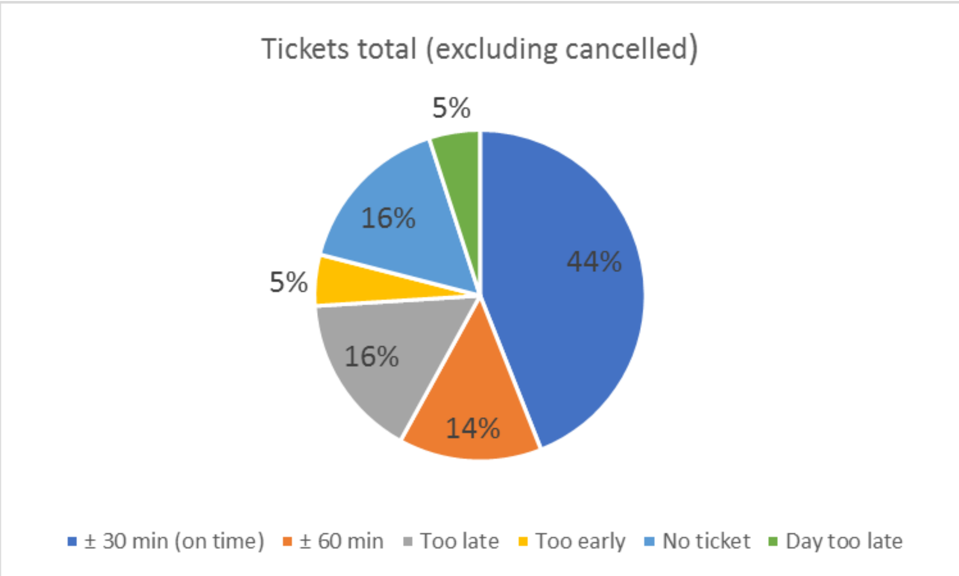


Figure 7 Reliability trucks (DVBH, Logistics manager , 2021)

2.4.2. Volume calculations

The volume calculations are used to calculate the number of arriving trucks. First in an Excel sheet all the objects in the building are chosen. This results in the parameters of the building build. Next, all the information about the needed materials and their type of transportation needed is extracted. The materials each have characteristics for their total volume. By using the total amount needed and the volume of one unit, the total volume of the material flow can be calculated. By adding the type of transport, the total number of trucks can be calculated. From the planning is extracted how much time each material has to be placed in the building. With this information the number of trucks in time can be calculated.

In a previous project at DVBH, the capacity of a crane is added to this calculation. With this added calculation the number of hours a crane is needed can be estimated more accurate. This new calculation investigates how much time a crane needs to move a certain type of material. Since the needed materials and the amounts are already known, the capacity of the crane can be calculated.

2.5. Supply Chain Manager

At DVBH the supply chain managers focus more on procurement. They first specify what needs to be procured, so which materials need to be bought and how many. Next, they analyse which suppliers can perform the job. They base this on the knowledge they have from the market which arose from previous contacts with suppliers. Therefore, the suppliers with which the company had a good experience are preferably used more often. The financial health of a supplier and the ability to deliver the needed materials are also considered.

Supply chain managers are already involved in a project starting from the tender. Here, they make decisions concerning the procurement strategy. This strategy defines when suppliers will be involved and whether there will be big or small suppliers involved. The main decisions such as the use of pre-fabricated objects are made by the company, but they do check if the suppliers have the option of delivering the elements in this way. The supply chain management does not influence the planning or the site-layout, these are determined by the project organisers which are explained in Section 2.2.

DVBH mainly works on two types of projects, utility and housing. In housing a lot of the projects are standardized. Therefore, these projects mainly use the same suppliers for all the projects. On average 30 to 40 suppliers are involved in a housing project. These suppliers also have a partner contract with Dura Vermeer and their performance is monitored. The utility projects are more unique and therefore require a lot of new suppliers every project. On average these projects have around 100 suppliers involved.

A supplier often hires a third party to transport the materials to the construction site. When setting up a contract, the supplier sets certain requirements for the maximum waiting time on a construction site. This is very dependent on the materials, but on average half an hour of waiting time is acceptable. The contractor and supplier together determine whether the truck should be self-unloading or whether a crane will unload the truck. This decision is based on the options of the supplier and the routes on the construction site. A contractor needs to pay the supplier more for a self-unloading truck, but a crane unloading a truck will also cost the contractor time and money. Together they agree upon the delivery time. The exact delivery day and time is later determined by the construction manager. The supplier gets information when the materials should arrive and at which storage place on site. In practice it is often the case that truckdrivers do not look at the provided information and arrive on a different date or time and only look in which city they need to be instead of the exact location of the construction site.

2.6. Construction manager

The construction managers manage every movement and change on the construction site. It differs per project when they become involved. This can be in the beginning of the project to think along or just before the construction phase. They make the planning of all the activities on a daily basis and keep track of the process. They also manage all employees working on site and all of the arriving trucks.

Additionally, they solve all of the arising problems, for example when equipment stops working or when a construction mistake is found. The construction manager is directly in contact with the suppliers about how many materials should arrive and when they should arrive. So, they make the planning of the arriving trucks on a daily basis as well. They set the final arrival day and time usually a week beforehand. There is no standardization on how the truck planning is made, but this is dependent on the construction manager and the project. Some construction managers for example make sure that every day on the same time a truck arrives of which the material is immediately used. Other construction managers have a construction site with more storage and make sure the trucks arrive early to create a buffer. They also determine via which gate trucks should arrive and to what area of the construction site they should go to.

The construction managers order the mobile cranes. The number of tower cranes is already determined by the project organisers, but when extra cranes are needed the construction manager orders these. The construction manager can also decide to have more overtime instead of ordering an extra crane. This is dependent on the delay and the budget of the project.

2.7. Conclusion

This chapter showed that there are employees from different departments involved in creating the overall planning, selecting the resources and setting the budget. During the preparation phase the project organisers determine the facilities needed and create a weekly planning for the project. During the same phase the suppliers are selected by the supply chain manager. During the construction phase, the construction manager finalises the daily planning a week beforehand and sets the arrival date for the suppliers. Most of the decisions made by the project organisers, supply chain managers and construction managers are based on experience from previous projects. The logistics manager supports these employees mainly with a logistics plan and two tools. The first tool is a transportation management tool in which manually the arrival time of trucks can be set which is automatically communicated with the supplier. This tool also creates the possibility to keep track of the actual arrival time and thus the reliability of the trucks. Currently, on average 44% of the trucks arrive on time. The second tool shows the material arrival on the construction site and visualises the busiest days. This chapter showed that multiple employees make decisions about the processes involving cranes on the construction site. These decisions are mainly based on experience.

3. Literature Study

Chapter 2 described the current situation of the logistics process of a crane of DVBH. This chapter describes a literature study about how the industry in general organizes the logistics processes. Section 3.1 describes some of the current practices of logistics management in the construction industry and important developments of the industry. Section 3.2 dives more into the factors that can influence the productivity of a crane according to literature. Section 3.3 describes possible scheduling methods which can take these factors into account and Section 3.4 describes how this can be solved. After this, Section 3.5. explains what is important when creating a dashboard. Lastly, Section 3.6 gives an overall conclusion of this chapter.

3.1. Logistics in construction

As mentioned in a good site layout and the management of the site layout evolution. The construction industry is lagging behind in terms of its logistics processes. The deficiencies in the flow of material are often a major cause of decreased productivity and financial losses. This section describes how the construction industry in general handles its logistics management. Section 3.1.1. describes the current methods and section 3.1.2. describes the current developments.

3.1.1. Current logistics management methods

The logistics process is generally managed by a site manager. In construction, there are multiple companies present at the site. Consequently, the site manager of one company has less authority to enable standardization across the site with multiple organizations. This makes good interaction between the different actors involved necessary (Sundquist, Gadde, & Hulthén, 2018). In the construction industry, there are multiple documents created to standardize this process. A construction logistics plan is developed before the construction phase and contains the used logistics methodology. A delivery management system is used to manage the assets arriving to a site and inform managers about the planned deliveries. Lastly, materials can be tagged with a barcode or an RFID (Radio-Frequency identification) tag and thus can be tracked (Whitlock, Aband, M.B., Pettang, & Nkeng, 2018).

Despite these preparations, there is still poor management of materials, equipment and tools which are partly caused by the characteristics of this industry. Building materials require large storage capacity. This capacity is not always available at every construction site. Additionally, the use of the available equipment can be further improved. The planning of these resources is sometimes lacking. For example, the delivery time of materials can be unknown beforehand and the offload of materials is not planned. Decisions are in this case based on intuition (Sundquist, Gadde, & Hulthén, 2018).

In the construction industry critical path methods and Gantt charts are commonly used to work through the project in a systematic way. Gantt charts show activities as bars against a horizontal time scale. Between the activities certain precedence rules can be applicable. When linking the activities that are dependent on each other, the total duration can be calculated. The longest path through the network which joins the activities is called the critical path. Figure 8 gives an example of a Gantt Chart with two linked activities. (Fewings & Henjewele, 2019). These methods have several limitations regarding the allocation of resources. It is known that resource allocation is an important factor in the creation of a construction planning schedule, but the use of mathematical models to analyse the resource allocation is minimal in the construction industry. Currently, there is a lot of research done in how to use computer-assisted technology for resource allocation in construction (Li, et al., 2009). Section 3.1.2. describes these developments.

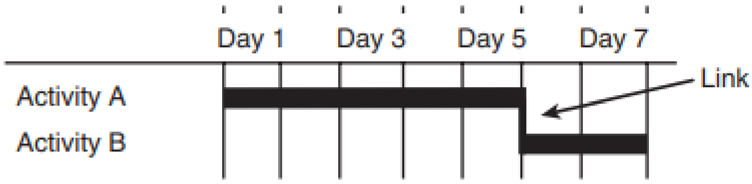


Figure 8 Gantt chart with link between activities (Fewings & Henjewele, 2019)

3.1.2. Developments in logistics management techniques

Beside the used plans and methods, the communication towards the other departments of the company is also important for a good logistics process. One of the major developments in creating and sharing data in the construction industry is Building Information Modelling (BIM). BIM can be defined as essentially value creating collaboration through the entire life cycle of an asset, underpinned by the creation, collation and exchange of shared 3D models and intelligent, structured data attached to them. This means that more data is used by all the parties involved which can eliminate waste and give more opportunities for optimization. BIM is mostly about giving the right information to the right people at the right time. For construction logistics this is also very important and therefore BIM can have a big influence on improving the coordination of the logistics process. Firstly, the logistical strategies can be communicated quickly. Second, the changes of the available storage space can be kept track of. Lastly, the created 3D designs of the project can be used to create 3D designs of the site layout (Whitlock, Aband, M.B., Pettang, & Nkeng, 2018). When a company implements BIM, it also tries to use standard formats. In this way all the data can be combined easier. This will also save a logistics manager time in collecting data from different sources and can give more possibilities for the use of artificial intelligence (AI) (Cheng & Chang, 2019).

3.2. Productivity of a crane

An important part of the logistics in construction is the material transportation. On the construction site the cranes are believed to determine the speed of the process, but cranes are also observed idle. Therefore, it is important to analyse the factors that influence the productivity of this recourse on the construction site. Section 3.2.1. till 3.2.5. describe several of these factors. After this, Section 3.2.6. summarizes these factors.

3.2.1. Storage capacity

In general construction sites have the possibility to create storage capacity. This has both advantages and disadvantages. An advantage of storage capacity is that it can create a buffer of materials on site. A disadvantage is that materials which are first moved to a storage place require additional handling for a crane. If there is storage room available, it is important that the conditions are good enough, so there will be no damage to the materials by for example water. If these conditions are not good a crane has to remove material. Additionally, storage places cause extra movement of people and equipment (Sundquist, Gadde, & Hulthén, 2018). A study of Strandberg and Josephson (2005) showed that 15% of the total working time of a construction worker is spent on moving material and equipment to the building project. Therefore, the productivity of a crane can be influenced by the storage capacity since extra handlings are needed especially when material needs to be removed.

3.2.2. Material delivery

In the construction industry material procurement decisions are often made without considering the available storage capacity on site and the dynamic construction site layout. Not looking at this interdependency can cause material shortage, unsafe site layout, improper storage and productivity losses (Said & El-Rayes, 2011). The route taken on the construction site and the dimensions of the storage places can influence the material delivery. Additionally, the size of the vehicles and the dynamic changes of the site layout must be considered when creating a schedule for the material delivery (Whitlock, Aband, M.B., Pettang, & Nkeng, 2018). In relation to the supply chain another common problem on-site is the delivery reliability. This can have different causes, for example neglecting the input of subcontractors in the planning process or contractors not knowing where and when materials will arrive. Additionally, the problem can be caused by the transporter instead of the supplier (Thunberg, Rudberg, & Gustavsson, 2017). The productivity of a crane can be influenced by the material delivery when it is not aligned with the available storage capacity causing extra handlings and when the arrival of trucks is not reliable.

3.2.3. Interaction resources

When multiple machineries are present at a construction site, it is important to also take their interaction into account. For the smooth running of the project, care must be taken for conflicts of time and space when looking at the resource movement (Whitlock, Aband, M.B., Pettang, & Nkeng, 2018). Al Hattab, Zankoul, Barakat and Hamzeh (2017) study the utility rates of two tower cranes working parallel. They showed that the results are improved when there is a good workload balance between the two cranes. They will work at a more similar rate without slowing the other crane down. The working area of a crane is not always the same. This study also showed that the results are better when there are as many tasks in the overlapping area as possible. The productivity of a crane can be influenced by the interaction between resources when tasks are aligned keeping possible conflicts into account.

3.2.4. Off-site manufacturing

In off-site manufacturing smaller construction components are assembled off-site. The prefabrication of these components has several advantages. First, the quality can be improved because of a higher precision. The assembly time can be reduced and the work environment is safer. Additionally, there is a reduced need for material transportation and less need for on-site storage. A drawback of this technique is that the decision needs to be made early in the design stage of the project. This is often during or before the logistics management techniques of the project are being formulated (Whitlock, Aband, M.B., Pettang, & Nkeng, 2018). Prefab components are not identical products, so they are created specifically for that construction project. This means that there is no stock of these products. Prefab objects are usually also more expensive for the project because they need to be moved by expensive cranes. The prefab components are usually delivered in a just-in-time (JIT) manner which means it is delivered at the time it is needed in the right quantity and at the right place. A too late delivery would cause extra costs because the crane and employees need to stay longer on site. Similarly, a too early delivery would cause extra costs because of the extra handling to the storage place. Prefab objects also require more storage place (Zhai, Zhong, & Huang, 2015). Off-site manufacturing influences the productivity of a crane because less, but bigger materials need to be moved.

3.2.5. Soft factors

Beside the named hard factors, the people on site can also influence the productivity of a crane. First a crane is operated by an employee. This employee needs to have the skills and experience to operate the machine. Additionally, the employee needs to be willing to follow new guidelines made by the logistics management instead of performing a task based on experience. The relationship with the other companies on the construction site can also be of influence. All the parties use the space available and agreements need to be made. The level of collaboration is in this case very important when making decisions about the site logistics. Lastly, also the weather can be of influence (Shapira & Elbaz, 2014). The productivity of cranes can also be influenced by soft factors like employee skills and experience, collaborations with other companies and the weather.

3.2.6. Summary of factors influencing the productivity of a crane

To summarise, this section showed that the productivity of cranes can be influenced in the following way:

- Storage capacity is important because extra handlings need to be done by the crane especially when material needs to be removed;
- Material delivery is important when it is not aligned with the available storage capacity causing extra handlings and when the arrival of trucks is not reliable;
- Interaction of resources is important when there is a possibility of aligning tasks to prevent conflicts;
- Off-site manufacturing is important because fewer, but longer movements are needed;
- Soft factors can be important when there is e.g., a difference in employee skills, weather influences.

3.3. Scheduling method

As mentioned in Section 3.1, it is important to have a clear division of the tasks and responsibilities on the construction site. Especially the crane needs to know what to do and when. Therefore, it is important to create a model which defines a schedule for the crane. Section 3.3.1. describes the possibilities of creating a schedule. After this, Section 3.3.2. describes how stochasticity can be implemented in the schedule.

3.3.1. Creating a schedule

Machine scheduling problems are broadly described in literature. Scheduling can be defined as the process of assigning a defined number of resources to a set of tasks that need to be accomplished. In machine scheduling, jobs (representing tasks) need to be processed by machines (representing resources). The aim is to find a sequence of jobs over time to be processed on machines such that a set of objective(s) is optimized without violating a set of constraints. Scheduling techniques are important to create a schedule when the aim is to reduce idle times, speed up the process and reduce operational costs (Abedinnia, Glock, Grosse, & Schneider, 2017).

Machine scheduling problems are often solved by using linear programming (LP). This technique is used in maximizing the efficiency of resources. LP problems contain an objective function which needs to be optimized subject to constraints. When a problem contains only integer variables, this can be solved using integer linear programming (ILP). This is in general harder to solve than an LP. If only some of the variables are non-negative integers, the problem can be solved with mixed integer linear programming (MILP). Lastly, a problem can contain a non-linear objective or constraints. These problems can be solved by using non-linear programming (NLP). In general NLPs are harder to solve than linear problems (Winston & Goldberg, 2004).

There are multiple studies performed about scheduling problems. This section describes some of these studies which solve similar problems. The problem which will be solved in this research has unique machines, jobs which need to be processed by one machine, unequal processing times and jobs with release times. The studies described in this section have at least one similar characteristic. Depending on the problem, the scheduling problems are formulated linear or non-linear. A linear formulation is e.g. proposed by Vanheusden, van Gils, Caris, Ramaekers and Braekers (2020). They formulate an MILP to solve a scheduling problem. In this study several tasks are assigned to timeslots. In this research the workload of order picking was divided over different time slots. The objective minimizes the difference between the minimum and maximum workload. The researchers use intermediate variables to linearize the constraints of determining the minimum and maximum workload. Tasks are assigned by defining start times. Baydoun, Haiït, Pellerin, Clément & Bouvignies (2016) formulate a MILP which creates a schedule for several jobs, over a timeframe. The jobs each have different release and due dates. Unlike the previously mentioned research which use timeslots, this research uses continuous time. The complete timeframe is split into periods, but multiple jobs can be completed within a time period. In this model the intensity at which a resource can be used is variable. Every period has a different value for the usage intensity. The resource cannot be used more than its maximum intensity, or less than its minimum intensity. For this model there is not an objective chosen, but this can be formulated by for example minimizing the total makespan or the costs of the extra used intensity. So, depending on the characteristics scheduling problems can be formulated linear and if needed can be linearized with intermediate variables.

Other authors use non-linear programming to solve their scheduling problem. Stojkovic, Soumis and Desrosiers (1998) solved the problem of planning airline crew during day-to-day operations. This problem contains flights which are considered as tasks. The number of tasks depends on the number of needed crew members per flight. Each task is assigned to a crew member. These tasks can only be minimally delayed. The objective in this research is to minimize costs while all tasks are assigned. This problem was mathematically formulated as integer non-linear programming model. The problem is non-linear because the costs depend on different resources. So, in the objective variables are multiplied to calculate the costs. Ighravwe and Oke (2014) solve a problem of maintenance workforce sizing. This problem is also non-linear formulated. The goal of this research is to maximize the productivity of the workforce. A second objective is used to minimize the number of maintenance personnel. In this case the productivity is measured by dividing the total cost of the output by the budget for the maintenance workforce, this is what makes the problem non-linear. The total cost of the output is defined in one of the constraints. These studies show that a scheduling problem can also contain elements which cannot be formulated linear.

3.3.2. Stochastic input parameters

A scheduling problem can be deterministic or stochastic. In the case of a deterministic model all of the parameters are considered to be known. When there is uncertainty in the input parameters, the model becomes stochastic (LI & Ierapetritou, 2008). Uncertainty in input parameters is important to consider when creating a schedule because it can cause infeasibility and production disturbances. A common stochastic input parameter described in literature is the demand of a product. Bakir and Byrne (1998) also describe this. They focus on a problem which contains multiple products with uncertainty in demand. They create a model which uses all the different possibilities for demand multiplied by their chance of occurring. This is also done in a model of Chen, Li and Tirupati (2002), but here multiple periods are considered. This model minimizes the costs, while demand is met. Since there is uncertainty in demand, there are several scenarios created for the demand of a product. In this case every period can have different demand. The demand in the new period is dependent on the demand in the previous period. Figure 9 shows the different scenarios.

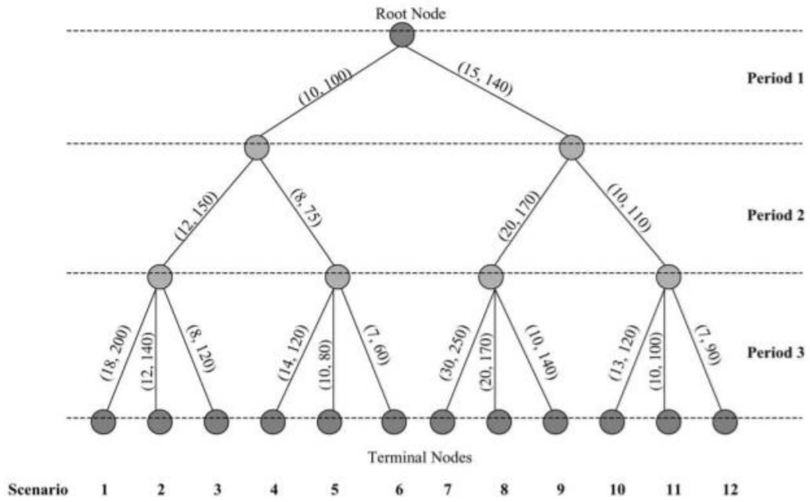


Figure 9 Tree structure of scenarios for demand (Chen, Li, & Tirupati, 2002)

The risk of creating all possible scenarios is that the number can soon explode. Therefore, the possibility of scenario reduction is important to investigate. In a study of Xu, Yi, Sun, Lan and Sun (2017) the simultaneous backward reduction method is used. Here, the principle is that the difference between the probability of the initial scenario set and of the scenario subset after the reduction is minimal. The first step is to select the scenarios which are to be reduced. So, the scenarios with the minimum distance to another scenario will be selected. In the next step the total number of scenarios is changed. After this the probability of the scenario is changed. When the total number of scenarios is still more than preferred, all the steps are repeated. In a similar study of Feng and Ryan (2016), the scenarios are also evaluated based on their distance. The distance is in this case the influence on the objective function instead of the probability. This distance is then used to cluster the solutions into the desired number of scenarios. From each cluster one scenario is selected to be used to calculate the solution.

3.3.3. Summary of possibilities to create a schedule

This section described how a machine scheduling problem can be formulated as finding a sequence of jobs without violating constraints while optimizing the objective. This problem can be solved using linear or non-linear programming. Depending on the type of problem this can be integer, mixed-integer or none of these. Scheduling problems are often solved using mixed integer linear programming or integer non-linear programming. One important distinguishment between scheduling problems is determining if there is uncertainty in the input parameters. In case there is uncertainty this can be considered by creating scenarios of all the possibilities. The number of possible scenarios can quickly explode. Therefore, clustering can be used to reduce the number of scenarios.

3.4. Solving Method

Section 3.3. defined how a model for the schedule can be created. This section describes how this model can be solved. The optimum of a model can be found by using an exact method. In some cases, this can become complicated to solve. Therefore, heuristics can be used to find a good solution. Section 3.4.1. explains exact methods and Section 3.4.2. explains heuristics.

3.4.1. Exact methods

There are multiple options to find an exact solution. By using full enumeration, the solutions of all possible alternatives are compared and the best is chosen. However, for large problems this can become infeasible. Therefore, other methods are also considered to find an exact solution for the problem. The next paragraphs describe three commonly used exact methods, the simplex method, Interior-point method and branch-and-bound.

Simplex method

The idea of the simplex method is to proceed from one basic feasible solution to another. So, it continuously improves the objective function by switching between basic feasible solutions until an optimal solution is found. A basic feasible solution is a solution on an extreme point in the area of feasible solutions. The simplex method constructs an efficient method in moving between these basic feasible solutions. The method moves from one basic feasible solution to an adjacent one. A solution is adjacent if it only differs by one basic variable. There is a global optimum if there are no improving directions along the edges from an extreme point. The simplex method can only be used for non-integer problems, but can be used to solve LP relaxations of an ILP problem (Luenberger & Yinyu, 2016).

Interior-point method

The interior-point method searches through the entire feasible region. So, unlike the simplex method not only the extreme points are evaluated. There are different algorithms designed to go through the search space and eventually converge to one solution. Since these algorithms search through the entire search space, they can also solve non-linear problems (Roos, Terlaky, & Vial, 2005).

Branch-and-bound

A method used more often for (mixed) integer programming, is branch-and-bound. Branching refers to the way the search space is partitioned. Bounding refers to finding valid bounds which can eliminate subsets of the search space without compromising optimality. First, a LP-relaxation needs to be solved. From the solution of this relaxation, the variables that should become integers are used to branch. For all the branches resulting from this variable, the objective is calculated again. The objective is compared to the current lower or upper bound. The branch is removed from the space if it is infeasible, an integer solution is found or when the solution is lower or greater than the bound (Oberdieck, Wittmann-Hohlbein, & Pistikopoulos, 2014).

3.4.2. Heuristics

Heuristics are designed to systematically find a good solution in an efficient manner. So, a global optimum is not guaranteed, but the goal is to quickly find a good solution. Heuristics can be subdivided in constructive heuristics and improvement heuristics. The next paragraphs describe these heuristics.

Constructive heuristics

Constructive heuristics create a solution from scratch. Components are added to an initially empty partial solution, until the solution is complete. This can be done period-by-period, either forward or backward. In job scheduling, constructive heuristics insert jobs one-by-one to the schedule. So, the size of the schedule increases with every iteration of the heuristic. Every type of constructive heuristic has its own rules to determine which job is selected next. The constructive heuristic bases this on characteristics of the jobs. For example, the job with the earliest due date can be selected first or the job with the smallest set-up time. These rules are mainly used to determine the sequence of the jobs (Prez-Gonzalez, Fernandex-Viagas, Garcia, & Framinan, 2019). The process stops when a complete schedule is created. Constructive heuristics are generally used to create an initial solution. Afterwards, improvement heuristics can be used to improve the objective value of the problem (Laha & Chakraborty, 2009).

Improvement heuristics

Improvement heuristics use a feasible solution as input and stepwise try to find a better solution. A common improvement heuristic is local search. This is a procedure which searches through the neighbourhood of the current solution. Starting from an initial solution at least a local optimum can be found by iteratively searching for a better solution in the neighbourhood of the solution. The neighbourhood is the set of solutions which can be obtained by performing simple modifications to the current solution. How the neighbourhoods are defined depends on the type of local search. Local searches can either explore the entire neighbourhood or a part. Additionally, a stopping criterion needs to be applied to define when to stop the algorithm. This choice needs to be carefully made to overcome the chance of finding a local optimum. (Buschkühl, Sahling, Helber, & Tempelmeier, 2010). There are multiple algorithms which search systematically through the neighbourhood to decrease the possibility of finding a local optimum. The most often used algorithms are described below.

- *Genetic algorithm*
  Genetic algorithm (GA) is a method to move from one population to a new population by using a selection of operators like crossover and mutation. Every population consists of multiple solutions. Crossover mixes the characteristics of multiple solutions of the previous population and mutation makes one random change. First, a set of initial solutions is created. These solutions are recommended to randomly cover the whole search space or to incorporate expert knowledge. The parameters of these solutions are used to create a new generation. Based on the solutions of this generation a new generation is created. It considers multiple solutions at the same time (Sun, Lu, Zhang, & Ruan, 2010). GA exploits a solution for improvements, but also explores the search space based on probabilities of mutation and selection. Generally, a GA does not take constraints into account. So, when a new solution is found with the operators, this solution is not always feasible with the set constraints. Therefore, techniques are developed for constraint handling. One of these techniques is for example inserting an extra step to eliminate or repair an unfeasible solution (Rodríguez & Jarur, 2005) (Kramer, 2017).Ga can be used when it is beneficial to evaluate multiple solutions at the same time. The algorithm can be adjusted to the characteristics of the problem by selected the operations and adding feasibility constraints.

- *Simulated annealing*
  Simulated annealing (SA) uses a probability of using a neighbour solution as the new solution. This probability is called the temperature. The temperature decreases when the number of iterations increases. Like other local searches, the method starts with creating an initial solution. Next, the neighbourhood is explored. When a neighbour solution is better than the current solution, this solution becomes the new solution. When the neighbour solution is not better than the current solution, a random number is generated between 1 and 0. If the random number is smaller than a probability function based on the temperature, the neighbour solution also becomes the new solution. This step decreases the probability of finding a local optimum which makes SA a useful algorithm (Vesga-Ramírez, et al., 2021).

- *Tabu search*
  Tabu search (TS) uses the memory of solutions it has found before. The information from previous iterations is used to move to the next solution. Like the other methods, first an initial solution is set. Next, the best neighbour is found. This neighbour is accepted if the stopping criteria are not met and if it is not on the tabu list. The tabu list stores information of the recent moves. The length of the list is dependent on the size of the problem. When the neighbour is accepted, the current solution will be added to the tabu list and the neighbour becomes the

new solution. The solutions on the tabu list stay for a certain number of iterations on the list. The iterations continue until the defined stopping criteria are met (Ponnambalam, Aravindan, & Rajesh, 2000).

3.4.3. Summary of possible solving methods

This section described the possibilities of solving the possible scheduling methods described in Section 3.3. There are two types of solving methods. First exact methods can be used to find an optimal solution. There are four possible exact methods for this research. These are: Full enumeration, Simplex method, Interior-point method and Branch and bound. The second solving method is using heuristics. These can either be constructing or improving the current solution. In general, constructive heuristics are used to create an initial solution. Improvement heuristics can be used to improve this initial solution.

3.5. Dashboard

Linear programs are based on numerical data which represents approximations of quantities because parameters can be hard to estimate. Therefore, generally a post optimality investigation is done of how a change in the data influences the solution. This is called a sensitivity analysis. When planning under uncertainty, it is critical to reflect the way in which decisions are made (Higle & Wallace, 2003). By creating a dashboard, the sensitivity analysis can be visualized towards the company. A dashboard is a performance management tool used by corporations to display critical data. When implementing a new plan, exploring progress is an essential step. A dashboard can help bringing attention to critical trends, seeing opportunities and fine-tuning priorities. Section 3.5.1. describes possible pitfalls of a dashboard. Next, section 3.5.2. describes important factors to create a usable dashboard.

3.5.1. Pitfalls dashboard

A study of Allio (2012) showed that a common pitfall when creating a dashboard is that it unfairly simplifies a complex world. Other risks are that the indicators and targets do not reflect the business activities, the number of indicators is too overwhelming, or the targets and indicators are set without consultation of the people who work with them. Therefore, it is important to include employees when setting the targets and indicators. This also helps in giving the employees more insight into the strategy of the corporation and translate the strategy more into terms that directly correlate with their responsibilities. Additionally, it is important to only use indicators that are clearly linked to strategic success, instead of filling the dashboard with as much data as is available. This does not mean that the indicators should be simple, but they should address critical links. Lastly, it is important to give context to the indicators. A simple visual vocabulary helps readers to quickly absorb more information (Allio, 2012).

3.5.2. Usability of a dashboard

The usability of a dashboard can be defined as how easy it is to use a user interface. These are dependent on five quality components. The first one is learnability. This defines how easy it is for a user to perform a basic task during the first use. The second component is efficiency. This defines how quickly tasks can be performed once the user has learned the design. The third component is memorability which is about how easily a user can return to its previous skill level after a period of not using it. The fourth component is about errors, how many errors are made and how sever are these errors. The fifth component is satisfaction. These components defines how pleasant the interface is to use (Yamamoto, 2013).

To create a usable dashboard, it is important to also involve the future users of the dashboard. Therefore, a dashboard can be created in different steps. Operational managers can be asked for their input in different ways. For example, they can be asked for indicators they find important via a small survey, they can be asked during a focus group to discuss these indicators or a mix of these methods can be used (Morana & Gonzalez-Feliu, 2015). Depending on the situation, steps can be formulated to define the indicators needed on the dashboard.

3.5.3. Summary of creating a dashboard

This section described possible pitfalls when creating a dashboard and components to create a usable dashboard. When creating a dashboard, it is important to involve the future users in the first steps of the process. Only indicators which clearly reflect the business activities should be used and they should not unfairly simplify a complex world. The usability of the dashboard can be estimated by examining the following components: learnability, efficiency, memorability, errors and satisfaction.

3.6. Conclusion

This chapter performed a literature review about how the construction industry manages its logistics processes, what can influence these processes and how other industries create and solve models to schedule logistics processes. The construction industry started with creating plans for logistics processes, but the current techniques used are still very basic. Currently, the construction industry is working on developing techniques to share more of the available data and to adjust all the processes to each other. Similarly, the factors influencing the productivity of a crane need to be adjusted to each other. Possible factors which can influence this productivity are the storage capacity on site, the material delivery of the suppliers, the interaction between different cranes, the choice of off-site manufacturing and multiple soft factors like employee skills and the weather. The construction industry can improve their logistics processes by adjusting the processes on site more to each other.

The second part of the literature review explained how the factors influencing logistics processes can be adjusted to each other by creating a schedule. This can be done by using linear programming. Depending on the problem, the problem can be formulated mathematically by using integer, mixed-integer, non-linear programming or a combination of these. For scheduling problems mixed integer linear programming and mixed integer non-linear programming are common to use. When creating a schedule often a part of the input is stochastic. This can be solved by creating scenarios for all of the possibilities for the input. Clustering can be used to decrease the number of scenarios.

After formulating the problem with linear programming, it can be solved optimally by using exact methods or systematically a good solution can be found with heuristics. The first exact method is going through the entire search space. This can be used when the search space is small enough to go through the entire search space. Otherwise, the simplex method can be used to find a non-integer solution for linear problems. This can be complemented with the branch-and-bound method to find an integer solution. Non-linear problems can be solved optimally by using the interior-point method. When using heuristics, an initial solution can be created with a constructive heuristic. This solution can be improved by using improvement heuristics like the genetic algorithm, simulated annealing or tabu search.

The last part of the chapter explained how a dashboard can be used to visualize the results. When creating a dashboard, it is important to involve the future users in the first steps of the process. Only indicators which clearly reflect the business activities should be used and they should not unfairly simplify a complex world. The usability of the dashboard can be estimated by examining the following components: learnability, efficiency, memorability, errors and satisfaction. This chapter showed that there are multiple possibilities to create new techniques to improve the crane productivity of construction companies, but these should be carefully chosen and the users should be actively involved.

4. The proposed scheduling method

Chapter 2 described the current situation of DVBH. Chapter 3 described possible methods given in literature to solve the problems of the current situation. This chapter combines the previous two chapters by proposing a scheduling method applicable to the situation of DVBH. Section 4.1. describes the context of the problem. Section 4.2. describes the scheduling method and the notation. Section 4.3. describes an algorithm to solve the proposed scheduling method. Lastly, Section 4.4. summarizes the conclusions of this chapter.

4.1. Define the problem context

This section defines the context of the problem which will be solved. First, Section 4.1.1. describes the situation on a construction site. Next, Section 4.1.2. describes which factors are taken into account. Lastly, Section 4.1.3. gives the simplifications of the problem which will be solved compared to the reality.

4.1.1. Situation construction site Dura Vermeer

Figure 10 gives an example of a construction site. This figure shows that a construction site has different areas. When a truck comes to the construction site, it first arrives at the waiting area. This area is usually not on the construction site itself and in this case also not on the figure. The number of spots on the waiting area differ per project and need to be reserved before the construction starts. Therefore, the number of waiting spots is determined before the start of the construction phase. When the truck receives a signal to come to the construction site, it can either go to the unloading area or to the crane. When a truck is self-unloading, it goes to the unloading area. Here, the truck moves the material to the storage after which it is moved to the project by the crane. When a truck cannot unload itself, a crane does this. After unloading, the truck leaves the construction site.

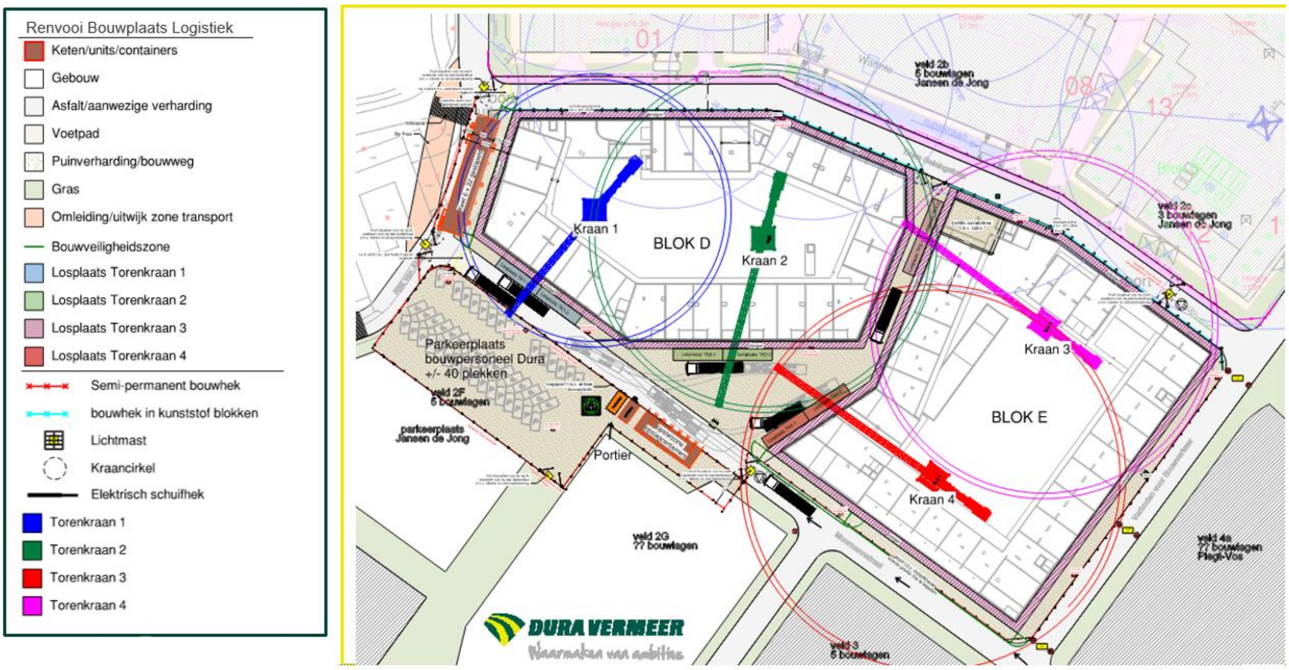


Figure 10 Example construction site (DVBH)

The size of the waiting area, the number of unloading areas and the storage capacity are all determined before the start of the construction phase by the project organisers. The number of cranes is estimated before the construction phase, but in case of mobile cranes, this can be adjusted by the construction manager during the construction phase. The construction manager also schedules the arrival time of the trucks. The next paragraphs give more information about the cranes and trucks.

Cranes
As mentioned in Section 2.2.2, there are two type of cranes. Tower cranes need to be rented for an entire day. These cranes are usually used for several sequential weeks because the set-up costs are too high to rent the cranes for several periods. The mobile cranes can be rented per hour. The supplier determines the minimum number of hours a crane needs to be rented on a day. So, a schedule for cranes should define how many hours the crane is rented. This is considered to be the only difference between the two types of cranes.

Trucks
Trucks can arrive at every moment of the day, but the company only registers their arrival time per minute. Therefore, the schedule can be discretized by defining the arrival time in minutes. Trucks receive a time at which they should come to the construction site, but for several reasons a truck can arrive earlier or later. These reasons are out of scope of the research because they are hard to influence as described in Section 1.3, but the reliability is taken into account when creating a schedule for the trucks. So the actual arrival time of a truck is stochastic input. When ILips is used, DVBH can keep track of how many trucks of a supplier arrive within a certain time period from the scheduled arrival time. Therefore, a discrete probability distribution is available per supplier of their arrival time reliability. This data is collected by scanning at arrival a ticket which they received after confirmation of the delivery. When the first truck arrives earlier, this truck automatically has to wait because the crane can only start working from the beginning of the first period, unless it is a self-unloading truck. So, when creating a schedule the probability distribution of the arrival time of a truck should be taken into account.

Self-unloading trucks can unload their own material on the site and move it directly to the storage place. Since there is limited storage place available, it is also important to consider the arriving time of these trucks. The crane only needs to move the material from the storage place to the project in this case. A self-unloading truck can only move material to the storage place when there is an unloading area available. The movement time of all the materials in a truck can be calculated by multiplying the movement time per material of this type by the number of materials in the truck. The material is moved to a position within the project. This position differs per material, so the swing of the crane can also be different per material. The difference in swing time is very minimal compared to the hook-up time. Therefore, this difference is negligible. The storage capacity should be taken into account when scheduling self-unloading trucks.

Trucks are willing to wait on the waiting spots, but not for an unlimited time period. The maximum waiting time depends on the type of material. If the unloading time is for example very small, a truck is not willing to wait very long. In order to simplify the problem formulation, one maximum waiting time is used for all trucks. As described in Section 2.5, 30 minutes is an acceptable waiting time in general, thus this time can be used for the schedule.

4.1.2. Factors taken into account in the problem formulation

Section 3.2. described what factors can influence the productivity of a crane. Since the schedule will be made to improve the productivity of a crane, it is important to consider these factors. Based on Section 4.1.1., the factors which can be of influence in the case of DVBH can be determined. The first factor that will be considered is the reliability of the arrival of trucks as this was also named as an important factor during the problem identification. Second, the site layout will be considered. This will be done by defining the storage space, waiting area and the unloading area and how this influences the workload of a crane. The interaction of the resources will not be considered. This is because the research will focus on tower cranes and mobile cranes. Tower cranes are not allowed to move in each other's area and the clashes between the mobile cranes can be neglected. So, there is no interaction between the resources. Off-site manufacturing will be considered by looking into the effect of pre-fabrication. This will not be done in the schedule, but in the dashboard. This can be done because the prefabricated objects decrease the number of arriving trucks while increasing the movement time. Therefore, only the input parameters change. Lastly, the soft factors will not be considered when creating a schedule, since these are hard to predict. They will be considered when implementing the dashboard and writing a recommendation for the company.

Figure 11 shows an addition to the calculation model described in Section 2.4.2. The figure shows the factors used for the calculation of the number of cranes. This calculation uses the crane capacity per material flow. So, this shows how many materials need to be moved and in what time this can be done based on the crane types and material types. The start and end times are extracted from the planning and are used to calculate the number of cranes needed in time. Additionally, this calculation takes the reliability of cranes into account. This is based on the reliability of the arrival time and the number of trucks. Lastly, the addition to the model also takes characteristics of the construction site into account. For the calculation of the number of cranes, the storage capacity, the size of the unloading area and the waiting area are the most important factors to take into account.

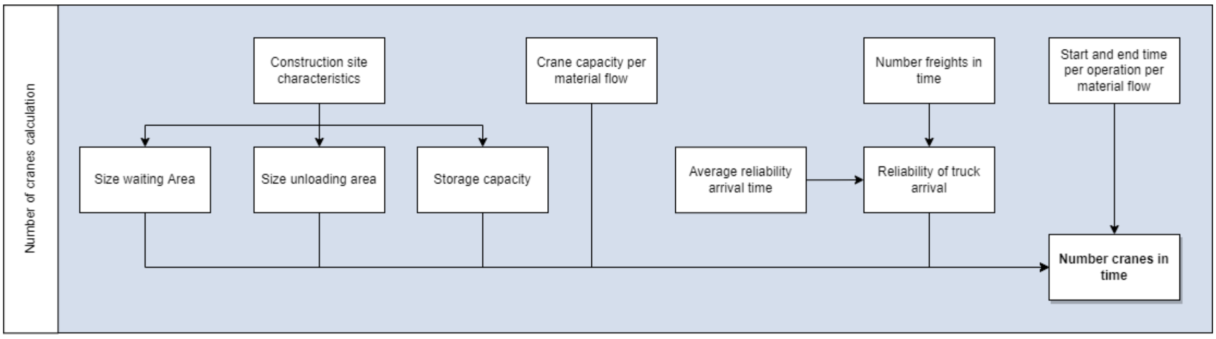


Figure 11 Extention volume model which calculated the need number of cranes

4.1.3. Simplifications

In reality there are more factors which influence the process on the construction site, but in order to make the problem formulation not too complicated these are not considered. These factors are:

- The routes of the trucks on the construction site, this can be of influence because it can take some time before the truck arrives to the crane. Additionally, trucks occasionally have to leave from the same gate. So, a new truck cannot arrive before the previous truck has left.
- The movement time of the crane is not always the same. Sometimes the hook-up time differs for the same material type. This is because of a lack of standardization. Additionally, the movement time increases when the height of the project increases. In this research this is not taken into account, but all the movement times are considered the same per material type.
- Sometimes multiple tower cranes are needed to cover the entire construction site even though this is not needed for the number of arriving trucks. This research does not take this into account, but only shows the minimum number of crane hours. In case more cranes are required to cover the entire area, these can always be added to the minimum number of cranes by the project organisers.

4.2. Selected scheduling method

This section explains how a scheduling problem can be formulated of the described problem in Section 4.1. First, Section 4.2.1. describes the formulation of the problem. Next, Section 4.2.2. describes the modification for the stochastic input. Section 4.2.3. gives the notation of the problem formulation. Section 4.2.4. explains the used objective and Section 4.2.5. describes the needed constraints. Lastly, Section 4.2.6. describes the made assumptions.

4.2.1. Formulation

Section 3.3. described possible methods to create a schedule. This section describes how the problem is formulated and how this relates to the problems described in Section 3.3. First, the scheduling problem is mathematically formulated. Like the planning airline crew problem, the arriving trucks will be considered as tasks which need to be assigned to a crane. The truck arrival will be modelled by using release and due dates for the tasks. Since the cranes need to be rented per number of hours, the day will be divided into different periods of an hour. The intensity at which cranes can be used will therefore be different per period. One truck can be emptied over multiple periods, but this does not have to take the entire period. Therefore, a non-integer variable will be used to define the arrival and due time of a truck. The movement time and arrival time will be determined in minutes. Therefore, the non-integer variables are rounded off to two decimals. Binary variables are used to see if storage places, waiting areas and unloading areas are used in a period. The problem is therefore similar to the linear described problems in Section 3.3. This problem will also only contain linear constraints, both integer and non-integer variables are used. So, mixed integer linear programming will be used to formulate the problem.

As described in Section 1.4., this research focusses on improving the productivity of cranes. Therefore, the objective will be to maximise the productivity. Productivity will be formulated as the ratio between the working periods of a crane and the rented periods. Cranes are always working the same number of periods because they need one handling for every truck. So, the objective can be linearized by using this as an input parameter instead of a variable.

4.2.2. Modification for stochasticity

Section 3.2.1. described how stochastic input parameters can be included in an LP model. This can be done by creating scenarios for the possibilities. In literature demand is generally the stochastic input. In this case the deviation of the actual arrival time compared to the scheduled arrival time of the truck is the stochastic input. So, a scenario tree can be created of the possible deviations of the trucks from their scheduled arrival time on the day. The first truck, for example, has several possibilities of deviation. Next, the second truck has several deviation possibilities. This continues until all of the possible deviations of all the arriving trucks are included.

Section 3.2.1. also described possibilities of scenario reduction. This is not included in this problem formultion, since the number of possible scenarios can be handled within the limits of Excel and within an acceptable computational time. The number of scenarios is further explained in Section 5.1.1.

4.2.3. Notation

Before the problem formualtion is described more in detail in the next sections, this section shows the used notations in this research.

Sets:

P	Set of all periods in a day, $p \in P$
T	Set of all trucks arriving on a day, $t \in T$
C	Set of all cranes available on a day, $c \in C$

S	Set of all scenarios of a day, $s \in S$
U	Set of all unloading areas available on the construction site, $u \in U$

Input parameters:

MT_t	Movement time, number of periods needed to move the material of truck t
L_t	L is 1 if truck t is self-unloading
V_t	Volume of material in truck t
CRP	Minimal crane rental period
$Smax$	Maximum storage available
$Wmax$	Maximum waiting time of a truck
$WAmax$	Maximum number of waiting areas
$OTmax$	Maximum overtime
D_{ts}	Deviation in scenario s of truck t from the scheduled arrival time
TMT	Total movement time of all cranes on a day

Decision variables:

RT_t	Release time of truck t which is the scheduled arrival time
DT_{ts}	Due time of truck t in scenario s
WT_{ts}	Waiting time of truck t in scenario s
WTL_{ts}	Waiting time of material of truck t in scenario s on storage place
I_{cs}	Total number of periods crane c is working in scenario s
O_c	Total number of periods crane c is rented
X_{ptcs}	X is 1 if crane c is emptying truck t in period p in scenario s
UA_{ptus}	X is 1 if unloading area u is used by truck t in period p in scenario s
Z_{pcs}	Z is 1 if crane c is working in period p in scenario s
Y_{tcs}	y is 1 if crane c is emptying truck t in scenario s
A_{tcs}`	A is 1 if unloading area u is used by truck t in scenario s
ST_{pts}	ST is 1 if storage is used by truck t in scenario s at period p
WA_{tps}	WA is 1 if truck t uses a waiting area in period p in scenario s
OT_{cs}	The overtime of crane c in scenario s
f_c	Intermediate variable to calculate the maximum working period
b_c	Intermediate variable to calculate the minimum working period
e_c	Intermediate variable to calculate the minimum working period without CRP

4.2.4. Objective

We propose the following objective:

$$\max \frac{TMT}{\sum_{c=1}^{C} O_c}$$

This objective defines the productivity of all the cranes. Productivity can be calculated by diving the input by the output. In this case the input is the number of periods cranes are working, TMT and the output is the number of periods cranes are rented, $\sum_{c=1}^{C} O_c$. TMT is given as input and is the sum of the movement time of all the trucks. O_c is further defined in the constraints of the problem formulation. A crane needs to be rented at least a certain number of periods. Therefore, O_c is an integer.

4.2.5. Constraints

There are several constraints which need to be incorporated in the problem formulation. This section describes which constraints are incorporated and how these are formulated.

Emptying a truck

A truck needs to be emptied in one time. So, there cannot be any waiting time for the truck once a crane started emptying it or once it started emptying itself. Therefore, X_{ptcs} is filled after the arrival time and the waiting time are over for MT_t time. The same is applicable for the unloading area. After the arrival and the waiting time are over of a self-unloading truck, the unloading area will be taken for MT_t time. The material of a self-unloading truck also needs to be moved from the storage place to the project. Therefore, X_{ptcs} is filled after the material is delivered to the storage area. Since the material does not need to be moved immediately from the storage place, an extra variable, WTL_{ts} is used to define the time the material is waiting on the storage place. Additionally, the problem formulation contains the constraint that a truck needs to be emptied by only one crane. Z_{pcs} shows if a crane, c is working in period, p in scenario, s. So, this is an integer variable and will be used when defining the productivity. This is formulated in the following constraints:

(1) $MT_t * Y_{tcs} = \sum_{p=RT_t+D_{ts}+WT_{ts}+MT_t*L_t+WTL_{ts}}^{DT_{ts}+MT_t*L_t+WTL_{ts}} X_{ptcs}$ for every t, c, s

(2) $\sum_{c=1}^{C} Y_{tcs} = 1$ for every t,s

(3) $\sum_{t=1}^{T} X_{ptcs} \leq Z_{pcs}$ for every p, c, s

(4) $MT_t * L_t * A_{tus} = \sum_{p=RT_t+WT_{ts}+D_{ts}}^{DT_{ts}} UA_{puts}$ for every t, u, s

(5) $\sum_{u=1}^{U} A_{tus} = L_t$ for every t, s

(6) $DT_{ts} = RT_t + MT_t + D_{ts} + WT_{ts}$ for every t, s

Waiting time

A truck is allowed to wait, but there is a maximum waiting time. Therefore, this is also incorporated in a constraint. A truck can arrive before the scheduled time. In case a truck arrives before the start of the working day, which is not self-unloading, the truck has to wait at least until the start of the working day. WTL_{ts} is the waiting time of the material on the storage place. In case this material comes from a truck that is not self-unloading, WTL_{ts} will always be 0 since the material is immediately moved to the project. This is formulated in the following constraints:

(7) $WT_{ts} \geq -(RT_t + D_{ts}) * (1 - L_t)$ for every t, s

(8) $WT_{ts} \leq \mathrm{Wmax}$ for every t, s

(9) $WTL_{ts} \leq M * L_t$ for every t, s

Waiting area

When there is no crane or unloading area available, a truck has to wait in the waiting area. The number of waiting spots in this area is not unlimited. Therefore, this maximum is incorporated in a constraint. To see if a waiting spot is used, the variable, WA_{tps} is used. The sum of WA_{tps} over all periods for a truck is equal to the waiting time of the truck in the scenario. This variable is 1 after the arrival of the truck until WT_{ts} has passed. The two following constraints formulate this:

(10) $\sum_{p=RT_t+D_{ts}}^{RT_t+WT_{ts}+D_{ts}} WA_{tps} = WT_{ts}$ for every t, s

(11) $\sum_{t=1}^{T} WA_{tps} \leq$ WAmax for every p, s

Storage capacity
When a self-unloading truck starts emptying itself, storage place is used. The storage capacity on a construction site is not unlimited. Therefore, constraints are added which show when storage place is used and make sure that the total places used do not exceed the maximum. The storage place is only used by self-unloading trucks and is defined as 1 for periods after the arrival time and waiting time of the truck are over until WTL_{ts} is over. For every period, the storage used by the materials of all the trucks cannot exceed Smax. This is formulated in the following constraints:

(12) $\sum_{p=RT_t+D_{ts}+WT_{ts}}^{DT_{ts}+WTL_{ts}} ST_{pts} = (MT_t + WTL_{ts}) * L_t$ for every t, s

(13) $\sum_{t=1}^{T} ST_{pts} * V_t \leq$ Smax for every p, s

Overtime
It is possible that a truck arrives after the scheduled time. When a truck is scheduled at the end of the day, the crane has to make overtime in this case. Overtime is acceptable for most projects, but there is a maximum overtime. This problem formulation assumes that there is overtime after 8 hours of working on a day. This is formulated in the following two constraints:

(14) $OT_{cs} \geq p * Z_{pcs} - 8$ for every c, s, p

(15) $OT_{cs} \leq$ OTmax for every c, s

Output
O_c can be defined as the difference between the last period a crane is working and the first period a crane is working. In order to make the constraints linear, intermediate variables are added. The output is equal to the number of needed crane hours which is needed for the project organisers. Since a crane needs to be rented for at least CRP periods, O_c needs to be at least higher or equal then CRP. The output is based on the maximum and minimum period the crane is used within all the scenarios. Therefore, the output is not different per scenario. This can be formulated in the following constraints:

(16) $O_c = f_c - b_c$ for every c

(17) $f_c \geq p * Z_{pcs}$ for every p, s, c

(18) $b_c \geq CRP$ for every c

(19) $b_c \geq e_c$ for every c

(20) $e_c \leq p * Z_{pcs} + k_{cs}$ for every p, s, c for which $Z_{pcs} = 1$

Domain variables
The variables which can be changed when solving the problem formulation can only vary within a certain domain. Constraint 21 shows the variables which are binary. Constraint 22 shows the domain of RT_t. This variable needs to be higher than 1 because the first period is period 1 and a truck cannot be scheduled before this period. The remaining variables need to be non-negative which is defined in constraint 23.

(21) $Y_{ct}, Z_{pcs}, ST_{pts}, L_t, A_{tcs}, WA_{tps} \in \{0,1\}$ for every p, t, c, s

(22) $RT_t \geq 1$ for every t

(23) $DT_{ts}, WT_{ts}, WTL_{ts}, I_{cs}, O_c, X_{ptcs}, UA_{ptus}, OT_{cs}, f_c, b_c, e_c \geq 0$ for every p, t, c, s

4.2.6. Assumptions

Most of the characteristics of the problem are included in the constraints. When using these constraints, several assumptions are made:

Every crane has the same MT_t

This research focusses on cranes in general. So, there is no difference between various types of cranes, and therefore MT_t is the same for every crane.

A truck has the same MT_t as a crane

Since self-unloading trucks are also taken into account, these trucks have a movement time for moving their material from their truck to the storage place. In this problem formulation, this movement time is considered to be the same as when a crane moves the material.

A truck needs to be emptied by one crane

In general, one crane empties a truck. For the simplicity of the problem formulation, this is considered to always be the case.

A truck is fully loaded

A truck is considered to be fully loaded. Therefore, the movement time of the material can be same for all of the trucks. In reality a truck may not be fully loaded because only a certain number of material is needed. In the preparation phase of the project, the number of trucks is estimated. Therefore this assumption will not have a big influence in this phase. In the construction phase, the problem can be resolved by filling in the half-filled truck separately in the input form and halving its movement time.

The maximum storage capacity stays the same throughout the entire construction phase

In the beginning of the construction phase, the construction project might not be big in size. So, in the beginning of the phase there might be more storage places available compared to the end of the project. For the simplicity of the problem formulation, the maximum storage is always considered to be the same.

The maximum waiting time is the same for every truck

We assume that every truck is willing to wait the same amount of time. In reality, this can differ per truck. A truck which delivers for example only a small number of materials which can be unloaded very fast is willing to wait for a shorter period than a truck that brings a lot of material and will take a lot of time to unload. Additionally, this can depend on the deviation of the arrival time from the scheduled time. Since there is no exact data about these relations, the maximum waiting time is assumed to be the same for all the trucks.

Only self-unloading trucks use the storage place and unloading area.

A self-unloading truck always uses storage places. Usually, the material of a non-self-unloading truck is directly moved to the project. Therefore, this truck can be unloaded in any area of the construction site. This is sometimes on the unloading area, but can also be somewhere else. Since a non-self-unloading truck can also be emptied somewhere else when the unloading area is taken, this problem formulation considers only self-unloading trucks to use the unloading area. In some cases, there is no room in the project for the material of a non-self-unloading truck yet. The material is then moved to the storage place first. Since this is hard to predict and does not happen often, this problem formulation assumes that only self-unloading trucks use the storage place.

A truck can be emptied by every crane

As can be seen in Figure 11, trucks move to an unloading area of a crane. Sometimes it is important a truck moves to a specific crane when its material is needed on that side of the project. In other cases the material is too heavy to be lifted by every crane. In order to decrease the complexity of the problem formulation, it is assumed that all the arriving trucks can be emptied by every crane.

A storage area is emptied at the end of the day

Construction managers generally only schedule trucks with materials which are needed on the same day. They do not order trucks to create a buffer of materials on the site for multiple days. Construction managers who have a lot of storage capacity on their site might order trucks some days before the material is needed. Since this is not often the case and increases the complexity of problem formulation, it is assumed that the storage area is empty at the end of the day.

4.3. Solving algorithm

In order to solve the problem described in Section 4.2, a solving algorithm needs to be selected. This section describes which solving algorithm is used and how. Section 4.3.1. describes the chosen algorithms. Next, Section 4.3.2. describes the possible constructive algorithms and Section 4.3.3. describes the possible improvement heuristics.

4.3.1. Used algorithms

Section 3.4 gave an overview of possible solving methods. This can either be an exact method or a heuristic. The problem formulation described in Section 4.2. varies the scheduled arrival time of trucks. This can be scheduled throughout the whole day. Assuming that trucks can only be scheduled per minute, there are 480 ($8 * 60$) possibilities to schedule the trucks. The number of trucks varies per day between 1 and 9 trucks. When the number of trucks grows the number of possible solutions grows exponentially. The search space can vary between 480 and 480^9. Therefore, the search space is too large to use full enumeration. Another option is the interior-point method. This method is generally used for non-linear problems. Since the problem is linear the interior-point method is less suitable than the simplex method. The problem formulation is mixed integer. So, when using the simplex method, an LP-relaxation is needed. This LP-relaxation can be used to find an optimal solution with the branch-and-bound method. Since both methods would be needed and the number of branches grows when the number of trucks grows, the computational time can become very high.

Another option is using heuristics instead of exact methods. When using a heuristic, this can be a constructive or improvement heuristic. Constructive heuristics generally are based on creating a sequence of jobs for scheduling problems. For this problem the sequence of the trucks is already set, but it is important to minimise the total rental period of the cranes. Therefore, simple constructive heuristics can be used for which an improvement heuristic is needed to improve the solution. The characteristics of trucks differ in movement time and whether they are self-unloading or not. Therefore, the constructive heuristics are partly based on these characteristics. There are three improvement heuristics which are considered in this research, genetic algorithm, simulated annealing and tabu search. With a genetic algorithm, multiple solutions which are not neighbours will be analysed and improved. With simulated annealing also worse solutions are accepted to prevent finding a local optimum. With tabu search the memory of previous solutions is used.

Since the computation time of the most suitable exact method which is a combination of the simplex method and branch-and-bound method is high, and heuristics can also give a good solution, heuristics are chosen as the most suitable solving method. First constructive heuristics will be used to create an initial solution. Next, improvement heuristics will be used to create a better solution. These heuristics are described in the next sections.

4.3.2. Constructive heuristics

For the initial solutions, constructive heuristics will be used. These methods are based on how the trucks are currently scheduled by the construction managers. Some construction managers for example spread the trucks evenly while others create a buffer of trucks first. The five used methods and their corresponding pseudo codes are explained below.

Equal spread

Construction managers would like to have a time buffer between arriving trucks. By equally spreading the arriving trucks over the day, this time buffer is maximized and the same for all the trucks. In the pseudo code below, the arrival time, RT_t of the trucks, t are evenly spread over the periods, P.

```
t = 1
For a = 1 to P + 1 step P/T
        RT_t = a
        t = t + 1
next a
```

Equal spread even periods

As previously explained, construction managers prefer to have a time buffer between arriving trucks. The previous heuristic has an equal time buffer between all the trucks. In this heuristic, time buffers of at least one hour are used. Every odd period is scheduled empty and the trucks are evenly spread over the remaining periods. The box below shows the pseudo code of this heuristic.

```
t = 1
For a = 1 to P + 1 step 2
        For b = 0 to 1 step (P/2)/T
                RT_t = a + b
                t = t + 1
        next b
next a
```

Buffer first period

The construction managers are always trying to keep their crane occupied. Therefore, they sometimes want a buffer of trucks to ensure there is always a truck to empty. In this constructive heuristic, the trucks are evenly spread over all the periods, but the first period is scheduled double to create an initial buffer of trucks. This has the following pseudo code:

```
t = 1
For a = 1 to T
    If t < 2 then
        RT_a = t
    Else
        RT_a = t − 1
    End if
    t = t + (P + 1)/T
next a
```

Movement time based

A construction manager makes an estimation of how long it takes to empty a truck. This heuristic schedules the trucks based on this estimation. The trucks are scheduled such that the time between proceeding trucks is the movement time, MT. The first truck is scheduled at the beginning of the day. A truck cannot initially be scheduled such that overtime is needed. Therefore, this is checked before the arrival time is set. This heuristic has the following pseudo code:

```
RT_1 = 1
h = 1
For a = 2 to T
    if h > (P + 1) − MT_a then
        h = 1
    End if
    RT_a = h + MT_{a−1}
    h = h + MT_{a−1}
next a
```

Movement time and self-unloading trucks based

This constructive heuristic is similar to the previous heuristic, but now it also takes into account whether a truck is self-unloading or not. If a truck is self-unloading it arrives earlier such that the material is unloaded when the material of the previous truck is moved. The first truck is scheduled at the beginning of the day. This has the following pseudo code:

```
RT_1 = 1
h = 1 + MT_1
For a = 2 to T
    If L_a = 1 then
        RT_a = h − MT_a
    Else
        RT_a = h
    End if
    h = h + MT_a
    if h > (P + 1) then
        h = 1
    End if
next a
```

4.3.3. Improvement heuristics

For this research three different improvement heuristics are analysed. For each heuristic the neighborhood of a solution is defined as all solutions in which the arrival time of one truck is changed. The neighbor is created by mutating the arrival time of the truck. Initially, the mutation is 0.5 period. This is further explained in Section 5.2. The heuristics are explained in the next paragraphs.

Genetic algorithm

For the genetic algorithm only mutation is used. Crossover is not used because changing the arrival time of two trucks only makes a difference when a self-unloading truck is changed with a non-self-unloading truck. In general, all the trucks of one type of material are delivered by the same type of truck and changing the arrival of the order of material delivery is not desired by the company. So, only the operator mutation is used. New solutions are eliminated if they are not feasible. The algorithm uses three stopping criteria for which the first one which is met is selected. The first criterium is that the loop is stopped when there are only neighbors with a lower objective value. The second stopping criterium is that the algorithm cannot exceed the maximum number of iterations. This number is based on the number of trucks scheduled for the day and is defined such that every truck can change the scheduled arrival time with half a day in total. The last criterium is that the algorithm is stopped when the objective value is the same for five iterations. This results in the following pseudocode:

```
While stopping criteria is not reached do
    For iteration = 1 to 5
        Generate initial solution with constructive heuristic
        For t = 1 to trucks
            For z = -0.5 to 0.5
                Set RT values of solution
                RT_t^neighbour = RT_t + z
                Generate neighbour solution
                If neighbour solution < current solution then
                    Current solution = neighbour solution
                End if
            Next z
        Next t
        Solution = current solution
    Next iteration
End
```

Simulated annealing

Simulated annealing decreases the chance of finding a local optimum by also accepting worse solutions. This is done by using a variable, T which decreases with every iteration by a reduction factor. The algorithm continues until T is smaller than 0.5. This results in the following pseudo code:

```
Reduction factor = 0.97
T = 1
Generate initial solution using constructive heuristic
While T > 0.5 do
        For t = 1 to trucks
                For z = −0.5 to 0.5
                        Set RT values of solution
                        RT_t^neighbour = RT_t + z
                        Generate neighbour solution
                        If neighbour solution < current solution then
                                Current solution = neighbour solution
                        Endif
                Next z
        Next t
                If current solution < solution then
                        Solution = current solution
                Else
                        Define r as random number between 0 and 1
                        If r > exp(-(solution – current solution)/T) then
                                Solution = current solution
                        Endif
                endif
        T = T * reduction factor
End
```

Tabu search

Tabu search remembers previous neighbours and creates a list to ensure that those neighbours are not chosen again in the next iteration. Neigbours are removed from the list after a certain number of iterations. For this research, The previous trucks and their corresponding change are on the list. This means that if RT_t of a truck is changed, the truck is placed on the tabu list and cannot be changed again the next iteration. The length of the tabu list is dependent on the number of trucks and is defined as 0.3 * trucks. The stopping criteria are the same as for the genetic algorithm.

```
Generate initial solution based on best constructive heuristic
While stopping criteria not reached do

        For t = 1 to trucks
                Check if truck is not on the tabu list
                For z = −0.5 to 0.5
                        Set RT values of solution
                        RT_t^neighbour = RT_t + z
                        Generate neighbour solution
                        If neighbour solution < current solution then
                                Current solution = neighbour solution
                        Endif
                Next z
        Next t

        Solution = current solution
        Update tabu list
End
```

4.4. Conclusion

This chapter described how the problem of DVBH is mathematically formulated and how this can be solved. When creating a schedule for the cranes on the construction site, it is important to take the volume of the material, the site characteristics and the reliability of the arrival of trucks into account. Since the arrival of trucks is not reliable, a stochastic input parameter is added to the problem formulation. Different scenarios of the actual arrival time are used when solving the problem. The problem is formulated as an MILP in which the objective calculates the productivity by looking into the ratio between the number of hours a crane has worked and the number of hours a crane is rented. The constraints make sure the trucks are emptied and the maximum waiting time, the number of waiting areas, the storage capacity, and the maximum overtime are not exceeded. Exact solution are not feasible for this problem because of high computational time. Therefore, heuristics are used as solving method. Simple constructive heuristics are used to create an initial solution. These methods are based on the input of construction managers. There are three possible improvement heuristics: a genetic algorithm, simulated annealing, and tabu search. This chapter created a formulation for the problem and possible solving heuristics. In the next chapter these solving heuristics are tested and the results of the dashboard are evaluated.

5. Evaluation Dashboard

Chapter 4 described the proposed solving method to solve the problem of DVBH. This chapter evaluates this by creating a dashboard. The chapter describes the input data and results from one project of DVBH. A second project of DVBH was analysed of which the input and results are shown in Appendix B and C. Section 5.1. describes the input data. Section 5.2. describes the evaluation of the heuristics. Next, Section 5.3. compares the decisions made for the project and the recommended decisions resulting from the dashboard. Section 5.4. describes the sensitivity analyses of the dashboard. Lastly, Section 5.5. gives the conclusions of this chapter.

5.1. Input

This section describes the input of project 1 used to evaluate the dashboard. The input of project 2 is summarized in Appendix B. The input is based on a project of DVBH. This project is at the end of the construction phase. The construction phase started in May 2021 and is planned to be finished in November of 2022. The involved suppliers are confidential and therefore anonymized in this chapter. First, Section 5.1.1. describes the dataset which was available of this project. Next, Section 5.1.2. describes the sets and Section 5.1.3. describes the input parameters.

5.1.1. Dataset

Project 1 used ILips to manage all of the arriving trucks. As described in Section 2.4.1, ILips is the transportation management system and keeps track of the scheduled and the actual arrival time of the trucks. Therefore, there is information about the reliability of the arrival of trucks. The supplier of which the truck originates is also known. Therefore, at the end of a project the reliability of the trucks of a supplier can be estimated. Additionally, this information can be used again for future projects. So, the database can be continuously updated and can become more accurate. When ILips is used for more projects, the data can be combined to get a better estimation of the reliability per supplier. This data can be used for future projects to see which supplier should be chosen.

DVBH gives every truck a code after it arrived. Table 1 gives an overview of the given codes. With these codes they can calculate the average reliability of trucks. This is also used to create figure 7 in Section 2.4.1.

Table 1 Overview used Codes in ILips

Code	Deviation
1	± 30 minutes
2	± 1 hour
3	> 1 hour on the same day
4	< 1 hour on the same day
8	No ticket
9	More than a day too early
10	More than a day too late

The reliability of the arrival of the truck is dependent on the supplier from which it originates. Therefore, the number of possible deviations and the corresponding probability is different for every supplier. The number of possible deviations is related to the codes given in Table 1. Table 2 shows the used average deviation per code. Since a truck is considered to be on time when it has code 1, the corresponding deviation is 0 minutes. Code 2 is split in code 2a and 2b since a truck can be late or early. On average trucks with code 2 are 45 minutes too late or too early. Trucks with code 3 are on average 2 hours too late and trucks with code 4 are on average 2 hours too early. Trucks with code 8, 9 and 10 are not taken into account because there are several reasons why a truck arrives on a different day or does not have a ticket. These changes in arrival are usually communicated with the construction manager. Since this deviation is known beforehand, it is not taken into account.

Table 2 Used average deviation per code

Code	Average deviation
1	0 minutes
2a	- 45 minutes
2b	45 minutes
3	2 hours
4	- 2 hours

Suppliers have observations of arriving trucks per code. When there are 0 observations of a code, this code is not considered as a possible deviation for that supplier. So, the number of possible deviations is also different per supplier. The maximum number of deviations is five, but this only occurs for 10% of the suppliers. Similarly, only 10% of the suppliers has four deviations. Table 3 gives an example of 2 arriving trucks with each 2 observations of different codes. Table 4 shows the corresponding scenarios of this day.

Table 3 Example observations per code of 2 trucks

Truck	Code				
	1	2a	2b	3	4
1	1	1			
2	1			1	

Table 4 possible scenarios with 2 trucks with 2 observations per truck

Scenario	Deviation per truck	
	1	2
1	0 minutes	0 minutes
2	0 minutes	2 hours
3	-45 minutes	0 minutes
4	-45 minutes	2 hours

5.1.2. Sets

This section describes all of the input variables of the dashboard which are periods, trucks, cranes, scenarios and unloading areas. The next paragraphs describe these further.

Period (p)

The whole day is divided into time buckets. The period describes the length of each bucket. The project organisers always work with the number of crane hours. Therefore, the period is taken as 1 hour. On a regular day, 8 hours can be scheduled, but it is possible to have overtime. The maximum overtime is described in Section 3.1.2. So, the total number of timebuckets is 8 hours + the number of hours it is possible to have overtime.

Truck (t)

The set of the arriving trucks arriving per day is calculated by using the total number of trucks per task and the number of days during which this task is performed. From the volume calculations mentioned in Section 2.4.2. the building tasks, their start and end week, the number of workable days within these weeks and the total number of trucks arriving for this task can be extracted. The evaluated project did not work with these calculations. Therefore, the number of trucks is derived from the data of ILips. This data contains information about how many deliveries arrived on a day and in a week and from which suppliers. Additionally, the percentage of trucks which use a crane is needed per supplier. Some of the arriving trucks only takeaway materials or the material only needs horizontal movement. For these trucks there is no crane needed. With this information the average number of trucks per week can be calculated for the preparation phase. Table 5 shows the results of this calculation for the first three weeks. This table shows that in week 31 5 trucks are arriving of supplier c which all need a crane. Table 17 in Appendix A shows the total table with the result of this calculation for the preparation phase. Table 18 in Appendix A shows the calculated arriving trucks per day for the construction phase.

Table 5 Number of arriving trucks per week per supplier of project 1

		Supplier															
% Crane Needed		100%	100%	100%	100%	100%	100%	0%	0%	0%	0%	0%	100%	100%	0%	0%	100%
Year	Week	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p
2021	31			5.00													
2021	35			18.00						1.00							
2021	38	14.00													1.00		

Crane (c)

The set of cranes shows how many cranes can be used for the project. In general, not more than 10 cranes are used on a project, so the maximum number of cranes is 10. Whether a crane is used or not, depends on the result of the dashboard.

Scenario (s)

The number of scenarios varies per week and is only taken into account for the project organisers. The number depends on the tasks performed during that week and which suppliers are used for this task. For every supplier different observations are done about their arrival reliability which are the given codes. Table 6 shows the results of the first three suppliers. Table 19 in Appendix A shows the observation of all the suppliers per code. If there are no observations, the supplier is expected to be on time. If a supplier does not have observations for a KPI code, this is not considered as a possible deviation. So, the total number of scenarios of a week is dependent on the number of trucks arriving that week and their corresponding supplier. According to table 5, in week 31 5 trucks arrive. So, on average 1 truck arrives per day. This truck is from supplier c. According to table 6, supplier c has 4 possible deviations. So, week 31 has 4 possible scenarios for the arrival of one truck.

Table 6 Observations per supplier of deviation from scheduled arrival time per code

Supplier	**4a**	**2a**	**1**	**2b**	**3b**	**Number of possible deviations**
a	7	7	33	4	35	5
b	0	0	1	0	0	1
c	6	0	7	3	19	4

Unloading area (u)

The variable unloading area shows which unloading area is used by a truck. The maximum number of unloading areas differs per project. For this project there are 3 possible unloading areas.

5.1.3. Parameters

This section describes the values of the input parameters which are movement time, self-unloading trucks, volume, crane rental period, maximum storage available, maximum waiting time of a truck, maximum number of waiting areas and maximum overtime. These are further explained in the next paragraphs.

Movement time (MT_t)

The time it takes to unload a truck and to move the material to the site differs per building task and is an estimation of the project organisers and construction managers. The construction manager of this project estimated that every truck takes 2 hours to unload which is independent from the material in it.

Self-unloading trucks (L_t)

Whether a truck is self-unloading or not is agreed upon with the supplier before the start of the construction phase. The supplier differs per construction task, so the number of self-unloading trucks are also different per construction task. The following suppliers agreed to use self-unloading trucks: b, c , e, g, h, I, j, k, l, n, o.

Crane rental period (CRP)

A crane can only be rented for a certain period. This period differs per type of crane and per supplier of the crane. The supplier of the mobile cranes for this project had a minimal rental period of 5 hours.

Maximum storage available ($Smax$)

The maximum storage places which are available also differ per project. For this project the exact storage capacity was never measured. The construction manager gave an estimation of a capacity for 4 truckloads.

Volume (V_t)

The volume of the material is important to know when the storage place is filled. This also differs per construction task. Since the maximum storage capacity is given in number of truckloads, the exact volume is not used for this case. The volume for every truck is considered to be exact one truckload.

Maximum waiting time of a truck ($Wmax$)

The maximum waiting time of a truck is dependent on the truck itself. As mentioned in Section 2.5. in general, the maximum waiting time is 30 minutes. Therefore, this value is also used for this project.

Maximum number of waiting areas ($WAmax$)

The maximum number of waiting places which are available also differs per project. For this project it was agreed that the nearest gas station can be used as waiting area. Since there is a large parking place, the maximum number of waiting places are considered to be unlimited for this project.

Maximum overtime ($OTmax$)

The maximum acceptable overtime on a day is dependent on the project team. This is determined by the construction manager and is 2 hours in this case.

Deviation (D_{ts})

The deviation of a truck in a scenario is dependent on the observations of the arrival time of the truck. Table 2 in Section 5.1.1. shows the value of the deviation per code. Table 19 in Appendix A shows the observations of all the codes per supplier.

Total movement time (TMT)

The total movement time of all the cranes of a day is dependent on the number of arriving trucks and their movement time. So, this can be calculated with the following formula: $TMT = \sum_{t=1}^{T} MT_t$

5.2. Results

This section evaluates the heuristics described in Section 4.3. The code for the heuristics is written in Visual Basic for Applications (VBA) in Excel. The volume calculations as described in Section 2.4.2. are also done in Excel. By using VBA the input can be changed in Excel and the output can be shown in the same file. This will make the created dashboard more usable for the company. The performance of the heuristics is based on the input described in Section 5.1. First, Section 5.2.1. describes the output of the five different constructive heuristics and the three different improvement heuristics. Next, Section 5.2.2. describes of the best heuristic the best definition of the neighborhood and the stopping criteria. Finally, Section 5.2.3. describes the performance of the heuristics compared to the solution found with the models created in Excel Solver and AIMMS.

5.2.1. Heuristics

Table 7 shows the results of the constructive heuristics. The table shows the calculated productivity, the number of needed crane hours and the computational time to find the optimal solution. The colors show the weeks with different productivities. So, week 35 shows that *Equal spread* and *Buffer first period* perform the worst and *Equal spread even periods* performs the best. The total score compares the constructive heuristics. For every week the heuristic performs the best, it gains 1 point and for every week it performs the worst it loses 1 point. The table shows that *Equal spread even weeks* and *Movement time and self-unloading trucks based* perform the best. *Equal spread even periods* performs 2 times better than *Movement time and self-unloading trucks based* and the other way around. These two constructive heuristics are used to compare the results of the improvement heuristics.

Table 7 Comparison constructive heuristics which shows that Equal spread even weeks and Movement time and self-unloading trucks based perform the best

Year	week	Constructive heuristics														
		Equal spread			Equal spread even periods			Buffer first period			Movement time based			Movement time and self-unloading trucks based		
		Prod.	Nr. crane hours	Comp. Time	Prod.	Nr. crane hours	Comp. Time	Prod.	Nr. crane hours	Comp. Time	Prod.	Nr. crane hours	Comp. Time	Prod.	Nr. crane hours	Comp. Time
2021	31	33%	6.00	00:00:01	33%	6.00	00:00:00	33%	6.00	00:00:01	33%	6.00	00:00:00	33%	6.00	00:00:01
2021	35	31%	12.35	00:00:02	36%	10.45	00:00:02	33%	11.40	00:00:01	31%	12.35	00:00:02	33%	11.40	00:00:01
2021	38	56%	9.00	00:00:00	75%	8.00	00:00:01	67%	6.00	00:00:01	75%	8.00	00:00:00	75%	8.00	00:00:01
2021	39	56%	8.40	00:00:00	75%	7.47	00:00:01	67%	5.60	00:00:01	75%	7.47	00:00:00	75%	7.47	00:00:01
2021	40	50%	4.80	00:00:00	50%	4.80	00:00:01	50%	4.80	00:00:00	50%	4.80	00:00:01	50%	4.80	00:00:00
2021	42	33%	9.60	00:00:01	33%	9.60	00:00:00	33%	9.60	00:00:00	33%	9.60	00:00:01	33%	9.60	00:00:00
2021	43	20%	11.00	00:00:01	44%	9.90	00:00:00	44%	9.90	00:00:01	44%	9.90	00:00:00	50%	8.80	00:00:01
2021	44	50%	8.00	00:00:00	67%	6.00	00:00:01	40%	5.00	00:00:00	67%	6.00	00:00:01	67%	6.00	00:00:00
2021	46	33%	7.20	00:00:01	33%	7.20	00:00:00	33%	7.20	00:00:01	33%	7.20	00:00:00	33%	7.20	00:00:01
2021	47	32%	11.00	00:00:00	40%	10.00	00:00:01	40%	10.00	00:00:01	36%	11.00	00:00:01	40%	10.00	00:00:00
2021	48	50%	11.04	00:00:10	68%	9.20	00:00:14	55%	10.12	00:00:11	60%	9.20	00:00:13	60%	9.20	00:00:12
2022	5	50%	8.80	00:00:00	67%	7.70	00:00:01	100%	7.70	00:00:00	67%	7.70	00:00:01	100%	7.70	00:00:00
2022	6	100%	4.20	00:00:01	100%	4.20	00:00:00	100%	4.20	00:00:01	100%	4.20	00:00:00	100%	4.20	00:00:00
2022	19	100%	1.60	00:00:01	100%	1.60	00:00:00	100%	1.60	00:00:01	100%	1.60	00:00:00	100%	1.60	00:00:01
Total score		-7			6			0			3			6		

Table 8 shows the results of the improvement heuristics with an initial solution found with *Equal spread even periods*. This table shows that the improvement heuristics only improved the results for a few weeks. This is improvement is less than expected. It also shows that the results are very similar except for week 43. Since, GA performs for one week better than SA and TS, this heuristic has the highest total score. The table also shows that week 35 and week 48 have a higher computational time. This is because in these weeks unreliable suppliers were used. As a consequence, there are a lot of scenarios in these weeks which increase the computational time.

Table 8 Results improvement heuristics on Equal spread even periods which shows that GA performs the best

Year	Week	Equal spread even periods								
		GA			SA			TS		
		Prod.	Nr. crane hours	Comp. Time	Prod.	Nr. crane hours	Comp. Time	Prod.	Nr. crane hours	Comp. Time
2021	**31**	33%	6.00	00:00:00	33%	6.00	00:00:02	33%	6.00	00:00:02
2021	**35**	36%	10.45	03:27:12	36%	10.45	03:27:12	36%	10.45	03:27:12
2021	**38**	75%	8.00	00:00:10	75%	8.00	00:00:12	75%	8.00	00:00:03
2021	**39**	75%	7.47	00:00:11	75%	7.47	00:00:12	75%	7.47	00:00:03
2021	**40**	50%	4.80	00:00:01	50%	4.80	00:00:01	50%	4.80	00:00:01
2021	**42**	33%	9.60	00:00:01	33%	9.60	00:00:01	33%	9.60	00:00:01
2021	**43**	50%	8.80	00:00:04	44%	9.90	00:00:03	44%	9.90	00:00:01
2021	**44**	67%	6.00	00:00:03	67%	6.00	00:00:03	67%	6.00	00:00:00
2021	**46**	33%	7.20	00:00:01	33%	7.20	00:00:01	33%	7.20	00:00:01
2021	**47**	40%	10.00	00:00:17	40%	10.00	00:00:21	40%	10.00	00:00:05
2021	**48**	68%	9.20	00:11:00	68%	9.20	00:05:21	68%	9.20	00:01:34
2022	**5**	67%	7.70	00:00:00	67%	7.70	00:00:00	67%	7.70	00:00:00
2022	**6**	100%	4.20	00:00:01	100%	4.20	00:00:01	100%	4.20	00:00:00
2022	**19**	100%	2.40	00:00:00	100%	2.40	00:00:00	100%	2.40	00:00:00
Total score		1			0			0		

Table 9 shows the results of the improvement heuristics which use an initial solution created by *Movement time and self-unloading trucks based*. This table shows that all weeks have the same productivity. Therefore, the improvement heuristics are compared based on the computational time. This table shows that TS performs for 6 out of the 14 weeks better than the other two improvement heuristics. In contrast to *Equal spread even periods*, GA performs the worst with this constructive heuristic.

Table 9 Results improvement heuristics on Movement time and self-unloading trucks based which shows that TS performs the best

Year	Week	Movement time and self-unloading trucks based								
		GA			SA			TS		
		Prod.	Nr. crane hours	Comp. Time	Prod.	Nr. crane hours	Comp. Time	Prod.	Nr. crane hours	Comp. Time
2021	**31**	33%	6.00	00:00:02	33%	6.00	00:00:02	33%	6.00	00:00:01
2021	**35**	46%	13.74	03:30:18	46%	13.74	03:14:12	46%	13.74	01:21:23
2021	**38**	75%	8.00	00:00:10	75%	8.00	00:00:10	75%	8.00	00:00:02
2021	**39**	75%	7.47	00:00:09	75%	7.47	00:00:10	75%	7.47	00:00:03
2021	**40**	50%	4.80	00:00:01	50%	4.80	00:00:01	50%	4.80	00:00:01
2021	**42**	33%	9.60	00:00:01	33%	9.60	00:00:01	33%	9.60	00:00:01
2021	**43**	50%	8.80	00:00:03	50%	8.80	00:00:04	50%	8.80	00:00:01
2021	**44**	67%	6.00	00:00:02	67%	6.00	00:00:02	67%	6.00	00:00:01
2021	**46**	33%	7.20	00:00:01	33%	7.20	00:00:01	33%	7.20	00:00:01
2021	**47**	40%	10.00	00:00:19	40%	10.00	00:00:19	40%	10.00	00:00:05
2021	**48**	60%	9.20	00:09:44	60%	9.20	00:04:42	60%	9.20	00:01:24
2022	**5**	100%	5.50	00:00:00	100%	5.50	00:00:01	100%	5.50	00:00:00
2022	**6**	100%	4.20	00:00:00	100%	4.20	00:00:01	100%	4.20	00:00:01
2022	**19**	100%	2.40	00:00:00	100%	2.40	00:00:00	100%	2.40	00:00:00
Total score		-1			0			6		

Table 10 compares the two best results of *Equal spread even periods* and *Movement time and self-unloading trucks based.* This table shows that the results differ in 3 weeks. *Movement time and self-unloading trucks based* performs for 2 out of these 3 weeks best and *Equal spread even periods* performs for 1 out of these 3 weeks best. *Movement time and self-unloading trucks based* also has lower computational time in 6 out of the 14 weeks compared to *Equal spread even periods*. Especially in week 35 the computational time is much lower. Therefore, *Movement time and self-unloading trucks* *based* is used as the constructive heuristic which is improved by TS for the remaining part of this research.

Table 10 Results TS which show that heuristic 5 performs the best for this algorithm

Year	Week	Equal spread even periods			Movement time and self-unloading trucks based		
		GA			TS		
		Prod.	Nr. crane hours	Comp. Time	Prod.	Nr. crane hours	Comp. Time
2021	31	33%	6.00	00:00:00	33%	6.00	00:00:01
2021	35	36%	10.45	03:27:12	46%	13.74	01:21:23
2021	38	75%	8.00	00:00:10	75%	8.00	00:00:02
2021	39	75%	7.47	00:00:11	75%	7.47	00:00:03
2021	40	50%	4.80	00:00:01	50%	4.80	00:00:01
2021	42	33%	9.60	00:00:01	33%	9.60	00:00:01
2021	43	50%	8.80	00:00:04	50%	8.80	00:00:01
2021	44	67%	6.00	00:00:03	67%	6.00	00:00:01
2021	46	33%	7.20	00:00:01	33%	7.20	00:00:01
2021	47	40%	10.00	00:00:17	40%	10.00	00:00:05
2021	48	68%	9.20	00:11:00	60%	9.20	00:01:24
2022	5	67%	7.70	00:00:00	100%	5.50	00:00:00
2022	6	100%	4.20	00:00:01	100%	4.20	00:00:01
2022	19	100%	2.40	00:00:00	100%	2.40	00:00:00
Total score		1			2		

5.2.2. Neighborhood and Stopping criteria

The results of Section 5.2.1. use a neighborhood for which RT of one truck is 0.5 period different compared to the original solution. This difference can also be increased to 1 or 2 periods. Table 11 shows the results of using different definitions for the neighborhood. This table shows that the results of the heuristic are similar. The productivity and the number of crane hours are the same in every week. The computational time is a bit different, but this difference is so small that it is neglectable. So, a change in neighborhood does not have an impact on the results. The table in Appendix C of the second project shows the same result. Therefore, the same neighborhood is kept and the remaining results in this chapter are based on a neighborhood of 0.5 period.

Table 9 Results comparison different neighborhoods which shows that the results are the same

Year	Week	Tabu search								
		0.5			1			2		
		Prod.	Nr. crane hours	Comp. time	Prod.	Nr. crane hours	Comp. time	Prod.	Nr. crane hours	Comp. time
2021	31	33%	6.00	00:00:01	33%	6.00	00:00:02	33%	6.00	00:00:01
2021	35	46%	13.74	01:21:23	46%	13.74	01:21:23	46%	13.74	01:20:21
2021	38	75%	8.00	00:00:02	75%	8.00	00:00:04	75%	8.00	00:00:04
2021	39	75%	7.47	00:00:03	75%	7.47	00:00:02	75%	7.47	00:00:03
2021	40	50%	4.80	00:00:01	50%	4.80	00:00:02	50%	4.80	00:00:01
2021	42	33%	9.60	00:00:01	33%	9.60	00:00:01	33%	9.60	00:00:01
2021	43	50%	8.80	00:00:01	50%	8.80	00:00:01	50%	8.80	00:00:01
2021	44	67%	6.00	00:00:01	67%	6.00	00:00:00	67%	6.00	00:00:01
2021	46	33%	7.20	00:00:01	33%	7.20	00:00:01	33%	7.20	00:00:01
2021	47	40%	10.00	00:00:05	40%	10.00	00:00:03	40%	10.00	00:00:03
2021	48	60%	9.20	00:01:24	60%	9.20	00:01:19	60%	9.20	00:01:18
2022	5	100%	5.50	00:00:00	100%	4.40	00:00:01	100%	4.40	00:00:01
2022	6	100%	4.20	00:00:01	100%	2.80	00:00:01	100%	2.80	00:00:01
2022	19	100%	2.40	00:00:00	100%	1.60	00:00:01	100%	1.60	00:00:01
Total score		0			0			0		

Section 4.3. defined the stopping criteria. These are defined as: there are only neighbors with a lower objective value, the algorithm cannot exceed the maximum number of iterations, the objective value

is the same for five iterations. When using the described heuristic in Section 5.2.1. with the neighborhood previously described, the maximum number of iterations was never reached. Therefore, these three stopping criteria are kept for the remaining results of the dashboard.

5.2.3. Comparison other solving methods

The result of the best heuristic is compared to the solution found by Excel solver and AIMMS. The next paragraphs describe this comparison.

Excel Solver

Excel has an add-in function to solve linear programming problems, the Excel Solver. One week of the project previously described is used to compare the results of the created dashboard with the results of the methods in Excel Solver. For this problem week 43 is used. In this week 11 trucks arrive. So, rounded off 2 trucks arrive on average on a day. The number of scenarios is assumed to be one, to improve the solvability in Excel Solver. The dashboard of this research found for this week a productivity of 100%.

Excel Solver has three different methods to solve a problem, GRG nonlinear, Simplex LP and evolutionary. The GRG nonlinear and evolutionary method both were able to find a solution for the problem. The decisions variable X is defined with a summation based on different variables and parameters. This is defined in constraint 1 as defined in Section 4.2.5. In contrast to Excel VBA and AIMMS, It was not possible to formulate the summation of this constraint linearly in Excel Solver. Therefore, the Simplex LP method could not find a solution in Excel Solver. Both the GRG nonlinear and evolutionary method found a solution with a productivity of 80%. Similar to the dashboard of this research, these methods do not guarantee to find an optimal solution. The found solution by Excel Solver is lower than the 100% productivity found by the heuristics of this research. So, the created dashboard in this case performs better than the methods used by Excel Solver.

AIMMS

The found solutions by the dashboard are also compared to the optimal solution. Therefore, the MILP formulation is used to create a model in AIMMS. Week 43 is again used to compare the results. For the AIMMS model the scenarios are taken into account. The two trucks of this week each have 5 possible deviations. So, 25 scenarios are possible for this week. When taking the scenarios into account the dashboard of this research found a solution of 50% productivity. The AIMMS model found a solution with 50% productivity as well and with the same values for the decision variables. So, in this case the AIMMS model and the heuristic in this research perform equal.

5.3. Comparison with crane rental past project

The project which is analysed, is almost finished. Therefore, the real decisions about the crane rental are already known. This section describes the decisions which are made and compares these to the results of the dashboard to see if the results of the dashboard are realistic and improvements could have been made. Section 5.3.1. describes the KPI with which the comparison is made. Section 5.3.2. describes the decisions made for the project and Section 5.3.3. compares these decisions with the results of the dashboard of this research.

5.3.1. KPIs

This research focusses on increasing the productivity of a crane. The actual productivity of a crane cannot be extracted anymore from finished projects. This is also hard to estimate from current projects because the only way to get data about this is by observing the cranes productivity. This will take many weeks to get reliable data, therefore only the number of needed crane hours calculated by the dashboard is compared to the actual rented number of crane hours. This is done by comparing the days during which a crane is rented with the number of hours a crane was needed according to the dashboard.

5.3.2. Historical decisions

This project rented one tower crane. The crane was on the project from 09-09-2021 till 09-02-2022. The construction manager also rented different type of mobile cranes. ILips gives information about the supplier of the mobile cranes. Therefore, the dates at which a mobile crane is rented can be extracted from ILips. There is no information about how long this crane was available. Since the number of hours the crane is rented is not known, this is assumed to be the minimal number of 5 hours.

5.3.3. Recommended decisions

Figure 12 shows the results of the dashboard of the research and the decisions made by the company. The blue line shows how many hours are needed based on the calculations of the dashboard and the orange line shows how many hours are rented on average that week. This means that when a mobile crane is rented one day for 5 hours, on average 1 hour per day is available that week. The orange line shows with a long horizontal line of 8 crane hours that a tower crane was rented from September 2021 till February 2022. The graph shows that most crane hours are needed during the rental period of the tower crane. There is one gap during this rental period when no crane hours are needed. This is because the construction manager finished the tasks for which a crane was required early. So, he rented the crane to his subcontractors this period. The graph shows that the tower crane could have been rented for a shorter period. So, with this dashboard this problem could have already been identified in the preparation phase of the project. There is one large peak before the tower crane rental period during which also no mobile crane was rented. This is because one week the material was delivered and put in storage. So, it could be moved to the project by the tower crane which was available the next week. The peak in May 2022 of the needed crane hours is almost the same as those rented. In total the dashboard calculated that 99 hours are needed while there were 186 rented. By using this dashboard, the periods during which less cranes could have been rented can be defined. So, the graph shows that the dashboard calculated a representative number of needed crane hours since these align with the rented crane hours. Additionally, the graphs visualizes where improvements could have been made.

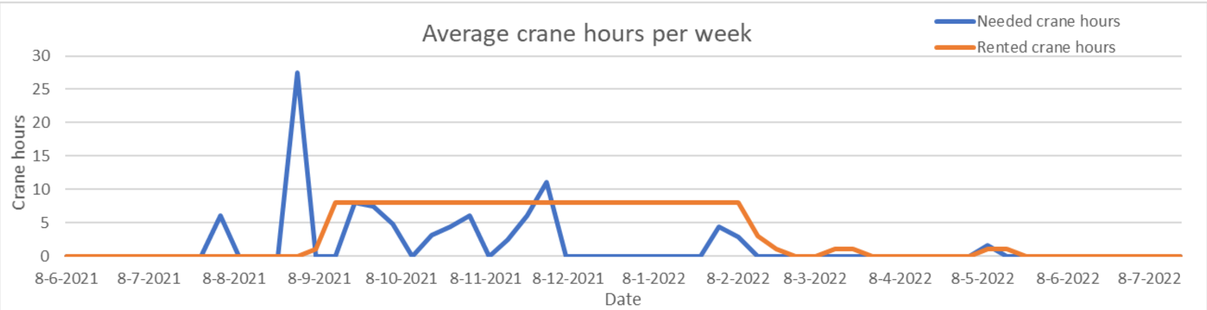


Figure 12 Comparison crane hours

Figure 13 shows the results of the comparison for the construction phase. This figure shows similar results, but for days instead of weeks. It shows the number of cranes needed to rent per day instead of the needed crane hours. It shows that most of the peaks are during the rental period of the tower crane and that at the end of this period no cranes are needed anymore. There are again cranes needed on days during which no crane was rented. This is because the subcontractor rented their own cranes for these materials or moved the material by hand. The dashboard does not take this into account because it defines per supplier if a crane is needed. For these suppliers cranes were needed for the material of their first trucks. This figure shows that for most days 1 crane was needed as was also budgeted. There are two peaks for which 2 cranes were needed per day. In reality there was only one crane needed. The dashboard is based on an estimation of the movement time of the crane. In this case the movement time is estimated as 2 hours which includes a buffer. This buffer was not needed on the busy days. This graphs shows again that the calculated needed cranes of the dashboard align with the actual number of rented cranes.

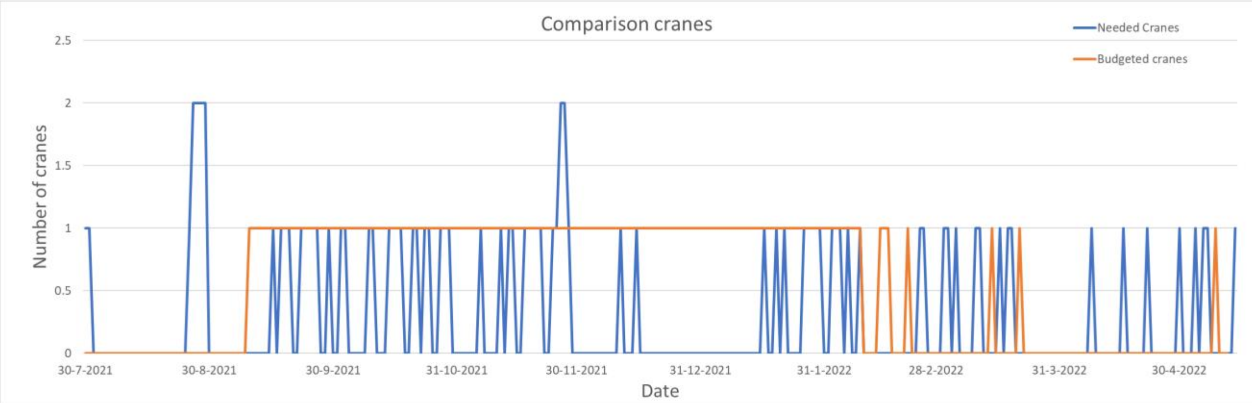


Figure 13 Comparison number of cranes

Figure 14 shows the calculated productivity. This figure shows that there are several days with only 40% productivity. These days are also often after each other. In construction it is not always possible to move construction tasks, because they are very dependent on each other. However, this graph shows which days could possibly be combined to improve the productivity. By automatically visualizing the productivity of a crane, the dashboard helps construction managers to look for possible improvements.

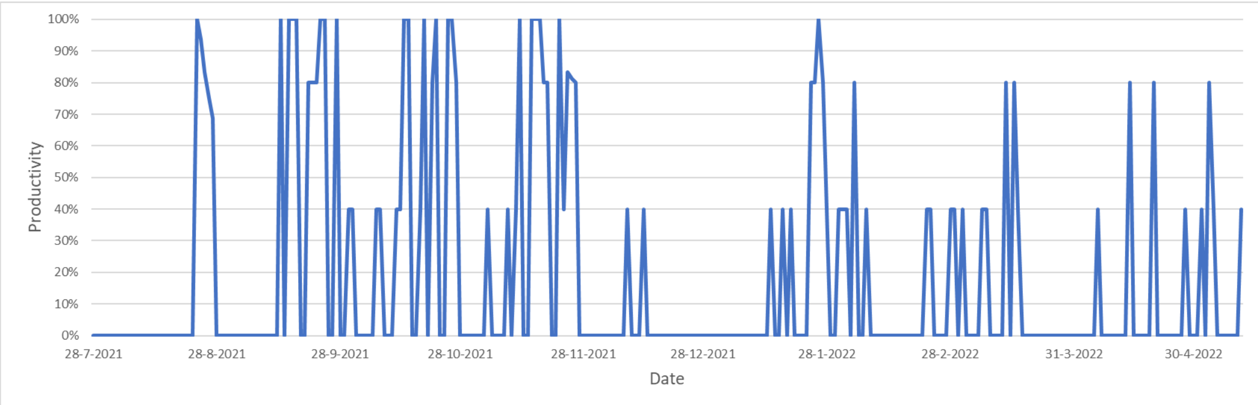


Figure 14 Calculated productivity per day

5.4. Sensitivity analysis

Not all the used input is known with certainty. This section describes the influence of a change in the input. First, Section 5.4.1. describes a change in an estimated input parameter. Next, Section 5.4.2. describes what the influence can be of a change in decisions made by the company.

5.4.1. Uncertainty input parameters

Only one input parameter is estimated, the movement time MT. This is an estimation made by the construction managers based on their experience because there are no numbers about the movement time for every type of material. Table 12 shows how the results of the dashboard change when MT is changed. The original MT of 120 is also shown. This table shows that a change in MT can have a big influence on the resulting productivity. The maximum change is in week 35 when the original 46% productivity changed to 75% with a movement time of 90 minutes. There is no clear relation between the change of MT and the change of the productivity. Figure 15 shows the same results in a graph and confirms that there is no clear relation. Figure 16 shows the results of the number of crane hours. This graphs shows that the number of crane hours decreases when MT decreases. So, the results show that MT should be chosen carefully and cannot just be a rough estimation because it has a big influence on the outcome.

Table 10 Results decreasing MT

Year	Week	Movement time													
		60		90		105		120		135		150		180	
		Prod.	Nr. crane hours	Prod.	Nr. crane hours	Prod.	Nr. crane hours	Prod.	Nr. crane hours	Prod.	Nr. crane hours	Prod.	Nr. crane hours	Prod.	Nr. crane hours
2021	**31**	25%	4,00	30%	5,00	28%	6,00	33%	6,00	31%	7,00	36%	7,00	43%	7,00
2021	**35**	50%	10,57	75%	10,57	68%	11,63	46%	13,74	44%	14,80	50%	13,74	40%	15,86
2021	**38**	60%	5,00	75%	6,00	73%	7,00	75%	8,00	69%	9,00	72%	9,00	55%	11,00
2021	**39**	60%	4,67	75%	5,60	73%	6,53	75%	7,47	69%	8,40	72%	8,40	55%	10,27
2021	**40**	33%	3,60	38%	4,80	43%	4,80	50%	4,80	44%	6,00	50%	6,00	60%	6,00
2021	**42**	25%	6,40	30%	8,00	28%	9,60	33%	9,60	31%	11,20	36%	11,20	43%	11,20
2021	**43**	40%	5,50	50%	6,60	49%	7,70	50%	8,80	43%	9,90	44%	9,90	30%	11,00
2021	**44**	50%	4,00	60%	5,00	68%	5,00	67%	6,00	63%	7,00	71%	7,00	75%	8,00
2021	**46**	25%	4,80	30%	6,00	28%	7,20	33%	7,20	31%	8,40	36%	8,40	43%	8,40
2021	**47**	50%	6,00	64%	7,00	64%	8,00	40%	10,00	35%	11,00	36%	11,00	23%	13,00
2021	**48**	71%	6,44	72%	8,28	54%	10,12	60%	9,20	55%	10,12	72%	8,28	55%	10,12
2022	**5**	100%	2,20	100%	3,30	85%	4,40	100%	5,50	88%	5,50	100%	5,50	100%	6,60
2022	**6**	100%	1,40	75%	2,80	85%	2,80	100%	4,20	73%	4,20	83%	4,20	100%	4,20
2022	**19**	100%	0,80	75%	1,60	85%	1,60	100%	2,40	73%	2,40	83%	2,40	100%	2,40

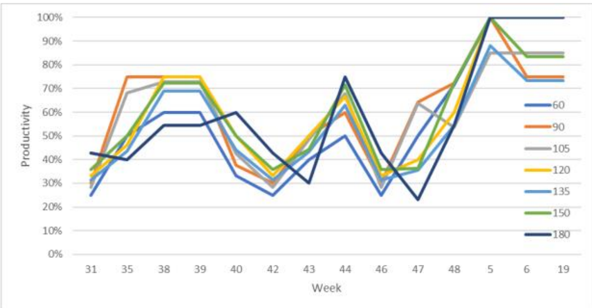


Figure 15 productivity with different values for MT

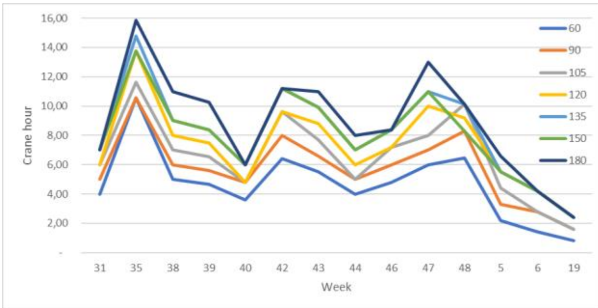


Figure 16 Number of crane hours with different values for MT

5.4.2. Possible decision changes

This section describes the influence of the decisions made. For example, the characteristics of the construction site can still be changed during the preparation of a construction project or the arriving week of trucks can be changed. The paragraphs below describe these changes.

Changing storage capacity

Table 13 shows the results of changing the storage capacity. This table also shows the original results with storage places for 4 trucks. The table shows that the storage capacity does not have a lot of influence on the resulting productivity and number of crane hours. Even with a storage capacity for 1 truck a feasible solution can be found for every week. The construction manager also indicated that he almost did not use the full storage capacity. So, the created dashboard also shows that less storage capacity could have been created on this construction site.

Table 11 Results change storage capacity which shows that the results remain the same

Year	Week	Storage capacity									
		1		2		3		4		5	
		Prod.	Nr. crane hours	Prod.	Nr. crane hours	Prod.	Nr. crane hours	Prod.	Nr. crane hours	Prod.	Nr. crane hours
2021	**31**	33%	6,00	33%	6,00	33%	6,00	33%	6,00	33%	6,00
2021	**35**	46%	13,74	46%	13,74	46%	13,74	46%	13,74	46%	13,74
2021	**38**	75%	8,00	75%	8,00	75%	8,00	75%	8,00	75%	8,00
2021	**39**	75%	7,47	75%	7,47	75%	7,47	75%	7,47	75%	7,47
2021	**40**	50%	4,80	50%	4,80	50%	4,80	50%	4,80	50%	4,80
2021	**42**	33%	9,60	33%	9,60	33%	9,60	33%	9,60	33%	9,60
2021	**43**	50%	8,80	50%	8,80	50%	8,80	50%	8,80	50%	8,80
2021	**44**	67%	6,00	67%	6,00	67%	6,00	67%	6,00	67%	6,00
2021	**46**	33%	7,20	33%	7,20	33%	7,20	33%	7,20	33%	7,20
2021	**47**	40%	10,00	40%	10,00	40%	10,00	40%	10,00	40%	10,00
2021	**48**	60%	9,20	60%	9,20	60%	9,20	60%	9,20	60%	9,20
2022	**5**	100%	4,40	100%	4,40	100%	4,40	100%	5,50	100%	4,40
2022	**6**	100%	2,80	100%	2,80	100%	2,80	100%	4,20	100%	2,80
2022	**19**	100%	1,60	100%	1,60	100%	1,60	100%	2,40	100%	1,60

Changing unloading areas

Table 14 shows the results of changing the number of unloading areas. This table shows again that the number of unloading areas does not influence the productivity of a crane. For week 35, 43 and 47 a feasible solution could not be found with 1 unloading area. Therefore, the minimum number of unloading areas is 2. The construction manager indicated the same for the unloading areas as for the storage capacity. So, the created dashboard shows that 2 unloading areas could have been used instead of 3.

Table 14 Results change unloading areas which shows that 1 unloading area is not enough

Year	Week	Unloading area							
		1		2		3		4	
		Prod.	Nr. crane hours	Prod.	Nr. crane hours	Prod.	Nr. crane hours	Prod.	Nr. crane hours
2021	**31**	33%	6,00	33%	6,00	33%	6,00	33%	6,00
2021	**35**			46%	13,74	46%	13,74	46%	13,74
2021	**38**	75%	8,00	75%	8,00	75%	8,00	75%	8,00
2021	**39**	75%	7,47	75%	7,47	75%	7,47	75%	7,47
2021	**40**	50%	4,80	50%	4,80	50%	4,80	50%	4,80
2021	**42**	33%	9,60	33%	9,60	33%	9,60	33%	9,60
2021	**43**		-	50%	8,80	50%	8,80	50%	8,80
2021	**44**	67%	6,00	67%	6,00	67%	6,00	67%	6,00
2021	**46**	33%	7,20	33%	7,20	33%	7,20	33%	7,20
2021	**47**		-	40%	10,00	40%	10,00	40%	10,00
2021	**48**	60%	9,20	60%	9,20	60%	9,20	60%	9,20
2022	**5**	100%	4,40	100%	4,40	100%	5,50	100%	4,40
2022	**6**	100%	2,80	100%	2,80	100%	4,20	100%	2,80
2022	**19**	100%	1,60	100%	1,60	100%	2,40	100%	1,60

Changing waiting area

Table 15 shows the result of changing the number of waiting spots. The current number of waiting spots is infinite. Often there are only a few waiting spots available. Therefore, the table also shows the result of 1 and 2 waiting areas. This table shows that this does not influence the productivity of the crane. Weeks 35 does not have a feasible solution with 1 waiting spot. So, the dashboard shows that at least 2 waiting spots are needed for this construction site.

Table 15 Results change waiting areas which shows that 1 waiting spot is not enough

Year	Week	Waiting spots					
		1		2		inf	
		Prod.	Nr. crane hours	Prod.	Nr. crane hours	Prod.	Nr. crane hours
2021	**31**	33%	6,00	33%	6,00	33%	6,00
2021	**35**			46%	13,74	46%	13,74
2021	**38**	75%	8,00	75%	8,00	75%	8,00
2021	**39**	75%	7,47	75%	7,47	75%	7,47
2021	**40**	50%	4,80	50%	4,80	50%	4,80
2021	**42**	33%	9,60	33%	9,60	33%	9,60
2021	**43**	50%	8,80	50%	8,80	50%	8,80
2021	**44**	67%	6,00	67%	6,00	67%	6,00
2021	**46**	33%	7,20	33%	7,20	33%	7,20
2021	**47**	40%	10,00	40%	10,00	40%	10,00
2021	**48**	60%	9,20	60%	9,20	60%	9,20
2022	**5**	100%	4,40	100%	4,40	100%	5,50
2022	**6**	100%	2,80	100%	2,80	100%	4,20
2022	**19**	100%	1,60	100%	1,60	100%	2,40

Changing Building method

Section 4.1.2. mentioned that the building method prefabrication can also influence the productivity of a crane. This is not taken into account with the scheduling method because prefabrication only influences the input of the dashboard. The movement time of prefabricated elements is longer, but fewer trucks will arrive in total. During the preparation phase, the dashboard can help decide what building method will results in the least number of crane hours. Table 16 gives an example of how the productivity and the number of crane hours change with different movement times and number of trucks. This table shows that the number of crane hours and productivity stay similar when MT changes to 240 minutes and the number of trucks decrease to 28 and 18. The number of crane hours between these two examples only decrease 0.5 hours. This is because the example uses an unreliable supplier. The number of crane hours increases substantially when MT increase even further to 360 minutes. The dashboard shows that the building method has a big influence on the productivity and needed number of crane hours and the dashboard shows how big this influence is.

Table 16 Results change week 35

MT (min)	Nr. trucks	Prod.	Nr. of crane hours
120	36	46%	13,74
240	28	40%	14,00
240	18	40%	13,50
360	24	47%	18,24

5.5. Conclusions

This chapter analysed the results of the solving method of Chapter 4, based on the input of an almost finished project of DVBH. The heuristics are formulated in Excel VBA. The results show that the best performing constructive heuristic is based on the movement time of the cranes and whether the trucks are self-unloading or not. This constructive heuristics performs for 2 out of 14 weeks better than other constructive heuristics and performs 0 out of 14 weeks worse than other constructive heuristics. The best improvement heuristic is Tabu Search. This improvement heuristics performs for 6 out of 14 weeks better than other improvement heuristics and performs 0 out of 14 weeks worse than other improvement heuristics. This heuristic is based on a neighborhood of 0.5 period difference in arriving time, but performs equal for a neighborhood of 1 or 2 periods. The results of the heuristics in Excel VBA are compared to the results of Excel Solver which uses the methods GRG nonlinear and evolutionary to solve the problem. The results of the heuristics in Excel VBA are also compared to the optimal solutions found with AIMMS. The comparisons are done based on one week of the analysed project. The performance of the methods in Excel solver is 20% lower than the solution found with the heuristic of the created dashboard. The solution of the AIMMS model is equal to the solution of the created heuristic. So, the performance of the created heuristic is better than Excel Solver and can be equal to the optimal solution.

The results of the heuristics of the created dashboard were also compared to the actual number of cranes rented of a finished project of DVBH. This comparison showed that the created dashboard can calculate the needed crane hours and the number of cranes accurately. With a visualization component, the dashboard also showed during which weeks too many cranes were rented. For future projects, the dashboard can make this visualization based on the input known in the preparation phase. This way the dashboard can show during which weeks changes can be made to improve the productivity of cranes.

A sensitivity analysis showed that the estimated movement time has a big influence on the productivity and needed number of crane hours per week. The sensitivity analysis showed a maximum change of 29% in productivity when the movement time decreased by 30 minutes. Therefore, this input parameter needs to be defined carefully. The sensitivity analysis also showed that the parameters of the storage capacity, the number of unloading areas and the waiting areas are not binding for the resulting productivity of the crane. By varying the values of these parameters, the dashboard can show what the minimal value of the parameter is to create a feasible solution.

6. The dashboard for the company

Chapter 4 and 5 described the solution method to solve the problem of DVBH. This chapter describes how the dashboard is implemented and how the company can use this. First, Section 6.1. explains the needed input and input forms. Next, Section 6.2. describes the output for the three different groups, project organisers, construction managers and logistics managers. In order to make the dashboard usable for the company, the input and output are created in Excel. Section 6.3. summarizes the limitations of using Excel for this dashboard. Lastly, Section 6.4. gives the conclusions of this chapter.

6.1. Input

There are three sheets which require input from an employee of DVBH. The first and second input sheet contain information about the trucks per construction task and the characteristics of the building site. The first sheet needs to be filled in by the project organizer and the second by the construction manager. Section 6.1.1. explains these input forms. The third input sheet requires information about the suppliers and their reliability. This sheet needs to be filled in by the logistics manager. Section 6.1.2. explains this sheet.

6.1.1. Input trucks and construction site

The first input form includes information about the building tasks which includes: the start and end date, the number of trucks in total, the supplier and the volume. All this data can also be extracted from the volume calculations described in Section 2.4.2. The project organiser needs to fill in additional data about the movement time, the percentage of self-unloading trucks and the percentage of cranes needed for the movement. Therefore, these are highlighted with a different color. Figure 17 shows what this input form looks like in Excel.

Input calculation model — DURA VERMEER

Construction task		Start day	End day	Building period in weeks	Number of trucks	Number of workable days	Number of trucks per day	Supplier	Possible deviations supplier	Volume	Movement time (minutes)	Self-unloading trucks (%)	Crane needed (%)
Site	Material												
	Pit												
	VBI												
Demolition	Demolition												
Ground	Ground												
Pile driving	Pile driving												
Foundation	Beams												
	Elevator pit												
	Piles												
Basement	Floor												
	Walls												
	Partition walls												
	Columns												
	Beams												

Figure 17 Input form trucks per construction part

The project organisers also need to fill in data about the characteristics of the building site. These include: the storage capacity, the number of unloading areas and the number of waiting spots. Lastly, the minimal rental period, the maximum waiting time of trucks and the maximum overtime need to be defined. Figure 18 shows what this looks like in Excel.

Site characterisitcs	
Storage capacity	
Number of unloading spots	
Number of waiting spots	

Other	
Crane rental period (hours	
Maximum waiting time truck	
Maximum overtime	

Figure 18 Input form site characteristics

The input form for the construction managers is similar. The characteristics of the construction site cannot be changed anymore during the construction phase. Therefore, these are not included in the input form of the construction managers. Additionally, at this phase of the project a more detailed planning is known. Therefore, compared to the project organisers input form, the construction tasks and their start and end time are more detailed.

6.1.2. Input suppliers

The logistics manager can get information from the transportation management system, ILips about the reliability of suppliers. This contains information about the KPI codes of the supplier as explained in Section 5.1.1. The logistics manager can continuously update this information when new data is acquired. Figure 19 shows the table in which this can be filled in. The logistics supplier can fill in the number of observations for a KPI code per supplier. The Excel file will automatically calculate the number of possible deviations and fill this in in the input form of Figure 17.

Supplier	KPI codes					Number of Deviations
	4a	2a	1	2b	3b	

Figure 19 Input form suppliers

6.2. Output

The output of the dashboard can be used for three different groups, the project organisers, the construction managers and the logistics managers. Section 6.2.1. explains the output which the project organisers can use, Section 6.2.2. explains the output which the construction managers can use and Section 6.2.3. explains the output which the logistics managers can use.

6.2.1. Project organisers

In a meeting with multiple project organisers, they indicated that they need to know how many hours a crane is needed. They need this information to know how high the budget should be set for the rental of cranes. Additionally, the productivity of these cranes is required to see what hours the crane is not working and so what buffer it has to clean the site or be used by sub-contractors. This is shown per week as the average per day. Figure 20 shows what this looks like in Excel. This sheet also shows the results of the calculation for the number of trucks per construction task per week. The sheet contains a button which the project organisers can use to update the result. This button is connected to the VBA code which runs the heuristics for the project organisers.

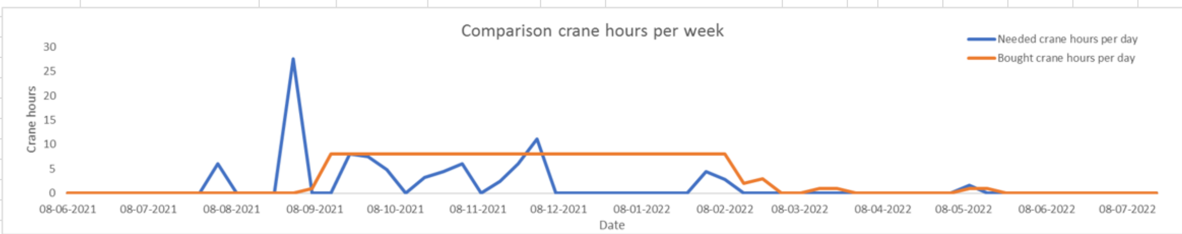
	Week	23	24	25	26	27	28	29	30	31	32
	Year	2021	2021	2021	2021	2021	2021	2021	2021	2021	2021
	First day of the week	08-06-2021	15-06-2021	22-06-2021	29-06-2021	06-07-2021	13-07-2021	20-07-2021	27-07-2021	03-08-2021	10-08-2021
Site	Material										
	Pit										
	VBI										
Demolition	Demolition										
Ground	Ground										
Pile driving	Pile driving										
Foundation	Beams										
	Elevator pit										
	Piles										
Basement	Floor										
	Walls										
	Partition walls										
	Columns										
	Beams										
Productivity											
Number of crane hours per day											

Calculate productivity

Figure 20 Output sheet project organisers with productivity and number of needed crane hours per day

Figure 21 shows the second output sheet for the project organisers. In this sheet the project organisers can fill in when they think a crane is needed and for how many hours. With this information the graph will be updated and a visual is made to see if the number of hours indicated by the project organisers is more than the needed number of hours according to the dashboard. When the costs are also filled in per crane, the total costs can be calculated. Lastly, this sheet also shows the difference between the number of hours for which the budget is set to rent a crane and the number of hours a crane is needed according to the dashboard.

Total overview



Crane type	Number of hours per week	Start day	End day	Costs per day
Tower				
Mobile				
Mobile				
Mobile				
Mobile				
Mobile				
Mobile				
			Total costs	0

Total	
Needed crane hours	96
Bought crane hours	186
Difference	**90**

Figure 21 Comparison budgeted and needed crane hours

6.2.2. Construction managers

The output sheet for the construction managers is the same as for the project organisers, but here the output is shown per day. In meetings with construction managers, they indicated that they need to know the number of cranes, the number of hours it is needed and the productivity of this crane. Figure 22 shows what this output form looks like. This sheet also contains a button to update the results. This button is connected to the VBA code which runs the heuristics for the construction managers.

	Year	2021	2021	2021	2021	2021	2021	2021	2021	2021	2021
	Day	1	2	3	4	5	6	7	8	9	10
	Date	28-07-21	29-07-21	30-07-21	31-07-21	1-08-21	2-08-21	3-08-21	4-08-21	5-08-21	6-08-21
Site	Material										
	Pit										
	VBI										
Demolition	Demolition										
Ground	Ground										
Pile driving	Pile driving										
Foundation	Beams										
	Elevator pit										
	Piles										
Basement	Floor										
	Walls										
	Partition walls										
	Columns										
	Beams										
Productivity											
Number of cranes											
Needed crane hours											

Calculate productivity

Figure 22 Output sheet construction managers with productivity, number of cranes and the time a crane is needed

The construction managers can see on a different output sheet what a good schedule for the day would be. Figure 26 gives an example of such a sheet. The construction manager can fill in the date of the day for which he would like to know the schedule. After pressing the button, Excel will update the number of trucks and their scheduled arrival time according to the best found solution. Additionally, Excel will show the number of cranes needed and their start and end time.

Figure 23 shows the schedule of a day in Project 2. As explained in Chapter 5, this project just started with the construction phase. Currently, the dashboard is being used to create the schedules of the arriving trucks on the busy days. This schedule shows that two trucks should arrive at the same time. This is because all the trucks with an even number are self-unloading. The schedule also shows that only 1 crane is needed. This schedule was also used as the input for ILips. The dashboard automatically created a schedule which was manually transferred to ILips. Compared to the previous situation in which the schedule was manually created, this dashboard saves time and systematically creates a schedule.

Day schedule

			Truck	Arrival time		Crane	Start time	End time
Day	0		1	07:00		1	7:00	14:00
			2	07:00				
Calculate day			3	08:30				
			4	08:30				
			5	10:00				
			6	10:00				
			7	11:30				
			8	11:30				
			9	13:00				

Figure 23 Output sheet which contains the day schedule

6.2.3. Logistics managers

The logistics manager wants to know what to focus on to improve the productivity of the cranes. Figure 24 shows the output sheet for the logistics manager. In this sheet the manager can fill in a change in the input of the dashboard. This change can also be using prefabricated elements. In this case both the movement time and the number of trucks change. In the graphs he can see what influence this has on the productivity and the number of needed crane hours. The original results will be shown with the blue line and the improvement will be shown with an orange line. On the right side of the figure the logistics manager can fill in the new values of the input. The sheet also contains buttons to calculate the new productivity and to set the values back to the original. So, this sheet functions as a dashboard for the logistics manager to know what to focus on next to improve the productivity of cranes.

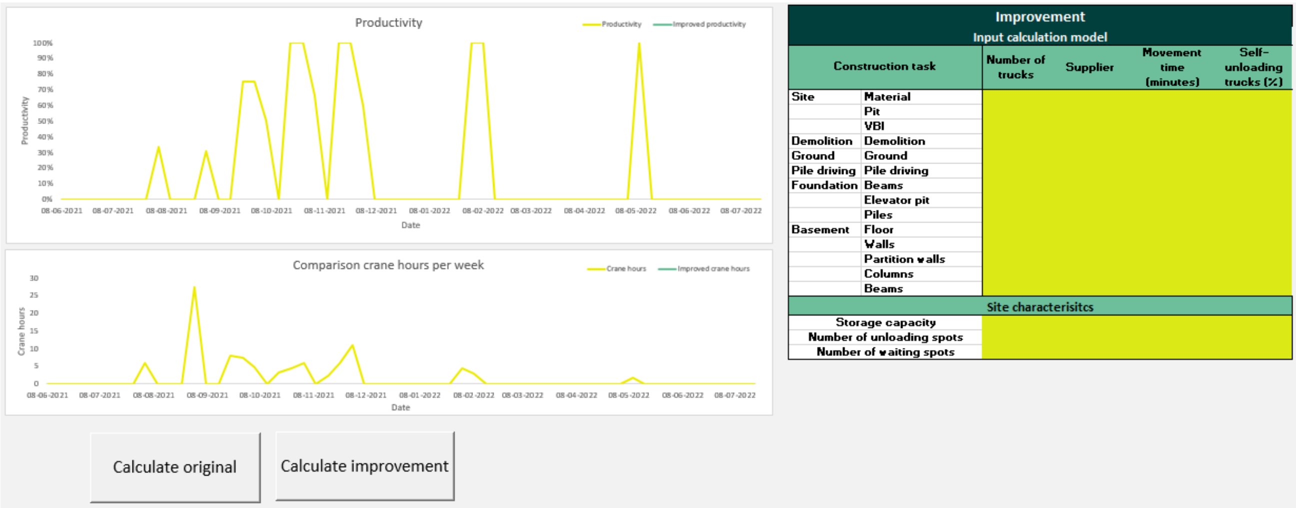


Figure 24 Output sheet for the logistics manager which contains a form to fill in the changes and graphs to visually show the result of the changes

6.3. Limitations dashboard

There are multiple limitations when using Excel instead of another software program. This section summarizes the most important limitations of the dashboard. The limitations named in this section are mainly related to the use of Excel. The general limitations of the dashboard are related to the assumptions which were explained in Section 4.2.6. The limitations are describes in the following paragraphs.

Linear programming in Excel VBA

For this research the MILP is solved with heuristics in Excel VBA, but there are a few limitations. First, a constructive heuristic defines the scheduled arrival time of the trucks. The waiting time is later defined such that the solution becomes feasible if needed. The improvement heuristics try to improve the solution based on the arrival time and only change the waiting time to make the solution feasible. In this way simple improvements can be made. When solving the MILP optimally, both the arrival time and the waiting time can be varied.

Input forms

As Section 6.1. showed, there are multiple input forms which need to be filled in by different employees. This takes effort of the employees and the document needs to be shared between the employees. All of the information needed in the input forms is already given in another software program of DVBH. Therefore, the employees have to fill in this information multiple times.

User-friendliness

The current Excel file contains a lot of sheets which are necessary to give the information needed by the different employees involved in the process. Therefore, it can take some time before the user understands the file and knows to which sheets it needs to navigate. To increase the user-friendliness, the future users gave feedback about the input forms two times during meetings. The lay-out options of Excel are limited. The color of the buttons can for example not be changed to match them with the other colors. The Excel file contains textboxes with information on how to use the document, but the user-friendliness can be further improved.

6.4. Conclusions

This chapter explained the input and output of the dashboard for the company. Multiple input forms for different employees of DVBH are created. Every employee needs different output and therefore different output sheets are created. So, there is not one dashboard created, but the project organisers, construction managers and logistics each have their own dashboard. The dashboard in Excel has multiple limitations. The first limitation is that the MILP cannot be optimally solved in Excel. Another limitation is that the input needed is already filled in in a different software program, but this cannot automatically be extracted from this program. Lastly, Excel is limited in the lay-out options. Therefore, the user-friendliness can still be improved. Even though there are some limitations, the current dashboard gives results to support different employees with decision-making about the cranes on the construction site.

7. Conclusion, Discussion and Recommendation

This chapter describes the conclusions, discussion points and recommendations for the company. Section 7.1. gives the conclusion of the research. Sections 7.2. explains the discussion points and Section 7.3. gives recommendations for future research.

7.1. Conclusion

Dura Vermeer Bouw Hengelo (DVBH) wants to improve its logistics processes on their construction sites. They noticed that the cranes often determine the speed of the construction process while they are also observed idle. So, either the crane is unnecessarily rented or the construction tasks can be done in a smaller timeframe. Therefore, this research focused on improving the net productivity of the cranes on construction sites of DVBH. This research answers the following research questions:

How can the net productivity of the cranes used in a construction project be improved?

Currently, a weekly planning for the cranes is manually made during the preparation phase of a construction project by project organisers. A daily planning for the cranes is made by the construction managers during the construction phase. The decisions for the plannings are mainly based on the experience of the employees. The logistics managers support these employees by giving more insights into the transportation of the material to the construction site. With this research also more insight can be given to the employees in the duration of the material movements on site. This is done by creating a dashboard to predict the productivity of a crane. The dashboard helps project organisers during the preparation phase with setting a budget for the rental of cranes and helps the construction managers during the construction phase with determining a schedule for the arriving trucks and with determining the number of needed cranes.

According to literature the construction industry uses basic techniques such as Gantt charts to define their logistics processes, but they are working on techniques to share more data within their company and with their suppliers and to align their logistics processes. The productivity of a crane is also influenced by multiple other processes. For the case of DVBH the reliability of the suppliers, and site characteristics like the storage capacity, number of unloading areas and number of waiting spots can be of influence for the productivity of a crane. Therefore, these factors are taken into account beside the material delivery when creating a dashboard for the scheduling problem.

I formulated the scheduling problem as a mixed integer linear program. In this formulation the arrival time of the trucks can be changed. The objective is productivity maximization of the cranes. The input parameters are assumed to be known with certainty except of the deviation of trucks from the scheduled arrival time since the arrival of trucks is not always reliable. Different scenarios are included in the formulation to include this uncertainty. This is only taken into account during scheduling in the preparation phase of a construction project. This problem was solved by using heuristics. To create an initial solution a constructive heuristic was used which defines the arrival time of a truck as the arrival time of the previous truck and adds its material movement time. When a truck first needs to unload itself, the movement time is again decreased from the total. This initial solution is improved with tabu search. The improvement heuristic looked through a neighborhood of solutions with the same arrival time except for one truck which differs 0.5 hours.

I used the solving method to create a dashboard for the scheduling problem. The dashboard was tested with the input of a real-life project of DVBH. The dashboard predicted for all the 14 weeks a realistic number of needed crane hours which was confirmed by the construction manager of the project. The estimated number of needed cranes for the construction phase was also similar to the actual number of rented cranes during these 14 weeks. During the whole project the crane was rented for a longer period than needed. A graph in the dashboard visualizes when crane hours were rented, but not needed. This graph also shows the difference between the rented crane hours and the needed crane hours of the previously mentioned 14 weeks. So, this graphs visualizes the weeks during which fewer cranes could have been rented. The dashboard can improve the productivity of cranes in future projects by showing during which weeks too many cranes are rented based on the given input.

A sensitivity analysis was performed to see the influence of the estimated movement time and the construction site characteristics. The movement time is an input parameter, but there are no exact numbers about this time for all type of materials. Therefore, this time is estimated by the construction managers. The sensitivity analysis showed that the movement time has a big influence on the productivity and needed number of crane hours per week. Therefore, this input parameter needs to be defined carefully. The construction site characteristics such as the storage capacity, the number of unloading areas and the waiting areas do not have a big influence on the resulting productivity of the crane. Additionally, the sensitivity analysis showed that using prefabricated material to decrease the number of arriving trucks while increasing the movement time can have a positive influence on the number of needed crane hours, but not on the productivity. The decision for the manufacturing method and the estimated movement time influence the resulting productivity the most.

The final dashboard was implemented in Excel. Other calculations were also done in Excel by the company. Therefore, the dashboard is most useful for the employees when Excel is used. In Excel, input sheets were created for the project organisers, the construction managers and the logistics managers. The Excel file gives output about the needed number of crane hours and productivity for the project organisers, the needed number of cranes and productivity of the construction managers and the influence of the input for the logistic manager. This results in a file with sheets for multiple users. So, multiple dashboards are created. Therefore, it can take some time for the user to understand how the file works. The user-friendliness could be improved by automatically extracting the input from other software programs. Despite these limitations the dashboard gives all the information needed by the different type of users and visualises these results to improve the decision-making.

This research used linear programming techniques to create schedules for a crane on a construction site. In literature, linear programming is not often used to solve scheduling problems of the construction industry. This research gave an example of how linear programming can be used to solve a scheduling problem of cranes. The created dashboard is already used in practice by a construction project of DVBH to create daily schedules. The dashboard can show which decisions should be made for the construction site and the number of arriving trucks to improve the productivity of the cranes. Additionally, the dashboard shows when the trucks should be scheduled to create a good schedule for the cranes. By visualizing the results, the weeks during which the productivity is low can easily be detected and the number of rented cranes or crane hours can be lowered in these weeks. This will improve the productivity of the cranes during the entire construction project.

7.2. Discussion

During the research employees from DVBH and from other suborganisations of Dura Vermeer gave input about the dashboard. These meetings showed that every suborganization has its own method of creating a budget and a planning for cranes. The final dashboard of this research is created for DVBH and therefore the assumptions are also based on their way of working and what they find important. So, when implementing this dashboard for crane scheduling of other suborganisations, these assumptions should be reconsidered. For example, one suborganisation indicated that the movement time of material is very dependent on the floor to which the material is moved. DVBH indicated that this does not have a big influence as stated in Section 4.1.1 as their projects generally have less floors. The current dashboard also assumes that all of the arriving material is processed on the same day, but this is not the case for all the projects. There are workarounds possible for this by changing the input data, but this requires extra efforts for the users. There are many possibilities to disregard these assumptions, but because of time constraints the updates are not implemented. So, the current dashboard is not generalizable for all of the projects of Dura Vermeer without reconsidering the assumptions.

The dashboard uses as input the reliability of suppliers. So far, only a few projects have kept track of the reliability of the arrival of trucks. The dataset shows how many observations a supplier has per category of deviations. When this dataset increases in the coming years, the number of observations will also increase. Currently only 10% of the suppliers has observations for all five categories. Most of the suppliers have observations for two categories. One week can contain multiple scenarios of all the arriving trucks which depends on the observations. The scenarios only take the categories into account for which there are observations. Therefore, currently the number of scenarios per week is limited, but this can increase during the coming years. So, the computation time of the solution method might also increase.

The created dashboard is a first tool to predict the productivity of the crane. Construction projects usually take a few years before they are completed. Therefore, evaluating the performance of the dashboard when it is used in the preparation and construction phase, can also take a few years. The dashboard was evaluated based on data of a finished project. Therefore, the input data was already known with certainty. So, the results could have been very different for the same project if it was used during the preparation of the project. Additionally, construction projects can be very different. Since the results can be very different on other projects it is important to keep evaluating the results.

7.3. Recommendation

The created dashboard in this research is still very basic, there are a lot of assumptions made. Therefore, there are still many possibilities to update the dashboard. It is now assumed that the movement time of all the crane types is the same. There are two types of trucks, trucks which can unload themselves and trucks which need to be unloaded by a crane. In this research it is assumed that trucks which can unload themselves have the same movement time as a crane. However, this does not have to be true for all of the cranes and trucks. A small difference can make the result more accurate. It is now also assumed that all of the trucks are full. A possible update might be to use the elements in the truck instead of a full truck load. This way also the unloading time can be estimated better. Additionally, the movements of the trucks on the construction site can be taken into account. There are for example construction sites where the first truck has to leave before the next can arrive. In a future research the dashboard can be updated such that the assumptions can be disregarded. With these updates, the dashboard is expected to give more accurate results for a variety of projects.

Since the dashboard is in a beginning phase, it is important to keep updating. For every project the results should be evaluated and the dashboard should be updated to create a more accurate estimation. When the dashboard is used for a project, it can already be updated during this project. Since the final dashboard should be used by both project organisers and construction managers, it is important to do this in close cooperation with these employees. This can be done by doing multiple feedback loops of showing the results to these employees and update the dashboard based on their feedback. So, before the dashboard can be fully adopted by the future users, the dashboard should be tested and evaluated by an employee who knows exactly how the dashboard works.

During the meetings with the employees it was noticed that it was not common to evaluate the made decisions. This dashboard gives more opportunities to document when cranes were rented and when more or less were needed than predicted. Therefore, this dashboard can also be used to evaluate the prediction after the construction phase. However, a possibility should be added to also document the reason of the difference. So, a recommendation is to further investigate the possibilities for this evaluation.

The last recommendation is to look into possibilities to automatically fill in the input form. A lot of the information needed such as the planning and the construction characteristics, is already known, but is documented in a different software program. Therefore, employees can find it annoying to fill in this information twice. An integration between these programs could be a good update to improve the user-friendliness.

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Appendix A: input values for dashboard evaluation

Table 17 Number of trucks per week per supplier

		Supplier															
% Crane Needed		100%	100%	100%	100%	100%	100%	0%	0%	0%	0%	0%	100%	100%	0%	0%	100%
Year	Week	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p
2021	31			5.00													
2021	35			18.00						1.00							
2021	38	14.00													1.00		
2021	39	14.00															
2021	40	6.00															
2021	41		1.00						1.00								
2021	42		7.00						1.00								
2021	43		11.00														
2021	44	10.00															
2021	45								1.00								
2021	46		5.00						1.00								
2021	47		15.00														
2021	48	18.00	5.00														
2021	50								1.00								
2021	51		1.00														
2022	3						1.00										
2022	4															1.00	1.00
2022	5					1.00	3.00	6.00			1.00						
2022	6	1.00		1.00	2.00		3.00										
2022	7						1.00										
2022	9				1.00									1.00			
2022	10				2.00	1.00											
2022	11				2.00									1.00			
2022	12				1.00	2.00						1.00	1.00				
2022	15				1.00												
2022	16				1.00	1.00											
2022	17				1.00	1.00											
2022	18					1.00											
2022	19				3.00	1.00											
2022	20					1.00											

Table 18 Number of trucks per supplier per day

	Supplier															
Date	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p
28-07-21			1.00													
29-07-21			4.00													
23-08-21			3.00													
24-08-21			8.00													
25-08-21			9.00													
26-08-21			10.00													
27-08-21			6.00													
13-09-21	3.00															
15-09-21	4.00															
16-09-21	4.00															
17-09-21	3.00															
20-09-21	2.00															
21-09-21	2.00															
22-09-21	2.00															
23-09-21	3.00															
24-09-21	4.00															
27-09-21	4.00															
30-09-21	1.00															
1-10-21	1.00															
7-10-21								1.00								
8-10-21		1.00														
12-10-21								1.00								
13-10-21		1.00														
14-10-21		3.00														
15-10-21		3.00														
18-10-21		1.00														
19-10-21		4.00														
21-10-21		2.00														
22-10-21		4.00														
25-10-21	4.00															
26-10-21	4.00															
27-10-21	2.00															
4-11-21								1.00								
9-11-21		1.00														
11-11-21								1.00								
12-11-21		4.00														
15-11-21		4.00														
16-11-21		4.00														
17-11-21		3.00														
18-11-21		2.00														
19-11-21		2.00														
22-11-21		4.00														
23-11-21		1.00														
24-11-21	9.00															
25-11-21	7.00															
26-11-21	2.00															
9-12-21								1.00								
13-12-21		1.00														
14-01-22						1.00										
17-01-22																1.00
19-01-22														1.00		
24-01-22							2.00									
25-01-22						1.00	1.00									
26-01-22					1.00	1.00	1.00									
27-01-22						1.00	1.00									
28-01-22							1.00									
31-01-22						1.00										
1-02-22						1.00										
2-02-22						1.00										
4-02-22	1.00		1.00													
7-02-22						1.00										
22-02-22													1.00			
23-02-22				1.00												
28-02-22				1.00												
1-03-22					1.00											
3-03-22				1.00												
8-03-22				1.00												
9-03-22				1.00												
14-03-22				1.00	1.00											
16-03-22											1.00	1.00				
17-03-22					1.00											
6-04-22				1.00												
14-04-22				1.00	1.00											
20-04-22				1.00	1.00											
28-04-22					1.00											
2-05-22				1.00												
4-05-22				2.00												
5-05-22					1.00											
12-05-22					1.00											

Table 19 observations of KPI codes per supplier

Supplier	4a	2a	1	2b	3b	Number of possible scenarios
a	7	7	33	4	35	5
b	0	0	1	0	0	1
c	6	0	7	3	19	4
d	0	0	1	0	0	1
e	0	0	1	0	0	1
f	0	0	1	0	0	1
g	0	0	1	0	0	1
h	1	1	4	0	2	4
i	4	0	0	2	1	3
j	27	6	16	7	26	5
k	0	0	1	0	0	1
l	0	0	1	0	0	1
m	0	1	0	0	0	1
n	0	0	1	0	0	1
o	0	0	1	0	0	1
p	0	0	1	0	0	1

Table 20 Number of possible scenarios per week

year	week	number of possible scenarios
2021	31	4
	35	16348
	38	125
	39	125
	40	5
	41	0
	42	4
	43	16
	44	25
	45	0
	46	4
	47	64
	48	2500
	50	0
	51	0
2022	3	0
	4	0
	5	1
	6	1
	7	0
	9	0
	10	0

	11	0
	12	0
	15	0
	16	0
	17	0
	18	0
	19	1
	20	0

Appendix B: input second project DVBH

Table 21 Input second project DVBH

Start month	29-06-2020
End month	20-12-2020
Number of periods	8
Maximum number of cranes	10
Unloading areas	1
Crane rental period	4 hours
Maximum storage available	1 truckload
Maximum waiting time	30 minutes
Maximum number of waiting areas	1
Maximum Overtime	2 hours

Table 22 Input per building task second project DVBH

Building Task		Startday	Endday	Number of trucks	Supplier	Number of possible deviations	Volume	Unloading time (min)	% self-unloading	% Crane needed
Bouwplaats	Materieel	29-06-20	20-12-20	13	a	2.00	1	60	0%	100%
	Bouwkuip	-	-	10	-	-	1	-	-	-
Sloopwerk	Sloopwerk	29-06-20	02-09-20	25	a	2.00	1	60	0%	100%
Grondwerk	Grondwerk	-	-	0	-	-	1	-	-	-
Heiwerk	Heiwerk	-	-	0	-	-	1	-	-	-
Fundering	Balken	-	-	0	-	-	1	-	-	-
	Poeren	-	-	0	-	-	1	-	-	-
Kelder	Vloer	-	-	0	-	-	1	-	-	-
	Wanden	-	-	0	-	-	1	-	-	-
	Kolommen	-	-	0	-	-	1	-	-	-
	Balken	-	-	0	-	-	1	-	-	-
BG-vloer	Begane grondvloer	05-09-20	20-10-20	13	b	4.00	1	60	0%	100%
Skelet	Wanden	15-09-20	05-11-20	75	c	5.00	1	30	100%	0%
	Kolommen	15-09-20	05-11-20	70	d	3.00	1	30	100%	100%
	Balken	15-09-20	05-11-20	26	c	5.00	1	30	100%	0%
	Verdiepingsvloer	05-10-20	20-12-20	46	e	1.00	1	60	0%	100%
	Betonstort vloer	05-10-20	20-12-20	11	f	1.00	1	60	0%	0%
	Staalconstructie	24-08-20	16-10-20	3	c	5.00	1	30	100%	0%

Table 23 Trucks arriving per week second project DVBH

	Building task									
Week	Materieel	Bouwkuip	Sloopwerk	Begane grondvloer	Wanden	Kolommen	Balken	Verdiepingsvloer	Betonstort vloer	Staalconstructie
27	0.50	-	2.50	-	-	-	-	-	-	-
28	0.50	-	2.50	-	-	-	-	-	-	-
29	0.50	-	2.50	-	-	-	-	-	-	-
30	0.50	-	2.50	-	-	-	-	-	-	-
31	0.50	-	2.50	-	-	-	-	-	-	-
32	0.50	-	2.50	-	-	-	-	-	-	-
33	0.50	-	2.50	-	-	-	-	-	-	-
34	0.50	-	2.50	-	-	-	-	-	-	-
35	0.50	-	2.50	-	-	-	-	-	-	0.33
36	0.50	-	2.50	-	-	-	-	-	-	0.33
37	0.50	-	-	1.81	-	-	-	-	-	0.33
38	0.50	-	-	1.81	-	-	-	-	-	0.33
39	0.50	-	-	1.81	9.38	8.78	3.25	-	-	0.33
40	0.50	-	-	1.81	9.38	8.78	3.25	-	-	0.33
41	0.50	-	-	1.81	9.38	8.78	3.25	4.14	1.00	0.33
42	0.50	-	-	1.81	9.38	8.78	3.25	4.14	1.00	0.33
43	0.50	-	-	1.81	9.38	8.78	3.25	4.14	1.00	-
44	0.50	-	-	-	9.38	8.78	3.25	4.14	1.00	-
45	0.50	-	-	-	9.38	8.78	3.25	4.14	1.00	-
46	0.50	-	-	-	-	-	-	4.14	1.00	-
47	0.50	-	-	-	-	-	-	4.14	1.00	-
48	0.50	-	-	-	-	-	-	4.14	1.00	-
49	0.50	-	-	-	-	-	-	4.14	1.00	-
50	0.50	-	-	-	-	-	-	4.14	1.00	-
51	0.50	-	-	-	-	-	-	4.14	1.00	-

Appendix C: Results heuristics second project DVBH

Table 24 Results GA which show that heuristic 3,4 and 5 perform the best for this algorithm

Year	Week	Genetic Algortihm														
		1			2			3			4			5		
		Prod.	Nr. crane hours	Comp. time	Prod.	Nr. crane hours	Comp. time	Prod.	Nr. crane hours	Comp. time	Prod.	Nr. crane hours	Comp. time	Prod.	Nr. crane hours	Comp. time
2021	39	14%	9.14	00:00:01	20%	6.85	00:00:01	33%	4.57	00:00:01	33%	4.57	00:00:01	33%	4.57	00:00:01
2021	40	14%	9.14	00:00:01	20%	6.85	00:00:01	33%	4.57	00:00:01	33%	4.57	00:00:02	33%	4.57	00:00:01
2021	41	33%	7.73	00:00:02	50%	5.52	00:00:03	67%	3.31	00:00:03	67%	5.52	00:00:02	67%	4.42	00:00:02
2021	42	33%	7.73	00:00:02	50%	5.52	00:00:03	67%	3.31	00:00:02	67%	5.52	00:00:03	67%	4.42	00:00:02
2021	43	33%	7.57	00:00:02	50%	5.41	00:00:03	67%	3.25	00:00:02	67%	5.41	00:00:03	67%	4.33	00:00:02
2021	44	33%	6.73	00:00:03	50%	4.81	00:00:02	67%	2.88	00:00:03	67%	4.81	00:00:02	67%	3.84	00:00:03
2021	45	33%	6.73	00:00:02	50%	4.81	00:00:02	67%	2.88	00:00:03	67%	4.81	00:00:03	67%	3.84	00:00:02
2021	46	100%	2.26	00:00:00	100%	2.26	00:00:01	100%	2.26	00:00:00	100%	2.26	00:00:00	100%	2.26	00:00:01
2021	47	100%	2.26	00:00:00	100%	2.26	00:00:00	100%	2.26	00:00:01	100%	2.26	00:00:00	100%	2.26	00:00:00
2021	48	100%	2.26	00:00:01	100%	2.26	00:00:00	100%	2.26	00:00:00	100%	2.26	00:00:01	100%	2.26	00:00:00
2021	49	100%	2.26	00:00:00	100%	2.26	00:00:01	100%	2.26	00:00:00	100%	2.26	00:00:00	100%	2.26	00:00:01
2022	50	100%	2.26	00:00:00	100%	2.26	00:00:00	100%	2.26	00:00:01	100%	2.26	00:00:00	100%	2.26	00:00:00
2022	51	100%	2.26	00:00:00	100%	2.26	00:00:01	100%	2.26	00:00:00	100%	2.26	00:00:00	100%	2.26	00:00:00
Total score			-7			0			7			7			7	

Table 25 Results SA which show that heuristic 3,4 and 5 perform the best for this algorithm

Year	Week	Simulated annealing														
		1			2			3			4			5		
		Prod.	Nr. crane hours	Comp. time	Prod.	Nr. crane hours	Comp. time	Prod.	Nr. crane hours	Comp. time	Prod.	Nr. crane hours	Comp. time	Prod.	Nr. crane hours	Comp. time
2021	39	14%	8.00	00:00:00	20%	5.71	00:00:00	33%	3.43	00:00:00	33%	3.43	00:00:01	33%	3.43	00:00:00
2021	40	14%	8.00	00:00:00	20%	5.71	00:00:00	33%	3.43	00:00:00	33%	3.43	00:00:01	33%	3.43	00:00:00
2021	41	33%	6.63	00:00:00	50%	4.42	00:00:00	67%	3.31	00:00:00	67%	3.31	00:00:01	67%	3.31	00:00:00
2021	42	33%	6.63	00:00:00	50%	4.42	00:00:00	67%	3.31	00:00:01	67%	3.31	00:00:00	67%	3.31	00:00:00
2021	43	33%	6.49	00:00:00	50%	4.33	00:00:01	67%	3.25	00:00:00	67%	3.25	00:00:00	67%	3.25	00:00:00
2021	44	33%	5.77	00:00:01	50%	3.84	00:00:00	67%	2.88	00:00:00	67%	2.88	00:00:00	67%	2.88	00:00:01
2021	45	33%	5.77	00:00:00	50%	3.84	00:00:00	67%	2.88	00:00:00	67%	2.88	00:00:01	67%	2.88	00:00:00
2021	46	100%	1.13	00:00:00	100%	1.13	00:00:00	100%	1.13	00:00:00	100%	1.13	00:00:00	100%	1.13	00:00:00
2021	47	100%	1.13	00:00:01	100%	1.13	00:00:00	100%	1.13	00:00:00	100%	1.13	00:00:00	100%	1.13	00:00:00
2021	48	100%	1.13	00:00:00	100%	1.13	00:00:00	100%	1.13	00:00:00	100%	1.13	00:00:00	100%	1.13	00:00:00
2021	49	100%	1.13	00:00:01	100%	1.13	00:00:00	100%	1.13	00:00:00	100%	1.13	00:00:00	100%	1.13	00:00:00
2022	50	100%	1.13	00:00:00	100%	1.13	00:00:00	100%	1.13	00:00:00	100%	1.13	00:00:00	100%	1.13	00:00:00
2022	51	100%	1.13	00:00:00	100%	1.13	00:00:01	100%	1.13	00:00:00	100%	1.13	00:00:00	100%	1.13	00:00:00
Total score			-7			0			7			7			7	

Table 26 Results TS which show that heuristic 3,4 and 5 perform the best for this algorithm

Year	Week	Tabu search														
		1			2			3			4			5		
		Prod.	Nr. crane hours	Comp. time	Prod.	Nr. crane hours	Comp. time	Prod.	Nr. crane hours	Comp. time	Prod.	Nr. crane hours	Comp. time	Prod.	Nr. crane hours	Comp. time
2021	39	14%	8.00	00:00:00	20%	5.71	00:00:00	33%	3.43	00:00:01	33%	3.43	00:00:00	33%	3.43	00:00:00
2021	40	14%	8.00	00:00:00	20%	5.71	00:00:00	33%	3.43	00:00:00	33%	3.43	00:00:00	33%	3.43	00:00:01
2021	41	33%	6.63	00:00:00	50%	4.42	00:00:00	67%	3.31	00:00:00	67%	3.31	00:00:00	67%	3.31	00:00:01
2021	42	33%	6.63	00:00:00	50%	4.42	00:00:00	67%	3.31	00:00:00	67%	3.31	00:00:00	67%	3.31	00:00:00
2021	43	33%	6.49	00:00:00	50%	4.33	00:00:00	67%	3.25	00:00:00	67%	3.25	00:00:00	67%	3.25	00:00:00
2021	44	33%	5.77	00:00:01	50%	3.84	00:00:00	67%	2.88	00:00:00	67%	2.88	00:00:00	67%	2.88	00:00:00
2021	45	33%	5.77	00:00:01	50%	3.84	00:00:00	67%	2.88	00:00:00	67%	2.88	00:00:00	67%	2.88	00:00:01
2021	46	100%	1.13	00:00:00	100%	1.13	00:00:00	100%	1.13	00:00:00	100%	1.13	00:00:00	100%	1.13	00:00:01
2021	47	100%	1.13	00:00:00	100%	1.13	00:00:00	100%	1.13	00:00:00	100%	1.13	00:00:00	100%	1.13	00:00:01
2021	48	100%	1.13	00:00:00	100%	1.13	00:00:00	100%	1.13	00:00:00	100%	1.13	00:00:01	100%	1.13	00:00:00
2021	49	100%	1.13	00:00:00	100%	1.13	00:00:00	100%	1.13	00:00:00	100%	1.13	00:00:01	100%	1.13	00:00:00
2022	50	100%	1.13	00:00:00	100%	1.13	00:00:00	100%	1.13	00:00:00	100%	1.13	00:00:01	100%	1.13	00:00:00
2022	51	100%	1.13	00:00:00	100%	1.13	00:00:00	100%	1.13	00:00:00	100%	1.13	00:00:01	100%	1.13	00:00:00
Total score			-7			0			7			7			7	

Table 27 Comparison improvement heuristics which show that tabu search performs the best

Year	Week	Genetic algorithm 3//4//5			Simulated annealing 3//4//5			Tabu search 3//4//5		
		Prod.	Nr. crane hours	Comp. time	Prod.	Nr. crane hours	Comp. time	Prod.	Nr. crane hours	Comp. time
2021	**39**	33%	4.57	00:00:01	33%	3.43	00:00:00	33%	3.43	00:00:01
2021	**40**	33%	4.57	00:00:01	33%	3.43	00:00:00	33%	3.43	00:00:00
2021	**41**	67%	3.31	00:00:03	67%	3.31	00:00:00	67%	3.31	00:00:00
2021	**42**	67%	3.31	00:00:02	67%	3.31	00:00:01	67%	3.31	00:00:00
2021	**43**	67%	3.25	00:00:02	67%	3.25	00:00:00	67%	3.25	00:00:00
2021	**44**	67%	2.88	00:00:03	67%	2.88	00:00:00	67%	2.88	00:00:00
2021	**45**	67%	2.88	00:00:03	67%	2.88	00:00:00	67%	2.88	00:00:00
2021	**46**	100%	2.26	00:00:00	100%	1.13	00:00:00	100%	1.13	00:00:00
2021	**47**	100%	2.26	00:00:01	100%	1.13	00:00:00	100%	1.13	00:00:00
2021	**48**	100%	2.26	00:00:00	100%	1.13	00:00:00	100%	1.13	00:00:00
2021	**49**	100%	2.26	00:00:00	100%	1.13	00:00:00	100%	1.13	00:00:00
2022	**50**	100%	2.26	00:00:01	100%	1.13	00:00:00	100%	1.13	00:00:00
2022	**51**	100%	2.26	00:00:00	100%	1.13	00:00:00	100%	1.13	00:00:00
Total score		-5			0			1		

Table 28 Results change neighborhood second project which show that they perform equal

Year	Week	Tabu search 0.5			Tabu search 1			Tabu search 2		
		Prod.	Nr. crane hours	Comp. time	Prod.	Nr. crane hours	Comp. time	Prod.	Nr. crane hours	Comp. time
2021	**39**	33%	3.43	00:00:01	33%	3.43	00:00:00	33%	3.43	00:00:01
2021	**40**	33%	3.43	00:00:00	33%	3.43	00:00:00	33%	3.43	00:00:00
2021	**41**	67%	3.31	00:00:00	67%	3.31	00:00:00	67%	3.31	00:00:00
2021	**42**	67%	3.31	00:00:00	67%	3.31	00:00:00	67%	3.31	00:00:00
2021	**43**	67%	3.25	00:00:00	67%	3.25	00:00:00	67%	3.25	00:00:00
2021	**44**	67%	2.88	00:00:00	67%	2.88	00:00:00	67%	2.88	00:00:01
2021	**45**	67%	2.88	00:00:00	67%	2.88	00:00:00	67%	2.88	00:00:01
2021	**46**	100%	1.13	00:00:00	100%	1.13	00:00:00	100%	1.13	00:00:01
2021	**47**	100%	1.13	00:00:00	100%	1.13	00:00:00	100%	1.13	00:00:00
2021	**48**	100%	1.13	00:00:00	100%	1.13	00:00:00	100%	1.13	00:00:00
2021	**49**	100%	1.13	00:00:00	100%	1.13	00:00:00	100%	1.13	00:00:00
2022	**50**	100%	1.13	00:00:00	100%	1.13	00:00:00	100%	1.13	00:00:00
2022	**51**	100%	1.13	00:00:00	100%	1.13	00:00:00	100%	1.13	00:00:00
Total score		0			0			0		