Designing a Construction Logistics Control Tower for City Development

A Case Study in Amsterdam Amstel III


Supply chain control tower (One Network Enterprises, 2019).

Author:

T. Tesselaar

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Designing a Construction Logistics Control Tower for City Development

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Tom Tesselaar
Student number: 4214714

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Graduation committee:

Chairperson	Prof. Dr. Ir. M.F.W.H.A. Janssen	Section ICT
First Supervisor	Ir. M.W. Ludema	Section T&L
Second Supervisor	Dr. A.M.G. Zuiderwijk-van Eijk	Section ICT
External Supervisor	Dr. W. Ploos van Amstel	Lector City Logistics

Preface

During my masters at Delft University of Technology I engaged in a specialisation in Supply Chain Management. During this specialisation I came across my first supervisor, IR. M.W. Ludema. He presented the opportunity to conduct my thesis as an intern at the Municipality of Amsterdam, department of traffic and public space, on the subject of cross chain control centres, or control towers, with a focus on construction logistics. Writing a master thesis is always challenging, what made it even more challenging was the COVID-19 virus of 2020.

During the first months of the thesis a spot was available at one of the Municipality offices. Due to the COVID-19 crisis 2020 this came to a halt, and the largest work from home experiment thus far started. This posed several challenges such as conducting interviews and having meetings with supervisors. Nevertheless, with a little help from my friends and the knowledge that my thesis subject was living in the heads of people working in industry, it felt like the thesis was finished in a blink of an eye.

There are lots of people I would like to thank as they helped me during my thesis. First of all I want to thank my first supervisor, Ir. M. W. Ludema, for presenting the opportunity to conduct my thesis at the Municipality of Amsterdam to me. Second I would like to thank my external supervisor, Dr. W. Ploos van Amstel, for the continues support, and the opportunity to work at his offices during the last weeks of my thesis. Third, my gratitude to my second supervisor, Dr. A.M.G. Zuiderwijk-van Eijk, and chair, Prof. Dr. Ir. M.F.W.H.A. Janssen, for the feedback and directions during our meeting.

As mentioned earlier I had a lot of support during the COVID-19 period from my friends, therefore I would like to thank them for our regular meetings. It really helped to keep me on track, and to have some feedback from fellow (MOT) students. Furthermore thanks to all the interns and supervisors at the Municipality of Amsterdam, especially for the feedback during our weekly intern hour. Finally I want to thank all the people I interviewed during my thesis. I enjoyed to talk about the subject, furthermore these conversations made the topic come alive. These interviews provided me with a direction, and presented insight into the social relevance and importance of enhanced coordination in construction logistics.

T. Tesselaar
tomtesselaar@hotmail.com
August 12, 2020

Summary

All over the world initiatives are undertaken to become more sustainable. Europe desires to reduce greenhouse gas emissions with 60% by 2050 (ERTRAC, 2017). Amsterdam wants to go even further by reducing greenhouse gas emissions with 55% before 2030 (Municipality Amsterdam, 2019a). These are ambitious but achievable goals. On the other hand both Europe and Amsterdam see a growing need for mobility and freight transport (Van Amstel, 2015). Within Amsterdam the logistical sector is one of the largest contributors of greenhouse gas emissions (van Luik, Luijten, Molin, van Amstel, & Vrijhoef, 2019). Moreover construction logistics account for roughly 35% of all traffic and emissions within Amsterdam city boundaries (Quak et al., 2011). This contradiction of growing need for transportation and reduction of greenhouse gas emissions can be aided by enhanced coordination of construction logistics for city development.

Currently construction logistics for city development is not coordinated properly. There are many reasons why coordination is hard to achieve. Some reasons result from the nature of the construction industry which is considered to be: fragmented, complex, converging, typified as make-to-order, and project driven (Staring, 2019; Janne, 2018; Lundesjö, 2015; Balm, Berden, Morel, & Ploos van Amstel, 2018). Some result from challenges in construction logistics, such as: limited site space (Siebelink, JT, & Adriaanse, 2019) and unclear division of responsibilities between construction site and organisations in the supply chain (Balm et al., 2018). Other reasons originate from issues in collaboration, such as lack of trust and low information sharing. In the years to come a total of 20 projects will be undertaken in Amsterdam Amstel III. At least 25 organisations would be involved in each of these projects (ECLLP, 2013; Emrath, 2015), resulting in 90 different organisations working in the same area at the same time. This, along with the previously stated contradiction, stresses the urgency for coordination of these projects, and their logistical streams. Therefore this thesis focused on:

Enhancing coordination of construction logistics for city development.

Coordination can be achieved through the use of ICT systems. The ICT systems found in literature can be used to coordinate specific parts of a supply chain. Some systems coordinate the supply and demand of an organisation (ERP), or try to coordinate the planning of several organisations (APS). Other systems specifically plan logistical operations (TMS) or warehouse operations (WMS). Non of these systems is designed to coordinate logistics, planning, and supply and demand of an entire supply chain, or construction project. There is a system that could coordinate multiple organisations and multiple supply chains. Such a system is called a control tower, or more specifically a construction logistics control tower. A construction logistics control tower can be defined as: a central node that monitors, plans and coordinates logistical processes for one or more construction projects by integrating relevant information systems and data sources.

As the definition implies, a control tower is a central system that is in contact with all relevant stakeholders. It could be a physical place, fully cloud based or a combination of the two, depending on further developments and implementation. During the thesis two perspectives on the control tower have been investigated: a control tower as described in literature and from the perspective of potential users. Both literature and empirical research provided requirements and functionalities for a control tower. In the literature it was found that a functional design was not proposed yet. From

the interviews it was found that not all organisations have a clear idea of what a control tower encompasses. A functional design aids in creating a more common vision for the opportunities a control tower holds. Therefore the thesis further focused on making a functional design for a construction logistics control tower for city development.

During the empirical research it was found what information resides in different types of organisations. This information was considered as input for the construction logistics control tower. The output of the control tower is a combination of functionalities found through interviews and functionalities found in the literature. In total 15 functionalities have been described, divided over three categories: planning and routing, information hub and decision making. The planning and routing functionalities concern what moves where at what time and in which amounts. A control tower also functions as a hub where information is stored, shared and analysed. The third category encompasses decision making on the gathered and analysed information.

Compared to the traditional situation some things will change when implementing a control tower. The control tower will take over the communication between all organisations involved in a project in the designated area. All organisations will still carry out most of their normal tasks. The differences are that the control tower will gather the material demand for an entire area, and communicate this total demand directly to the assigned wholesalers/suppliers. In doing so the control tower optimises the material stream going in the area. Less vehicles are needed as consolidation can be achieved along with higher load factors. Route and delivery information can be communicated directly to the transporting organisations, along with other relevant information from the construction logistical plans or BLVC documents. The deliveries are planned to meet the construction processes. These processes are monitored and analysed using KPI's to see whether the construction project is going according to the up front made agreements. These KPI's are also used to make forecasts to adjust transport and construction schedules to optimise logistics and minimise nuisance and down time.

Further benefits of the control tower are: single point of contact, central information flow, choice in information sharing through modules, guaranteed access to information, coordinated construction logistics for an entire area, coordinated road blocks, decrease in traffic intensity, higher load factors, and lower nuisance and greenhouse gas emissions. A potential downside is that some logistical service providers might have to change their business model, and that preferred wholesalers/suppliers of a contractor might not be chosen by the control tower. However, both these downsides depend on further development and implementation of a control tower. Therefore it is essential to include potential users in the further developments.

A construction logistics control tower should not become a resource available to a select few. It should be open to all organisations involved in the construction projects in a certain area. Some information should even be public as it could aid in relations with residents of the area, or provide emergency services with crucial information about road blocks and traffic. The facilitation of a control tower should be done by a neutral, impartial, capable, reliable and most of all trustworthy organisation. This organisation could help during further developments, but also in the creation of a more common shared vision of a control tower.

Table of Content

List of Figures

List of Tables

Chapter 1: Introduction

The logistical sector is one of the largest contributors to CO2 emissions (van Luik et al., 2019). Around 30% of all mass transported within the Netherlands is construction related (Quak et al., 2011), the amount of vans with workers and materials is even larger. This makes construction logistics the largest source of freight transportation within cities, and therefore the main contributor to air pollution. Within the municipality of Amsterdam vehicles supplying construction projects account for 30-40% of the total traffic, and thereby it accounts for 35% of CO2 and 10% of particular matter and nitrogen-oxides emissions (Quak et al., 2011). The city of Amsterdam wants to lower their CO2 emissions with 55% by 2030, compared to 1990 (Municipality Amsterdam, 2019a). They, however, also want to realise 50.000 new houses by 2025 (Municipality Amsterdam, 2019b). This poses a contradiction as realising new houses demands more transport which produces greenhouse gas emissions.

This contradiction is not just visible in Amsterdam, but in the whole of Europe. The European Union set the goal to reduce particulate matter by 80% and nitrogen-oxides by 90% by 2030 (ALICE/ERTRAC, 2015). Furthermore the EU aims to reduce greenhouse gas emissions from the transport sector with 60% by 2050 compared to 1990 levels (ERTRAC, 2017). On the other hand Europe sees a growing need for mobility and freight transport (Van Amstel, 2015). Here again the choice between aiding growth or sustainability becomes visible. A roadmap has been made by two European groups[1] for research in logistics (ALICE/ERTRAC, 2015). Their aim is to set research priorities in relation to logistics. The roadmap has four objectives: decarbonisation, liveability, reliability and safety (Van Amstel, 2015). These objectives can be achieved by properly coordinating construction supply chains and especially construction logistics.

1.1 Construction Supply Chains

Coordination in the construction industry is hard to achieve, partly due to the conservative nature of the industry (Robinson, 2018). Figure 1.1 gives a generalised example of a construction supply chain. A more elaborate description will be presented in section 3.2. This example shows the material and information flow between some of the stakeholders in the supply chain. Construction supply chains have the following characteristics: it is fragmented, complex, converging, typified as make-to-order, and project driven (Staring, 2019; Janne, 2018; Lundesjö, 2015; Balm et al., 2018). The fragmentation has to do with the high variety of disciplines working in the industry (Lundesjö, 2015). High fragmentation results in more complexity. Furthermore there are at least 25 organisations involved in an average construction project, (ECLLP, 2013; Emrath, 2015) adding to the complexity. The converging characteristic is mainly due to the material streams originating from different places, but are all used in one project. Construction projects can be typified as one-of-a-kind, since the construction industry is driven mostly by client demand, resulting in a make-to-order industry. Due to this one-of-a-kind make-to-order projects there is low standardisation (Lundesjö, 2015).

One of the most important things within construction is logistics. Especially since properly coordinated construction logistics can lead to higher productivity, lower costs, less waste and less

[1] The European Road Transport Research Advisory Council (ERTRAC) and the Alliance for Logistics Innovation through Collaboration in Europe (ALICE).

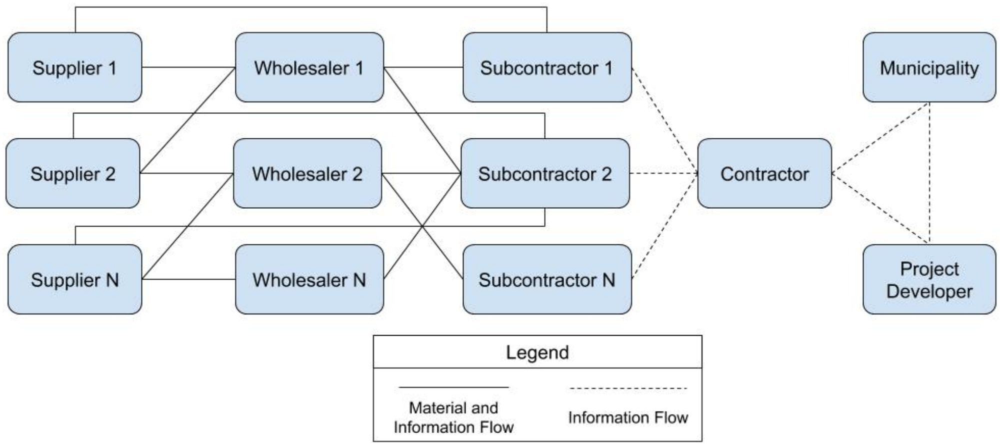

Figure 1.1: Example of a construction supply chain.

hindrance for the environment (De Bes et al., 2018; van Luik et al., 2019). Furthermore every construction project demands lots of materials, personnel and equipment to be delivered in the right amount, at the right time, and at the right location (Balm et al., 2018). Currently construction logistics is hardly coordinated, especially when considering multiple construction projects in one region.

Coordinating construction logistics within one project, although difficult, could be done manually. When multiple construction projects are involved it becomes much harder, even as there are limited systems described in literature that can coordinate these kinds of activities and processes. One of the systems is a construction logistics control tower.

1.2 Construction Logistics Control Tower

A construction logistic control tower can be considered as a central node that monitors, plans and coordinates logistical processes for one or more construction projects by integrating relevant information systems and data sources. Where coordination can be defined as: the process of organising different activities, or people, in order to make them work together effectively. There is, however, no agreement within the literature on which primary functions a control tower should have. The functionality differs per company desiring a control tower (Trzuskawska-Grzesińska, 2017). There is agreement about the potential benefits, which mainly are (Staring, 2019; Bhosle, Kumar, van Doesburg, & Sparks, 2011); end-to-end visibility, information hub and optimisation. In order to achieve these benefits the control tower has to be integrated with different ICT systems such as advanced planning systems (APS), warehouse management systems (WMS), transport management systems (TMS) and building information modelling (BIM) (van Merrienboer & Ludema, 2016). Using ICT can lower the amount of movements within construction with more than 50% (De Bes et al., 2018). Furthermore, these ICT systems, when integrated in a control tower, provide insights into the state of affairs with regard to both construction and logistical planning, such as consequences of disruptions (van Merrienboer & Ludema, 2016). With the integrated ICT systems logistical planning can be done more efficiently, lowering the costs and reducing last minute changes.

Within the literature there is not much known about the combination of ICT systems and control towers. What is known, is that the combination, as well as the individual technologies, provide several benefits to keep construction projects within schedule, reduce costs and therefore be more efficient (Shehab, Sharp, Supramaniam, & Spedding, 2004; Stadtler & Kilger, 2008; Hollmann, Scavarda, & Thomé, 2015; Siebelink et al., 2019; Schrauf & Berttram, 2016). There are some general views of how a control tower should be organised, mainly focusing on the roles, set-up and general information within the tower (Bhosle et al., 2011; Grefen & Dijkman, 2013; Hofman, 2014; De Bes et al., 2018; van Luik et al., 2019). According to Staring there are several obstacles with regards to the development of control towers within the construction industry, such as a lack of a clear business case for the involved organisations, perceived risks of data sharing, and an industry-wide protocol that dictates the information exchange among data exchanging organisations (Staring, 2019). This is in agreement with earlier research done by Trzuskawska-Grzesińska, which finds that there is a knowledge gap regarding the configurations of supply chain control systems, or control towers. The configuration is what links the ICT systems regarding things as, how data is extracted and combined to produce valuable output (Trzuskawska-Grzesińska, 2017).

Another aspect that has not yet been understood are the implications for stakeholders involved in a control tower (Staring, 2019). Stakeholder involvement is vital to the success as a control tower relies on these stakeholders to function properly. Making a functional design for a control tower while involving stakeholders complements this insufficiently described part in the literature. To make a functional design it needs to be known what application the tower has, where it gets its information from and who it grants access to.

1.3 Thesis Objective

Making a functional design for a construction logistics control tower while involving stakeholders is a step towards a fully designed and operational control tower. Through a control tower, coordination in construction logistics can be enhanced. Therefore this thesis has the following research objective:

Enhancing coordination of construction logistics for city development.

The research objective will be accompanied by four research questions (RQ) and two research objectives (RO). The methodologies aiding in finding answers to these questions will be discussed in Thesis Project Methodology.

RQ1: What is the state-of-the-art in coordinating construction logistics?

RQ2: What is known about construction logistics control towers within the literature?

RQ3: Which coordination and information systems are used by organisations active in construction logistics, and what data resides in these systems?

RQ4: What is a control tower perceived to be by organisations active in construction logistics?

RO1: Making a functional design for a construction logistics control tower for city development.

RO2: Evaluating the proposed functional design.

As said before the municipality of Amsterdam wants to become more sustainable. Within the city around 35% of greenhouse gas emissions is produced as a result of construction logistics. Therefore the city of Amsterdam is the perfect place to design a construction logistics control tower for. The main focus will lie on an area that will be redeveloped in the coming years: Amsterdam Amstel III (ZO!City, 2018; O-Team, 2018). Areas up for redevelopment pose several logistical challenges, which can be faced using a control tower. Furthermore, stakeholders were interviewed about desired functionalities and their willingness to share information with third parties.

1.4 Scoping

Before the research will be conducted scoping is needed to provide guidance and limits. There will be a focus on control towers within the construction logistics field. Therefore other types of control towers will not be included. A construction logistics control tower will use data from ICT systems available within the construction supply chain. There will be no limit on the type of systems, or sources, providing information to the control tower. By including all sorts of information sources the most broad and diverse applications are considered. In finding functionalities it is desired to have an open mind about the input, transformation and output of data. The focus lies on designing a control tower. Therefore physical (hardware and software) requirements of the system are out of scope.

1.5 Report Outline

Chapter 1: Introduction
Construction Supply Chains, Construction Logistics Control Tower, Thesis Objective,
Scoping, Report Outline

↓

Chapter 2: Thesis Project Methodology
Thesis Approach, Methodology per Research Question, Thesis Deliverable,
Relevance of the Thesis

↓

Chapter 3: Construction Supply Chains (RQ1)
Construction Industry, Construction Supply Chain Description, Construction Logistics,
Coordination in Construction, Coordination Systems

↓

Chapter 4: Construction Logistics Control Tower (RQ2)
Introduction to Construction Logistics Control Towers, General Requirements from Literature,
General Functionalities from Literature, Designs Known in Literature

↓

Chapter 5: Empirical Research in Construction Logistics (RQ3+4)
Construction Project Network Analysis, Data Availability and Data Sharing,
Vision of a Construction Logistics Control Tower, General Requirements from Stakeholders,
General Functionalities from Stakeholders, Stakeholders Willingness to Use a Control Tower,
Potential Facilitators Proposed by Stakeholders

↓

Chapter 6: Functional Design of a Construction Logistics Control Tower (RO1+2)
In- and Excluded Requirements, Minimal and Desired Functionalities,
Desired Data per Functionality, Functional Design, Proof of Concept, Reflection on the Design

↓

Chapter 7: Conclusions and Recommendations (RQ1+2+3+4 RO1+2)
Findings, Recommendations,
Limitations and Future Directions, Reflection

Figure 1.2: Report outline.

Chapter 2: Thesis Project Methodology

This chapter elaborates on the approach chosen for this thesis (section 2.1). The approach is followed by a methodology section (section 2.2), in which the methodologies used to answer the different research questions are discussed. Afterwards the deliverable for this thesis is discussed (section 2.3). Finally the relevance of the thesis is elaborated on (section 2.4).

2.1 Thesis Approach

This thesis used *design science research* as its main approach. Design science research involves the creation of an artefact to solve real-world problems, while creating new knowledge (Simon, 1996; Vaishnavi, Kuechler, & Petter, 2019). Before new knowledge can be created it needs to be known what information already is available. Design science research is guided by the following steps (Vaishnavi et al., 2019):

1. Awareness of the problem
2. Suggestion
3. Development
4. Evaluation
5. Conclusion

During the first step awareness of the problem is created, which can be seen as defining a problem statement. The second step focuses on finding suggestions to solve the problem. Thereafter one suggestion is selected for further development. Finally the development will be evaluated and conclusions will be drawn from the cycle. The steps of the design cycle were used as guidelines for the research and research question formulation. The questions will be elaborated on later in this chapter (section 2.2).

The first two steps were conducted using literature review and desk research. A *case study* was used during the development phase. During the case study stakeholders were involved for development and evaluation phase. Stakeholder involvement was identified as insufficiently described in literature at the start of this thesis. Furthermore, it is desirable to include stakeholders early in the development process (Janne, 2018; Bryson, 2004).

The case study was conducted to find; what information and coordination systems are used by organisations, their vision of a control tower, which functionalities stakeholders would desire in a control tower, to find requirements for the functional design, and to evaluate the design. Furthermore participants will be asked to provide insights in the current situation of the supply chain. The case study was focused on Amsterdam Amstel III, as the area will be redeveloped in the years to come. Therefore it has a lot to benefit from enhanced coordination of construction logistics. During this thesis it was not known which organisations will be involved in the redevelopment of the area. It is known that the area will be redeveloped along with at least ten construction projects. This means that there are different organisations which will work together on diverse projects over a long time period. This thesis, however, was completed within a six months time period. Therefore only a single point in time can be taken to evaluate the case. Furthermore the opportunity given by the municipality of Amsterdam only consists of this single case. The chosen area will be elaborated on further in the box below.

2.1.1 Case Introduction

Located in the south-east of Amsterdam lies the area Amstel III. Amstel III is situates alongside the train tracks between the Johan Cruijff Arena and the Amsterdam UMC location AMC (Municipality Amsterdam, n.d.-a). It can be accessed by the A2 and A9 or using metro stations Bullewijk and Holendrecht (Municipality Amsterdam, n.d.-a). The area can be split up into two parts, a business park, alongside the A2, and an office park alongside the train tracks. With over 50.000 work spaces Amstel III is the third largest working location in Amsterdam (Projectbureau Zuidoostlob, 2011). This area will be up for redevelopment in the coming years (O-Team, 2018; ZO!City, 2018). There will be lots of projects undertaken which shall lead to a total of 15.000 new houses by 2040, a decrease in office floor space and an increase in hotel, restaurant, cafe, recreational and business park areas (Projectbureau Zuidoostlob, 2011; Municipality Amsterdam, n.d.-a).

Projects

There are several projects to be undertaken in the coming years. These projects can be found in two websites from the municipality of Amsterdam. The first is the implementation program 2020, which shows all projects to be started in 2020. The second website shows all ongoing projects and projects to be started in Amstel III. The projects shown on this second website might have an overlap with projects from the implementation program as 2020 is progressing while this thesis is written. The locations of the projects found on both websites is visualised in Figure 2.1, and they are elaborated on in Appendix A.

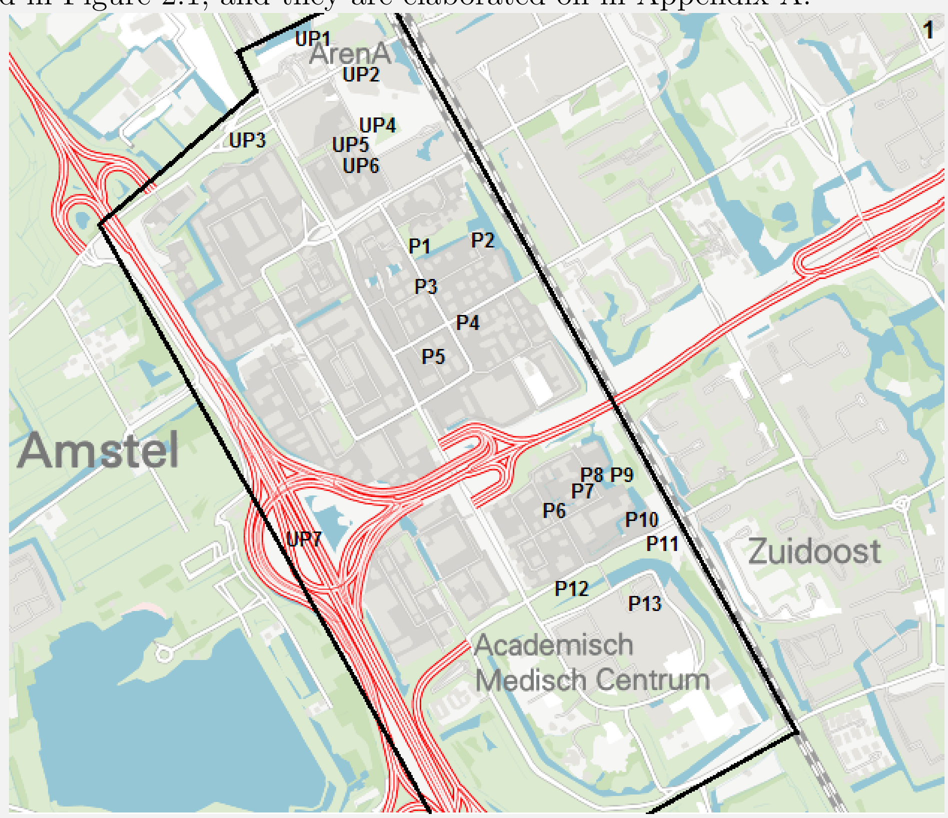

Figure 2.1: Locations of current and future projects Amsterdam Amstel III (Municipality Amsterdam, n.d.-g, 2020a).

In total around 20 projects will be undertaken in Amsterdam Amstel III. An average project involves at least 25 construction companies[a]. Suppose that there is an overlap of 25% in organisations working on the different projects, and that in a time period of a year around 25% of the projects will be constructed simultaneously. Then around 90 different organisations will be working on these projects in the same time period. When considering the average project then it can be seen that there will be a large amount of transport movements for both materials, equipment and personnel (Buck Consultants International, 2020). Normally each individual project would make its own construction and logistical schedules without taking the other projects into account. This could result in large amounts of inbound material on one day, causing large congestion while another day almost no materials will be delivered. Uncoordinated logistics can result in undesired effects such as unexpected road blocks or other inconveniences. These undesired effects can result in longer travel times, waiting times and delays for both public and private parties. Currently there is some logistical coordination within projects themselves, even less to nothing is coordinated between different projects. This overarching coordination poses benefits such as, but not limited to, fewer transportation movements, less pollution, less hindrance and higher productivity (De Bes et al., 2018; van Luik et al., 2019). The municipality of Amsterdam has several policy goals focusing on logistics, three examples are aiming to reduce greenhouse-gas emissions (Municipality Amsterdam, 2019a), increase mobility (Municipality Amsterdam, n.d.-k), and increasing road safety (Municipality Amsterdam, n.d.-l). These goals could be aided in achieving their goals by a more coordinated construction logistics.

Conclusion

It can be seen that there are a lot of organisations involved in the redevelopment of an area. Furthermore there will be a lot of organisations working simultaneously on these projects. This can cause disruptions for both the public and organisations working on projects in the area. Coordination is required to negate the severity of these disruptions.

[a]Large construction projects involve multiple contractors, around 50 subcontractors and at least 25 suppliers (ECLLP, 2013). A housing project involves one contractor and on average 22 subcontractors (Emrath, 2015).

First awareness about the problem needs to be created following the first step of the design research approach. This is done by answering the first research question: *What is the state-of-the-art of coordination in construction logistics?* The second step, suggestion, is partly answered by this same question. The state-of-the-art provides several options to enhance coordination in construction logistics for city development. One of the suggestions is a control tower, which is elaborated on during the second research question: *What is known about construction logistics control towers within the literature?* The focus of this question lies on literature, as stakeholders are included during the case study. In the case study several steps of the design approach are taken; suggestion, development and evaluation. Suggestion and development are included in the third and fourth research questions; *Which coordination and information systems are used by organisations active in construction logistics, and what data resides in these systems?* and *What is a control tower perceived to be by organisations active in construction logistics?* The development phase is considered in the first research objective: *Making a functional design for a construction logistics control tower for city development.* Finally the evaluation phase is done during the second research objective: *Evaluating the proposed functional design.*

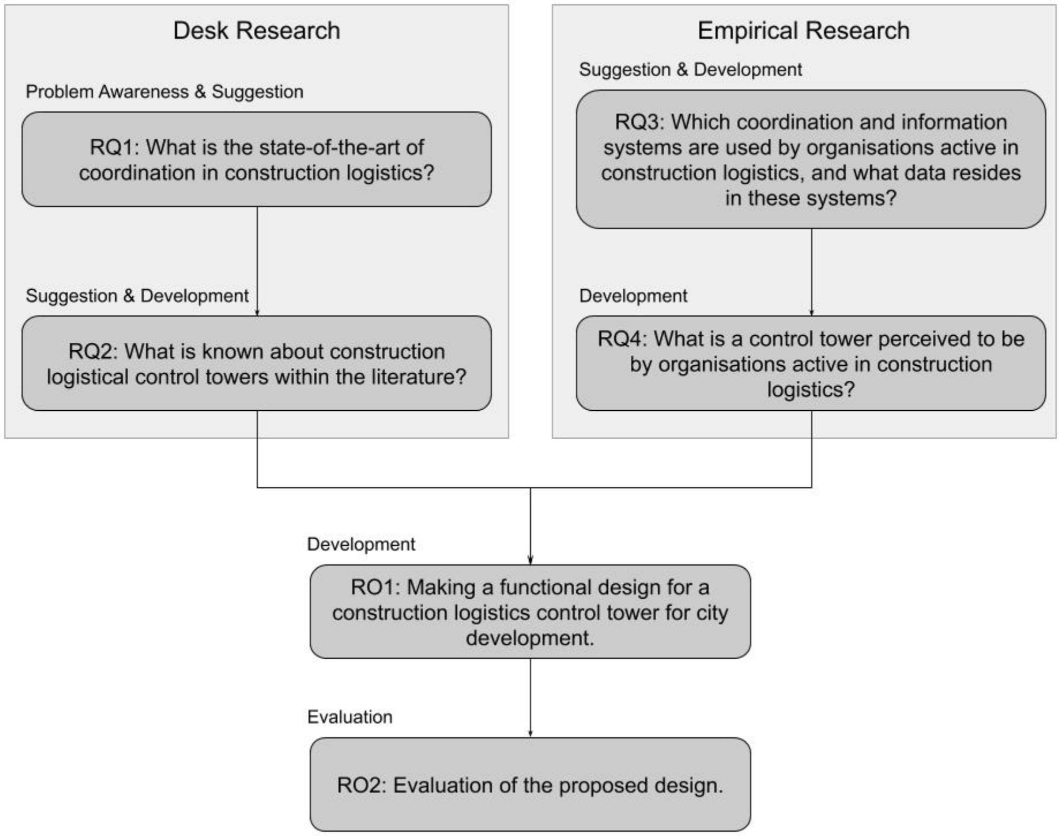

Figure 2.2: Visualisation of the research approach.

The chosen approach is visualised in Figure 2.2. The first two research questions focus on finding answers in literature. The third and fourth research question were answered through empirical research. These two approaches come together in the first research objective, where the design is made based on both literature and case study results. The two approaches are also used in the evaluation of the proposed design.

2.2 Methodology per Research Question

The methodologies used to find answers to the questions posed are discussed in this section. Each research question or objective is followed by what part of the problem statement is expected to be answered with it along with proposed methodologies for finding these answers.

RQ1: What is the state-of-the-art of coordination in construction logistics?

At the start of the design cycle awareness of the problem needs to be created. This awareness was created by finding the state-of-the art of coordination in construction logistics. To find an answer background information about construction and construction logistics was required. It needs to be known how construction logistics is coordinated. Furthermore potential coordination mechanisms and systems need to be elaborated on. These systems could provide suggestions for a design. All information was found through conducting a literature review.

Literature Review

The literature review used, amongst others, Google Scholar as database. The literature was conducted to gain a better understanding of construction supply chains and construction logistics. Specifically in the areas of construction industry characteristics, coordination and collaboration within the construction industry, and ICT systems for coordinating construction logistics activities. During the review no time frame was used, as literature about all subjects, except for ICT systems, is still relevant in gaining background knowledge. On the subject of ICT systems literature before 2000 was not included in the review. Literature before 2000 was not considered to describe currently used ICT systems accurately as they evolve over time. The scope was not put more recent as it was found in the first articles that the maturity of ICT use is not very high.

A description of a construction supply chain was made using the supply chain operations reference model. With the *supply chain operations and reference (SCOR) model* supply chains can be designed and current chains can be improved (logistiek.nl, 2006). It can be seen as an unified model which describes processes. Within the model five processes are central; source, make, distribution, plan and return (logistiek.nl, 2006). The model also encompasses three levels, of which the first two are most important for this thesis. The first level finds the key performance indicators, and the second visualises the current state of the supply chain (logistiek.nl, 2006). This helps to create transparency in the supply chain. Using the SCOR-model will help to gain a better understanding of the entire supply chain from supplier to end-user.

RQ2: What is known about construction logistics control towers within the literature?

Answering this question resulted in a clear definition of a control tower. The answer proposed a purpose and potential governance models. Furthermore general requirements and functionalities were discussed. Lastly the answer elaborated on three general design parts. The answers were found by conducting a literature review and by making a business model canvas.

Literature Review

This part of the literature review was focused on finding out what is known about control towers, preferably in a construction logistics environment. This aided in gathering basic knowledge of control towers along with functionalities and requirements for the design. Furthermore it provided a knowledge base for the remainder of the thesis. Literature before 2000 was not included as the concept of control towers in construction logistics has been developed in the past years. A safety margin was put in place to ensure noting was left out accidentally. The term construction was added to the search for literature about control towers due to the overlap in literature with the aviation field.

Business Model Canvas

A business model canvas (BMC) creates a common language in a visual way (Osterwalder, Pigneur, & Tucci, 2005), and it is especially suitable for innovative enterprises (Alias, Özgür, Jawale, & Noche, 2014). Normally a BMC would be conducted for a firm to create insight in their business model. However, a control tower is not perceived as a business, it is an innovation overarching several organisations. A BMC could still be useful, since it helps to understand the underlying business model of a control tower. It also provides an overview of what a control tower encompasses for the rest of the report. A BMC creates an understanding of the business model by using nine blocks (Osterwalder et al., 2005): value proposition, target customer, distribution channel, relationship, value configuration, core competency, partner network, cost structure and revenue model. These nine blocks are the main contributors to most business models. When combined in an overview they will help to capture, visualise, understand, communicate and share the business logic (Osterwalder et al., 2005).

RQ3: Which coordination and information systems are used by organisations active in construction logistics, and what data resides in these systems?

Answering this question provided insights in the coordination and information systems organisations active in construction logistics use, and what data is available by these organisations. First it needs to be known which types of organisations should be taken into account, as the case did not present specific organisations. This was done by conducting a network analysis. Information was gathered from the organisations by conducting semi-structured interviews.

Network Analysis

The network analysis was conducted to find organisational types to include during the development phase. These organisations should be included in finding solutions for enhancing coordination in construction logistics. The analysis provided insights into the values, power and interests of organisations on the subjects of construction supply chains and construction logistics. Interrelationships between different organisations are useful to know, since this might indicate trust or at least provides insight into the overall system. A stakeholder-interrelationship diagram and a power-interest grid were used during the network analysis.

Interrelationships between organisations were visualised using a *stakeholder-issue interrelationship diagram*. This diagram can be used to show which organisations have interest in issues, and how they might be related to one and other (Bryson, 2004). These issues could be more than meant in the traditional sense of the word, they could for instance also be different involvement in construction logistics. The diagram shows linkages between organisations through the issues they have in common. Via these linkages it can also be seen which organisations need to collaborate in order to achieve a certain goal.

A *power-interest grid* was made to map the power and interest organisations have in a certain issue. It was used to show which organisation has interest in construction logistics, and which have power to influence outcomes. A second power interest grid can be made to find interest and power in coordinating construction supply chains.

By combining the answers from the stakeholder-issue interrelationship diagram and the power interest grids it was found which organisation(s) should be involved in finding solution(s) to enhance coordination in construction logistics. These organisations were interviewed to gather information on several subjects.

Interviews

The interviews were used to answer multiple research questions. The interviews were semi-structured and focused on gathering qualitative data. If during an interview certain topics seem to emerge helping to gain a better understanding for the thesis, it might be better pursuing that direction and later on continuing with prepared questions. With a structured interview there is less room for deviations.

The first part of the interviews focused on gaining knowledge about the participants organisation. Afterwards the subject of data was discussed to find answers to RQ3. Regarding the subject of data participants were asked about their use of information and coordination systems. If they used such systems it was asked what they used them for, and which data these systems hold. Further questions regarded the current state of information sharing and desired information. Questions around the current state were directed at information receiving from others and information providing to others. The questions about desired information were posed to find an ideal state of information sharing. It was also asked if the participants hold information that is not allowed to be shared with third parties. These questions were asked to get an overview of the current state of organisations data availability and willingness to share information.

RQ4: What is a control tower perceived to be by organisations active in construction logistics?

Answering this question provided the vision of a construction logistics control tower as perceived by organisations active in construction logistics. This vision was accompanied by requirements and functionalities for a potential control tower. Furthermore willingness to use a control tower was discussed, along with a potential facilitator for a control tower. The answered were found through conducting semi-structured interviews.

Interviews

During the last part of the semi-structured interviews participants were asked five questions regarding control towers. The first question focused on their vision of a control tower. In the second question participants were asked about potential functionalities a control tower should have. The third question focused on finding requirements for a control tower. The requirements could be split into information storage and information sharing requirements, and for facilitation or participation of a control tower. A fourth and fifth question were directed at finding out willingness to use a control tower and potential facilitators.

RO1: Making a functional design for a construction logistics control tower for city development.

This objective can be considered as the development phase of the design cycle. No specific methodologies were used to make the functional design. All required information was already presented by answering the previously stated research questions. Requirements and functionalities for the design are found in the answers of RQ2 and RQ4. The data required to enable the functionalities is found by answering RQ3. Thereby the design combines information found in both literature and through the conducted empirical research.

RO2: Evaluating the proposed functional design.

After a design is made it can be evaluated, corresponding to the final step of design science research. This evaluation was done by first seeing if the design meets the posed requirements. Then validation through stakeholder interviews is discussed, which mainly focuses on the correctness of the data presented in the design. The third evaluation step is done by means of robustness, or in different words; what is still able if data is missing? Finally the benefits of sharing data with a control tower are discussed. Data sharing will be less likely to occur if there are no benefits for the organisations sharing their data.

2.3 Thesis Deliverable

A major part of the deliverable of this thesis is a functional design of a construction logistics control tower. This design shows the data available within certain organisations active in construction and construction logistics. The other side of the design shows potential functionalities and their data requirements. From a social point of view the thesis provides insight into two components; the willingness to share data between stakeholders and perceptions of a control tower. The perception of a control tower goes further then a definition. The perception of requirements, functionalities, willingness to use and facilitation are incorporated as well. This could be very useful for further research into the topic of construction logistics control towers. From a scientific perspective the thesis adds to the literature and research objectives by specifying functionalities. Furthermore stakeholder involvement in construction logistics control towers was not yet covered in the literature. The thesis helps in getting closer to a total design and further in the future an operational construction logistics control tower.

2.4 Relevance of the Thesis

The conducted thesis is relevant in three domains, it has both scientific and social relevance, and it is relevant for the Delft University of Technology master programme Management of Technology. The relevance is presented in the same order.

2.4.1 Scientific Relevance

Scientific relevance has been discussed in the introduction under section 1.2. Therefore only key points will be discussed. Within the literature there is not much known about the combination of ICT systems and control towers. This thesis elaborates on the functionalities of control tower and the data requirements. This data resides in different ICT systems used by organisations active in construction logistics. There are obstacles regarding the development of construction logistics control towers, such as lack of clear business case (Staring, 2019). The thesis uses a business model canvas to visualise the business logic, and elaborates on the visions described in the literature and by organisations active in construction logistics. Furthermore stakeholders have not yet been involved in the development of a control tower (Staring, 2019). The data required for a control tower, and its functionalities resides in these stakeholders. Therefore it needs to be known if they are willing to use a control tower and share their data with it. A functional design is not described in literature (De Bes et al., 2018; Hofman, 2014; Grefen & Dijkman, 2013). This design is a next step in further developing a control tower. A functional design shows which ICT systems could be coupled to the control tower, and which functionalities it should have. This functional design is proposed at the end of this thesis, and helps to clarify the business case by elaborating on the functionalities and data requirements. This thesis therefore adds to the literature, and aids in the development of an artefact.

2.4.2 Social Relevance

A construction logistics control tower poses benefits for all stakeholders involved, ranging from cost benefits to less traffic and lower emissions (Shehab et al., 2004; Hollmann et al., 2015; Siebelink et al., 2019; Schrauf & Berttram, 2016). These are not perceived by the organisations active in construction logistics, as there is no common vision and clear business case. The individual visions of different organisations were identified through interviews. The benefits and potential of a control tower was also shown by making a functional design. A control tower could aid the municipality in reaching their goals on environmental and logistical aspects, for instance car-free or carbon neutral/zero emission.

2.4.3 Management of Technology

The Management of Technology programme learns students to explore and understand technology as a corporate resource. It shows how technology can be used to design and develop products and services that maximise customer satisfaction while maximising corporate productivity, profitability and competitiveness (TU-Delft, 2020). An example of such a technology is a control tower. A control tower can be used for coordinating construction logistics. By coordinating construction logistics benefits could be achieved for both organisations and customers. The benefits for customers could be higher service level, lower waiting times and lower costs. For the organisation using a control tower as corporate resource these benefits could be higher information availability, higher productivity per vehicle and higher profit per transportation movement.

The control tower requires collaboration to coordinate the entire supply chain. Furthermore, a control tower requires sharing of data to function as supposed to. The organisations using a control tower are therefore both data providers and data receivers. Currently organisations only collaborate to achieve the end of a project, not to enhance efficiency, and they do not often share data. Implementing a control tower therefore requires a change of business thinking. These managerial implications are topics discussed during the Management of Technology programme.

Chapter 3: Construction Supply Chains

This chapter is written to provide a literature basis about construction and construction logistics. This literature basis will be used to find an answer to the following research question: *What is the state-of-the-art in coordinating construction logistics?* By answering this question a main problem statement of the current state of construction supply chains can be defined.

Some background information about the construction industry (section 3.1) and a construction supply chain (section 3.2) are required as this is the environment construction logistics operates in. After these two sections are presented construction logistics is elaborated on (section 3.3). Furthermore to find the state-of-the-art of coordination it needs to be known what currently is coordinated in construction (section 3.4). This requires knowledge of coordination systems described in the literature (section 3.5). The chapter ends with a conclusion (section 3.6) to discuss the findings of this chapter, and proposes a problem statement for the remainder of the thesis report.

3.1 Construction Industry

Presenting the state-of-the-art of coordination in construction logistics is harder without knowledge of the environment it operates in. Therefore information about the construction industry is necessary. There construction industry is elaborated on by first presenting its characteristics (subsection 3.1.1). These characteristics are followed by trends observed in the literature (subsection 3.1.2). The construction industry is project based, therefore construction projects are discussed (subsection 3.1.3).

3.1.1 Characteristics of the Construction Industry

A construction supply chain has the following characteristics: it is fragmented, complex, converging, typified as make-to-order, and project driven (Staring, 2019; Janne, 2018; Lundesjö, 2015; Balm et al., 2018). The fragmentation has to do with the high variety of disciplines working in the industry (Lundesjö, 2015) along with the temporary nature of the consortia they work in (Balm et al., 2018). High fragmentation results in more complexity. Furthermore there are a lot of companies involved in one project, which adds to the complexity (Staring, 2019). The converging characteristic is mainly due to the material streams origination from different places, all ending up in one project (Staring, 2019; Janne, 2018). Each construction project can be considered material intensive and will be supplied irregularly depending on the construction phase (Balm et al., 2018). The construction industry is mainly driven by client demand. Each client demands different specifics to be included in the project, therefore projects can be typified as a one of a kind (Janne, 2018), resulting in a make-to-order industry (Staring, 2019). Due to this one of a kind make-to-order projects there is low standardisation.

Balm et al. (2018) add that a new logistical setup is required at each construction site due to the unique and temporary location. They further add that construction activities are performed in a sequential order. Therefore delays will occur if one activity is not completed on time, or if materials are not delivered at the right time and place, and in the ordered numbers (Balm et al., 2018).

3.1.2 Trends in Construction

A trend that can be observed in construction is the shift from the development of new areas outside city boundaries (greenfield) towards redevelopment of existing areas within city boundaries (brownfield) (Janne, 2018). This requires adaptions in construction planning, especially in construction logistics. The main consequences resulting from this shift towards brownfield redevelopment are according to De Bes et al.: limited space on site, more rules to comply with, pressure to minimise project duration, taking into account external events, and changes in design and material use (De Bes et al., 2018). This means things will change within the construction industry such as: restrictions (in- and outbound but also spacial) for logistical activities, more coordination with the municipality, and pressure to reduce emissions (De Bes et al., 2018; Janne, 2018). Another trend is the increase in off-site fabrication, or prefabricated parts. The difference with normal construction is that, instead of material deliveries and production on site, the materials will be delivered to a production site, and the finished parts will be delivered to the construction site. The benefits of prefabrication is that buildings can be constructed more quickly while using less resources (Lundesjö, 2015). Since these parts are prefabricated the logistics will need to adapt, other types of vehicles are required and the dependence on coordination and planning increases.

There are two methods that have emerged over the past decades: construction consolidation centres and construction logistical plan (CLP or BLVC). These methods can be considered good practice, although they are not commonly used (Lundesjö, 2015). A *construction consolidation centre* or construction hub is a distribution centre where most of the materials needed in a construction project are delivered and temporarily stored (Lundesjö, 2015). The last mile transportation into the city is arranged from this hub. Construction hubs have lots of benefits of which less construction related traffic in the city (De Bes et al., 2018; Vries & Ludema, 2012), and more just-in-time deliveries (van Luik et al., 2019) are amongst the most important ones.

A *construction logistics plan* (CLP), or BLVC-document in Dutch, is required by the municipality of Amsterdam before a permit to start construction can be obtained (BLVC, n.d.; Balm et al., 2018). BLVC stands for accessibility, livability, safety and communication (in Dutch bereikbaarheid, leefbaarheid, veiligheid en communicatie). A BLVC plan contains an explanation of the project, a description of the environment, a risk analysis accompanied by reduction measures, a phasing plan and measures regarding accessibility, livability, safety and communication (House of Tenders, n.d.; Lundesjö, 2015). Furthermore it contains a plan to reduce hindrance for the surrounding environment accompanied by a point of contact for the project. The guidelines set in a BLVC need to be adhered to during the projects duration (Balm et al., 2018).

3.1.3 Construction Projects and Phases

There are three types of construction projects: infrastructure, utility construction and housing construction. Infrastructure projects range from highways and bridges to drainage and pavements. These projects require heavy duty equipment and high volumes of materials. Coordination is very important as deliveries, for instance asphalt, are often just-in-time and can not afford delays. Utility construction projects and housing projects have similar features, the difference lies in destination and requirements for use. Housing construction projects result in a place to live, while utility construction in definition results in all but houses. The major factor these two types of construction share are the four phases of construction; site preparation, substructure construction, shell construction and final construction. These four phases are visualised in Figure 3.1. Site preparation involves the demolition of buildings, clearing of building sites, and land preparation for substructure construction activities (OECD, 2001). The next phase, substructure construction, focuses on the construction below ground level (The Constructor, 2009). This part of the construction transfers the loads from the above parts to the underlying soil (The Constructor, 2009). Substructure construction involves footing and plinth of a building, creating a foundation for further construction works. The following phase is shell construction, which involves constructing the structure of the building making it wind- and waterproof (Geertsma, 2014). This phase entails flooring, roofing, walls, windows and doors. The inside construction will be done in the last phase: final construction. This phase finalises the construction process by making the building ready for use (Niels, 2019). Final construction involves plumbing, carpentry, electrics, tiling and painting (Niels, 2019).

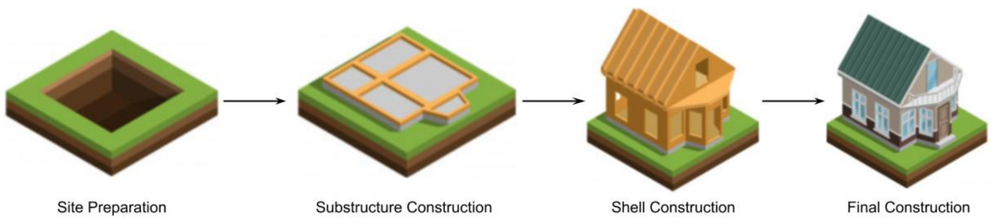

Figure 3.1: The four different construction phases.

Before these four construction phases start a design is made, this can be seen as the pre-construction phase. During pre-construction materials and construction methods will be selected and the planning and site layout will be made (Siebelink et al., 2019). This phase is the main determinant for logistics operations, therefore the main logistical planning should be incorporated in the pre-construction phase (Siebelink et al., 2019). Construction and transportation planning are considered as two of the most important sources of information within the construction process (De Bes et al., 2018). These two, however, are rarely shared, while this is crucial for proper construction supply chain management (De Bes et al., 2018). As these are not shared, or linked, coordination becomes more important to keep within budget, on schedule and to meet requirements. This pre-construction phase is partly defined by the tender and the requirements it holds.

3.2 Construction Supply Chain Description

A general supply chain has been presented in the introduction (Figure 1.1). This section provides a more elaborate description of a construction supply chain. This is done using the supply chain operations and reference (SCOR) model as a guideline. The SCOR model provides a framework that according to the Supply Chain Council (2010) links business process, metrics, best practices and technology features into a unified model to support communication and to improve the effectiveness of supply chain management. The SCOR model encompasses three levels (Supply Chain Council, 2010). The first level is elaborated on shortly and the second is used for the supply chain description. The description is made by an alteration to the business scope diagram (subsection 3.2.1), followed by a thread diagram (subsection 3.2.2).

In the first level key performance indicators (KPI's) are found, which can be used to monitor and measure progress and performance of a project (logistiek.nl, 2006). Before starting a project it desirable to discuss the definition of, and how to measure the KPI's. In most projects large amounts of actors are involved, which all might have their own objectives, definitions and ideas on the KPI's (Ludema, 2016a). Defining the KPI's, measures and desired results up front creates a common language for performance measurement. Ludema (2016a) specified KPI's focused on construction logistics and can be found in Appendix B.

3.2.1 Workflow Diagram

A workflow diagram is an alteration of the SCOR's business scope diagram combined with the process models. Similarly to a business scope diagram, a workflow diagram shows the different suppliers and process within the business. The difference here is that the business is a project which simultaneously is the end product for the client. Normally the client would be shown separately, just as production would be. A process model shows the different parts of a process and therefore is more useful. It also shows the entire order and make process, which already is shown by the thread diagram. Therefore a combination is made to show the material flow from source to waste including returns. This diagram is shown in Figure 3.2.

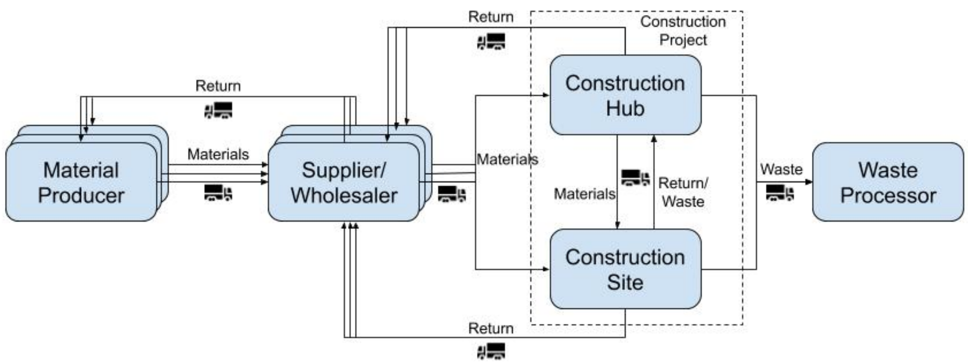

Figure 3.2: Material workflow diagram of a construction project.

From Figure 3.2 it can be seen that there is a transport step between each of the blocks. This transportation is either carried out by the block it originates from or by a logistics service provider. Furthermore each line has an annotation to give insight in the nature of the movement. There are multiple material producers and wholesalers/suppliers involved in one project, and just one construction hub and one construction site. Therefore the material producer and supplier/wholesaler are visualised as multiple blocks. The waste processor could be either single or multiple depending on the type of waste created by the project.

3.2.2 Thread Diagram

What is not shown in Figure 3.2 is the sourcing of materials, the make processes and the temporary storage, which are visualised in a thread diagram. In a thread diagram the entire supply chain, from supplier to end-user/product is shown and described using five processes: source (S), make (M), distribution (D), plan (P), and return (R) (logistiek.nl, 2006). The thread diagram, as shown in Figure 3.3, is proposed by van Merrienboer and de Vries (2016, p. 9-10), and used following the description of a construction supply chain based on.

The municipality sets the criteria for final delivery and other critical moments in the construction process during the tender phase. Based on these criteria, the contractor will indicate how requirements will be met (P4, planning of final delivery).

During the pre-construction phase the project planning for the actual construction will be made (P3, plan production) by the contractor. This schedule is divided into six week and one week schedules, which are leading for controlling the supply chain. The planning is made by talking to subcontractors about their material requirements. The project planning is also used for contracts with suppliers in which agreements are made for the supply during the project (P2, plan deliver). These contracts denote what needs to be delivered where and when the delivery will take place. Suppliers can adjust their production planning (P3, plan production) based on the contracts made. In more elaborate supply chains the supply and demand between factory and supplier is coordinated over longer time periods (P1, plan supply chain). Contractors, however, rarely coordinate the supply and demand over multiple projects.

The client order decoupling points most of the time determine the physical processes: make-to-stock (M1), make-to-order (M2), and engineer-to-order (M3). Make-to-stock processes are mainly standardised products with little variation. The make-to-order processes produce with a bit more variety. Engineer-to-order processes are designed to fully satisfy customer needs, and therefore have high variety per order. The construction site can be seen as an engineer-to-order process as it produces unique objects that are designed to meet customer demand. The construction site gets supplied by a variety of different chains, which can consist of a combination M1, M2 and M3. The suppliers can provide labour, materials and equipment.

Most of the time a supplier delivers goods at the gate of the construction site (D1, D2 or D3). If the goods delivered will not be used immediately they will be assigned a random spot at the construction site for temporary storage. This is where the process for the supplier stops, it does not mean the end of supply itself. The goods need to be moved from temporary storage to the place where it will be used (D4, supply within the construction site). When a construction hub is used, than deliveries will take place there. Only things that immediately will be used to construct will be delivered on site. Other materials will be delivered later from the hub to the site (also denoted by D4).

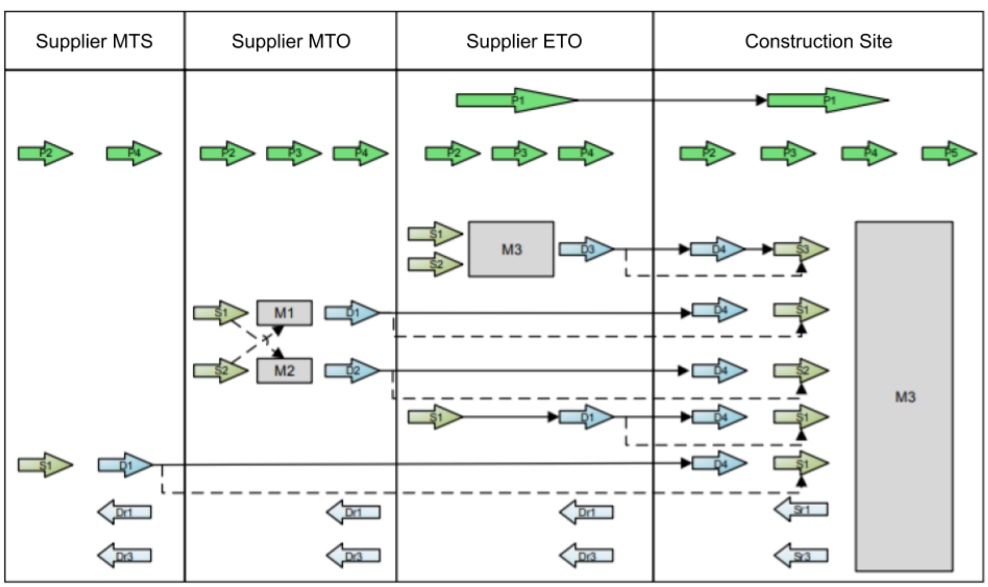

Figure 3.3: SCOR thread diagram for construction logistics processes, as proposed by van Merrienboer and de Vries (2016, p. 10).

In the thread diagram products need to be ordered or sourced. If the ordering is from stock it is S1, if it is ordered from a distributor use S2 and if the order is customised to a specific need then S3 is the right choice. Make-to-engineer processes still can function without using an S3 as customised products can be made with standard of the shelf goods. There are also return streams present at a construction site, such as packaging, wrongly delivered goods, and surplus goods (too much ordered and left over at end of project). Studies show that 10-20% extra goods are ordered to cover fluctuations (van Merrienboer & de Vries, 2016). While not widely done, it is wise to coordinate these return streams as it would account for higher load factors (P5 plan return, and Sr physical return of goods).

3.2.3 Section Conclusion

From Figure 3.2 it can be seen that there is a need for logistics between every set of actors and even within what is considered as one project. Figure 3.3 showed a more elaborate description of the same supply chain, excluding waste streams. Even within the construction site itself there is need for logistics, as materials are temporarily stored, moved and returned. It seems as if most processes are planned (P1-P4) and some coordination between the source and deliveries takes place, there however is not enough coordination. There is no P1 overarching the boundaries of suppliers and/or the construction site. With an overarching P1 the material flow would be better streamlined reducing inventory and cost while creating a more continues workflow (Hoekstra & Romme, 1987).

3.3 Construction Logistics

Now that the environment is known and a description of the supply chain is given it is time to zoom in on construction logistics. Construction logistics might be considered as one of the most important parts within construction. Especially since properly coordinated construction logistics can lead to higher productivity, lower costs, less waste and less hindrance for the environment (De Bes et al., 2018; van Luik et al., 2019). Furthermore every construction project demands lots of materials and other resources to be delivered on-time, at the correct location (Balm et al., 2018), and therefore demands properly coordinated logistics.

This section first provides a further introduction to construction logistics (subsection 3.3.1). Then the challenges in construction logistics are discussed (subsection 3.3.2) and finally a short conclusion is given (subsection 3.3.3).

3.3.1 Introduction to Construction Logistics

The literature has many definitions for logistics, of which the definition by the Council of Supply Chain Management Professionals (CSMP) is most clear and relevant for this thesis. They define logistics as *"the process of planning, implementing, and controlling procedures for the efficient and effective transportation and storage of goods including services, and related information from the point of origin to the point of consumption for the purpose of conforming to customer requirements"* (CSMP, 2013, p. 117). The construction site can be considered as point of consumption in the construction industry. The customer varies in the construction industry, the customer of the entire project is the project developer, while the contractor can be considered customer during construction.

A quick-scan carried out by Buck Consultants International shows that construction logistics holds the highest transport volumes, and comes third in total value of activities when compared to all other logistical sectors (Buck Consultants International, 2020). Just over 70% of construction logistics is carried out over road (Buck Consultants International, 2020), which is a vast amount.

Most road transport cover small distances, only 10% covers more than 100km (Buck Consultants International, 2020)[1]. Within the municipality of Amsterdam construction logistics accounts for 30-40% of all traffic (Quak et al., 2011).

Table 3.1: Categories of road transported goods and percentage of weight, distance, weight distance and CO2 emissions (Buck Consultants International, 2020).

Category:	Weight:	Distance:	Weight Distance:	CO2 Emissions:
Stone, sand, gravel, clay, peat, and other minerals	56%	5%	54%	23%
Other construction materials and products	22%	23%	20%	42%
Non identifiable goods in containers	5%	2%	10%	7%
Equipment, tools and parts	3%	13%	3%	9%
Residential and municipal waste	3%	4%	4%	4%
Cement, chalk and gypsum	2%	1%	4%	NA
Remainder	9%	52%	5%	15%

Table 3.1 provides an overview of the top 5 transported goods over road in construction taking into account weight, distance, weight distance and CO2 emissions per category. The table has been taken from a study for the whole of the Netherlands, therefore percentages might differ slightly for Amsterdam specifically. Nevertheless Table 3.1 provides an indication of what is transported for construction purposes. From Table 3.1 it can be seen that materials required for the substructure- and shell construction phases result in the highest percentage weight distance. Most of the CO2 emissions, however, result from other construction materials and products. These other materials can be are required in the final construction phase. Therefore measures need to be taken in different construction phases depending if weight distance or emissions are more important.

3.3.2 Challenges in Construction Logistics

There are several challenges and barriers to overcome in construction logistics. Some of these originate from the characteristics of the construction industry, others from issues in logistics, or they could result from collaboration. The construction industry is, according to Lundesjö (2015), being criticised for being uncoordinated, wasteful and disruptive. This can be seen by the ordering of larger volumes than required delivered long before they are needed (Lundesjö, 2015). This results in higher transportation movements than required and an overflow of materials on site. Furthermore Lundesjö (2015) states that *"it is widely acknowledged that logistics is less advanced in construction than in other industries"*, which is quite alarming due to the impact logistics has on construction projects (Lundesjö, 2015, p. 65).

According to Balm et al. (2018) there is an unclear division of responsibilities between construction site and organisations in the supply chain. This often results in inability to (un)load vehicles

[1]Percentage of transported distance over road: >20km 40%, 21-50km 22%, 51-100km 18% 100km<10%, unknown 10% (Buck Consultants International, 2020).

at time of arrival, which causes congestion on and around the construction site. These effects can also be seen in the inefficient logistical planning. The inefficient planning is not only caused by the unclear division but also by lack of data availability. Construction progress is hindered when logistics is planned inefficiently, it furthermore causes an increase in transport movements (Balm et al., 2018). Both inefficient planning and unclear division of responsibilities result in inefficient logistics on site, as a site plan is not made or adhered to. Inefficient on site logistics lead to increased costs, loss of material, express deliveries and hazards for on site personnel (Balm et al., 2018). This stresses the point that logistics has a large impact on construction projects.

Construction logistics faces other issues, which can be divided into internal and external logistics. The internal logistical issues are: limited space and storage capacity, material damage, waste, and unsafe working conditions (Siebelink et al., 2019; Lundesjö, 2015). Most of the internal issues can be attributed to the decreasing size of the construction site resulting from the shift towards brownfield development. From an external point of view the following logistical issues arise: traffic due to multiple projects, wrongly timed deliveries, conflicting resources, superfluous material stored and poor coordination (Siebelink et al., 2019). In addition De Bes et al. (2018) found that construction companies themselves barely have an overview of logistical activities, material flows and productivity on site. Therefore coordination should be enhanced to avoid undesired consequences such as additional cost, increased project time, and added risks (Lundesjö, 2015).

Another challenge within construction logistics is collaboration. Construction logistics is currently not properly coordinated, partly due to lack of collaboration. Collaboration between actors involved in logistics is not easy to establish (De Bes et al., 2018; Berden, Morel, van Amstel, & Balm, 2019). One of the reasons is that the supply of materials takes place through a complex chain of many directly and indirectly involved parties (Ludema, 2016b). Another reason is that due to the segregation within the construction sector the main contractor turned into the party winning tenders, and outsources the rest to less specialised subcontractors (Ludema, 2016b). This makes the network of organisations involved in one project quite large. All these organisations have their own requirements and thereby influence the project. Making a construction logistics planning is quite labour intensive, especially since alterations in schedules and execution are manually adjusted (De Bes et al., 2018). Therefore support of ICT systems is required to make construction logistics more coordinated (De Bes et al., 2018). Berden et al. (2019) describes some more collaboration barriers within the construction industry as: poor information systems, lack of sense of urgency, conflicting goals and values, lack of trust, lack of communication, and lack of perceived benefits. Most of these challenges can be derived from the conservative nature of the construction industry.

3.3.3 Section Conclusion

There are lots of challenges within construction logistics. Most of these challenges can be assigned to a lack of coordination in construction and construction logistics. By enhancing coordination in construction logistics load factors can be increased, resulting in less transportation movements to deliver the same amount of materials. These higher load factors can be achieved during supplying the construction site but also by collecting return streams. Furthermore enhancing coordination can result in more just-in-time deliveries. These just-in-time deliveries result in less material on site which could get lost or damaged. Another challenge is that site sizes are becoming more limited, due to the trend towards brownfield construction, requiring more coordination to keep as much space as possible free. Coordination through consolidation could reduce the number of vehicles arriving at the construction site. This, however, does require more collaboration between competing organisations.

The problem statement that coordination in construction logistics is lacking does not mean that there currently is no coordination at all. Some parts of the construction supply chains are coordinated, which will be elaborated on in the next section.

3.4 Coordination in Construction

Throughout the previous sections it has been mentioned several times that coordination and collaboration in construction logistics needs to be enhanced. The coordination within one organisation and in some cases multiple organisations is done using ICT systems such as ERP and APS, which will be elaborated on further in section 3.5. Coordination can also be achieved through collaboration, as organisations could work together effectively through collaboration.

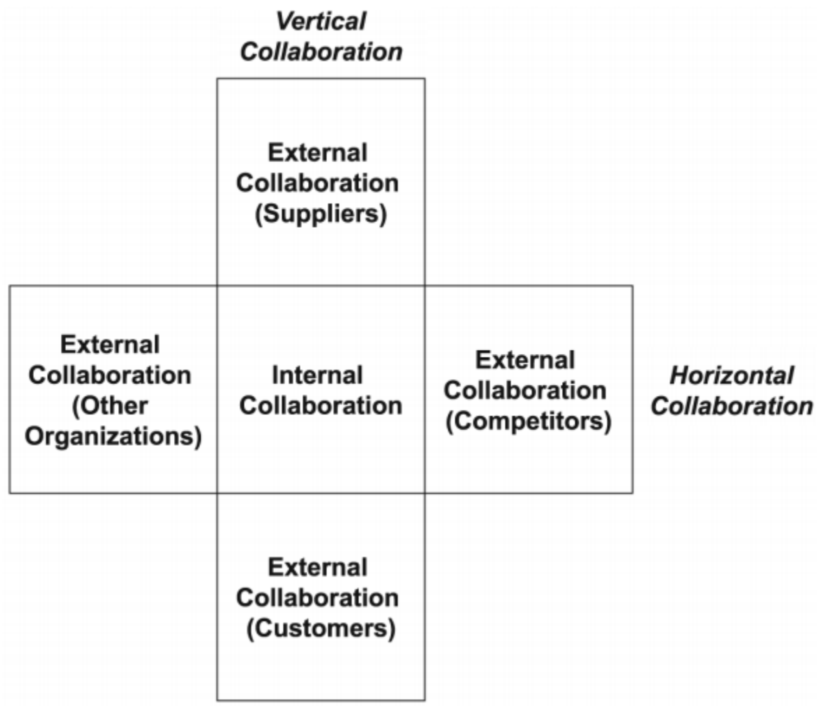

Figure 3.4: The scope of collaboration, as proposed by Barratt (2004, p. 32).

There are three main categories of collaboration in a supply chain: internal integration, horizontal collaboration and vertical collaboration (see Figure 3.4). Internal integration is a from of collaboration between different departments within one organisation (Barratt, 2004). This internal integration can be aided by ICT systems as described in section 3.5. Horizontal collaboration occurs when unrelated or competing organisations cooperate to share information or resources (Simatupang & Sridharan, 2002). These organisations have similar positioning in their respective supply chains (Staring, 2019). For example horizontal collaboration could present itself between contractors of the different projects. Vertical collaboration occurs when an organisation collaborates with its customer or supplier (Barratt, 2004), to serve relatively similar end customers (Simatupang & Sridharan, 2002). For example collaboration could be between a supplier, logistical service provider and subcontractor. There is lots of room for collaboration within the presented case as there are multiple projects undertaken in the same time period by similar actors. All these projects can be coordinated by means of vertical and horizontal collaboration.

Coordination can be facilitated through information sharing between different supply chain organisations (Ludema, 2016b). By sharing information each organisation can streamline their own processes, which could result in synergy. This information sharing can be facilitated in such a way that organisations themselves take what they need, or via an appointed organisation that facilitates the information sharing. There are already several information and communication sharing systems known within the literature that can aid in coordination. These will be described in section 3.5. Using ICT-systems to aid in coordination and collaboration might be useful as collaboration within the construction industry is considered to be a challenge (Quak et al., 2011; Ludema, 2016b). This is partly due to the temporary nature of construction projects, and therefore temporary collaboration between organisations.

3.5 Coordination Systems

Coordination can be achieved through the use of ICT systems. The systems described in this section have been found in the literature, and provide an overview of how different aspects of organisations and supply chains can be achieved. The found systems are not specifically designed for the construction industry, those will be described later in section 5.2. The described systems could be applied in the industry as the nature of the organisation (manufacturing, sales, transport, etc) are similar. There are more systems described in the literature than described in this section, such as MRP, MRP-II, CPFR and DMS, which are elaborated on in Appendix C.

3.5.1 Enterprise Resource Planning

Enterprise resource planning (ERP) systems have as a main function to integrate and manage all functions within an organisation, and to facilitate information flow between supply chain processes (Shehab et al., 2004; Cheng, Law, Bjornsson, Jones, & Sriram, 2010). ERP has the abilities to automate and integrate business processes, enable implementation of measures to enhance productivity, share data across the company, and produce and access information (Shehab et al., 2004). According to Cheng et al. there are four major limitations to ERP systems, namely: unable to facilitate supply chain structure changes, lack of modular and open system architecture, limited functionality beyond managing transactions, and low efficiency in sharing data with supply chain partners (Cheng et al., 2010).

3.5.2 Advanced Planning Systems

Advanced planning systems (APS) have three main characteristics: integral planning, true optimisation and hierarchical planning system (Stadtler & Kilger, 2008). According to Stadtler and Kilger true optimisation is achieved by *"properly defining alternatives, objectives, and constraints for the various planning problems and by using optimizing planning methods, either exact ones or heuristics"* (Stadtler & Kilger, 2008, p. 84). The hierarchical system is a compromise between the first two characteristics, as either can not be achieved without the other (Stadtler & Kilger, 2008). The integral planning is achieved in three levels: short-term, mid-term and long-term (Stadtler & Kilger, 2008). These levels can also be seen as operational planning (short- and mid-term combined) and strategical planning (long-term) (Stadtler & Kilger, 2008). APS systems can be seen as an integration of several ERP systems, creating an overarching planning system.

3.5.3 Transport Management Systems

Transport management systems (TMS) in general manage the planning, control, monitoring and optimisation of transport networks and logistics chains (Nettsträter et al., 2015). Some of its functions are order management, transport planning and optimisation, for a full list see Figure 3.5. These systems store information about the properties of the transport activity. These properties can be considered as (Hofman, 2014; Whitlock, Abanda, Manjia, Pettang, & Nkeng, 2018): type of cargo, physical characteristics (such as weights and dimensions), specifics (such as temperature and hazards), origin and destination, and duration of the trip.

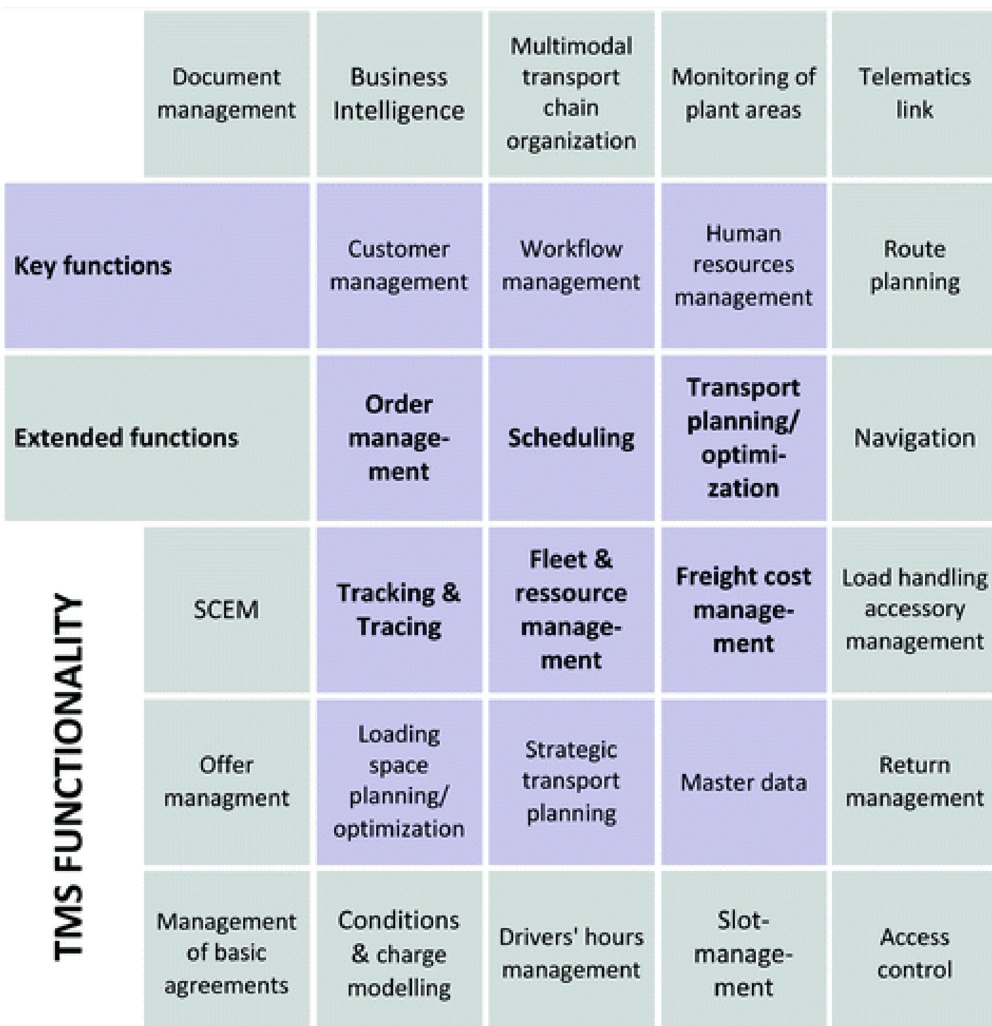

Figure 3.5: Key and extended functionality of a typical TMS, as proposed by Nettsträter et al. (2015, p. 6).

3.5.4 Geographical Information Systems

Around 80% of all business data has geographical elements (Sarkar, 2007), making systems to analyse these elements quite useful. Geographic information systems (GIS) is developed to manage and analyse spatial data (Liu et al., 2017). GIS helps in finding answers to questions such as; What is the best route for delivery trucks? How should deliveries be scheduled? What is the best location for delivery hubs? How can the fleet be optimised to meet service goals and minimise costs? Therefore the most important components of GIS are the location information itself and the attributes related to this location (Liu et al., 2017).

3.5.5 Warehouse Management Systems

Warehouse management systems (WMS) aim to control the movement and storage of materials within a warehouse and process the linked transactions (Ramaa, Subramanya, & Rangaswamy, 2012). The primary purpose of a WMS is to control the movement and storage of materials within a warehouse (Nettsträter et al., 2015). The key and extended functionalities of a typical WMS are provided in Figure 3.6. A WMS can be paper-based, wireless or a combination of both. Furthermore it could also be connected to an overarching ERP system.

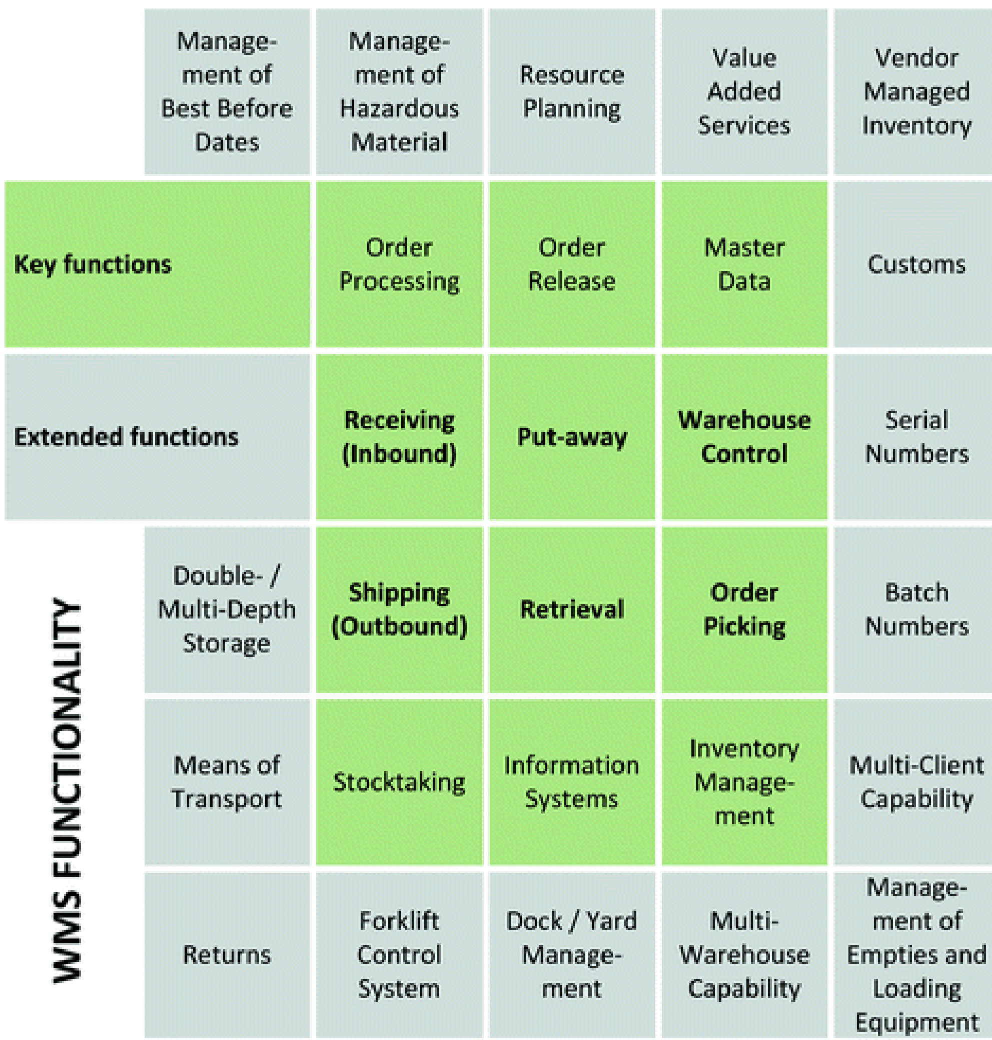

Figure 3.6: Key and extended functionality of a typical WMS, as proposed by Nettsträter et al. (2015, p. 5).

3.5.6 Building Information Modelling

Building Information modelling (BIM) can be seen as an up-to-date 3D model of the project which provides insights and tools for scheduling, design, construction and management (Whitlock et al., 2018; Pérez, Fernandes, & Costa, 2016), and therefore poses benefits at all stages of the project life-cycle (Bryde, Broquetas, & Volm, 2013). It is structured in three main object categories; building elements (components of the design solutions that should be scheduled in construction activities), site facilities and work spaces, and equipment (both static and dynamic) (Getuli, Ventura, Capone, & Ciribini, 2016). Planning can be integrated into BIM, which is called 4D BIM, and when cost related data is integrated BIM becomes 5D (Deng, Gan, Das, Cheng, & Anumba, 2019). The construction schedule can be characterised by an iterative and detailed process (De Bes et al., 2018). When scheduling is added to BIM it aids the adaption of the schedule for the entire chain. BIM can be connected to geographical data from GIS to provide information of the inventory and deliveries of materials from different suppliers throughout the different construction phases (Deng et al., 2019). This aids the scheduling of the project and logistics throughout the phases.

3.5.7 Section Conclusion

The described systems can be used to coordinate specific parts of a supply chain. Some systems coordinate the supply and demand of an organisation (ERP), or try to coordinate the planning of several organisations (APS). Other systems specifically plan logistical operations (TMS) or warehouse operations (WMS). Non of these systems is designed to coordinate logistics, planning and supply and demand of an entire supply chain, or construction project.

3.6 Chapter Conclusion

In this chapter the characteristics of construction and construction logistics were discussed to find the state-of-the-art of coordination in construction logistics. This was done by conducting a literature review and by using the SCOR-model to provide an overview of an example construction supply chain. From these sections it was found that the amount of coordination currently taking place in the construction supply chains could be enhanced further. By enhancing coordination in construction logistics benefits such as fewer transportation movements, higher load factors and reduced emissions could be achieved.

Multiple information and coordination systems have been described, all designed to enhance coordination in particular ways. Some of these systems are designed to manage just one part of the supply chain while others are trying to manage planning of several organisations together. Most of the described systems are however not capable of coordinating an entire supply chain, let alone multiple supply chains. This is partly due to the complex nature of the construction industry.

There is a system that can aid in complex logistic environments and desires data sharing and collaboration: a construction logistics control tower. Such a control tower is designed to oversee and coordinate logistics for one or multiple construction projects within one area. Furthermore it is neutral, independent and relies on the data from different organisations to function properly, making them collaborate with one and another via this external system.

Chapter 4: Construction Logistics Control Tower

Chapter 3 described the state-of-the-art of construction supply chains and showed that coordination of construction logistics should be enhanced. It was proposed that a control tower could be a solution to coordinate multiple construction projects, and thereby multiple supply chains. This raises the second research question, which is answered in this chapter: *What is known about construction logistics control towers within the literature?* By answering this question the current state-of-the-art of control tower, as described in the literature is presented. How a control tower is perceived by stakeholders will be discussed in chapter 5.

This chapter first provides an introduction to the concept of construction logistics control towers (section 4.1). The introduction consists of a definition and potential governance models, and is accompanied by a business model canvas to visualise what a control tower encompasses. The introduction is followed by general requirements (section 4.2) and potential functionalities (section 4.3). Afterwards the known design parts of a control tower are discussed (section 4.4). The chapter ends with a conclusion (section 4.5) in which this chapters research question is answered.

4.1 Introduction to Construction Logistics Control Towers

When talking about a control tower, most people immediately think about an air traffic control tower, which is different than the control tower proposed in this thesis. To omit further discrepancies a definition of a construction logistics control tower is given along with the purpose a control tower serves (subsection 4.1.1). Afterwards governance models for a control tower are discussed (subsection 4.1.2). Finally a business model canvas (subsection 4.1.3) is made to elaborate further on what a control tower encompasses.

4.1.1 Definition and Purpose

To better understand the concept of control tower a clear definition must be provided. This definition is accompanied by the purpose a control tower serves. A control tower is a central coordination system for multiple logistical chains (Ludema, Rinsma, & de Vries, 2016b), thereby it is creating a more integral ecosystem compared to the traditional supply chain model (Schrauf & Berttram, 2016). The main difference between this ecosystem and the traditional model are that the traditional model is more linear, and the ecosystem has a central component (Schrauf & Berttram, 2016). These and other differences are shown in Figure 4.1. The figure shows that a control tower should be a central node in contact with all stakeholders involved in the process. It is already shown that a control tower keeps track of product flow between organisations, and that it helps plan product flows and align the demand and supply. The organisations shown in Figure 4.1 are not construction related, more information about construction organisations will follow in section 5.1.

The integral ecosystem described in Figure 4.1 is not a clear definition of what a control tower is and what it can be used for. Conceptually control tower components share data via data stores with a data management layer in between to keep track of changes (Hofman, 2014). Within the literature a control tower has been described as a hub for visibility, decision-making and action, using real-time analytics (Bhosle et al., 2011; Dalmolen, Moonen, & van Hillegersberg, 2015). For

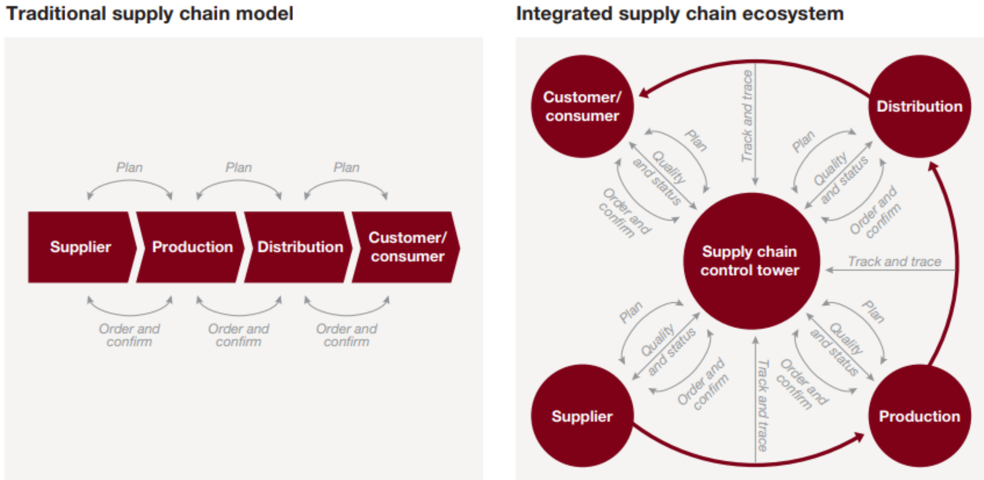

Figure 4.1: Traditional supply chain compared with the integral ecosystem, as proposed by Schrauf and Berttram (2016, p. 10).

this thesis the following definition, based on Staring (2019), is used: A construction logistic control tower can be considered as a central node that monitors, plans and coordinates logistical processes for one or more construction projects by integrating relevant information systems and data sources. This control tower could be a physical place, fully virtual/cloud based, or a combination of both (Dalmolen et al., 2015; Trzuskawska-Grzesińska, 2017; Staring, 2019).

The main purpose of a construction logistics control tower is to enhance coordination between logistics chains and construction projects (Ludema et al., 2016b). The control tower will rely on shared information and thereby the integration of multiple ICT systems to enhance coordination. Several of the to be integrated systems were explained in section 3.5. The integration will require trust and coordination between the organisations involved (Cheng et al., 2010). The most important sources of information within construction projects are the construction and transport planning, and inventory information (van Merrienboer & de Vries, 2016). A control tower therefore requires the input of these sources along with real-time information in order to function properly (van Merrienboer & de Vries, 2016). This information can be exchanged using a platform from which all involved parties can share the data needed from their respective systems. In both cases governance is required to ensure the information exchange and collaboration work as promised.

4.1.2 Governance Models

Control towers are designed to coordinate multiple construction projects, and therefore interact with lots of organisations. Decisions need to be made to coordinate this variety of projects and organisations. The process of decision making and ruling based on provided information by the involved actors can be considered as governance (Bevir, 2012; Morel, Balm, Berden, & van Amstel, 2020). Currently organisations involved in a construction project share information with all organisations (Lundesjö, 2015). This process of information sharing can be considered as complicated and inefficient (Lundesjö, 2015). Therefore a governance structure should be chosen to reduce complexity and increase efficient information sharing.

According to Schilling (2017) there are three governance mechanisms to manage collaborative relationships of organisations: alliance contracts, equity ownership, and relational governance.

Alliance contracts are made to ensure two things; to make partners aware of their rights and obligations in the collaboration, and that partners have legal grounds to act on if a partner should violate the contract (Schilling, 2017). Contracts are widely known within the construction industry and applied at every project. In equity ownership partners contribute capital to the collaboration and own a share of the equity in the alliance (Schilling, 2017). Equity ownership can be used to create a sense of ownership and commitment, and therefore align goals (Schilling, 2017). Relational governance is the most self-enforcing of the three, as it is based on trust and reputation (Schilling, 2017).

According to Newell, Robertson, Scarbrough, and Swan (2009) there are three forms of trust: companion trust, competence trust, and commitment trust. Companion trust is based on judgement of goodwill or friendships, and rests on the moral foundation that other will not harm others in the network (Newell et al., 2009). Competence trust is based on the perceptions of competencies of the other, with an attitude of respect for the abilities of others to complete their tasks (Newell et al., 2009). Commitment trust is based on contracts and agreements in which parties are expected to gain mutual benefit from the relationship (Newell et al., 2009). Collaboration in construction most of the time starts with commitment or competence trust. Which are the most swiftly forming but easy to break. It is less likely for a organisation to be involved in future projects when an agreement is broken or if competencies are not meeting expectations.

The relational governance described by Schilling is similar to the network topography governance described by Bevir. The network topography governance model is characterised by a relatively flat structure, where actors cooperate voluntarily in pursuit of mutual benefits (Bevir, 2012). The actors in the network depend on each other for key resources, and gain trust through repeated beneficial interactions (Bevir, 2012). This model resolves conflicts through diplomacy, as there is reliance on each other to gain mutual benefits (Bevir, 2012). The network would therefore be damaged if one of its actors behaves opportunistically (Bevir, 2012). This model is representative since the construction industry is based on mutual benefit and trust through repeated conformation. Furthermore there is a dependency between the organisations in the network to complete a construction project. The performance of one organisation affects the circumstances in which others have to operate. There is one aspect of the model that does not fit in the construction industry, the voluntarily cooperation. There is no voluntary cooperation between subcontractors as a contractor chooses these subcontractors.

For a control tower the network topography governance model could be suitable. Actors engage voluntarily in a control tower as it holds benefits for the complete network. These benefits can only be achieved through collaboration and reciprocal information exchange, create a dependence for key resources. Contracts might be an additional mechanism to this model to ensure data is shared and agreements are met. Equity ownership might not be beneficial as it makes the control tower less independent. Using to the equity share organisations can influence processes or gain extra benefits/information.

Another suitable governance model is described by Balm et al. (2018). Their smart governance concept can be used at two levels. The first is the municipality level, which describes all construction projects starting in the coming years within a specific area (Balm et al., 2018). The second level can be used as a tool by organisations involved in these projects (Balm et al., 2018). The model consists of seven steps, shown in Figure 4.2, of which the first and last step are in the first level, and the others in the second.

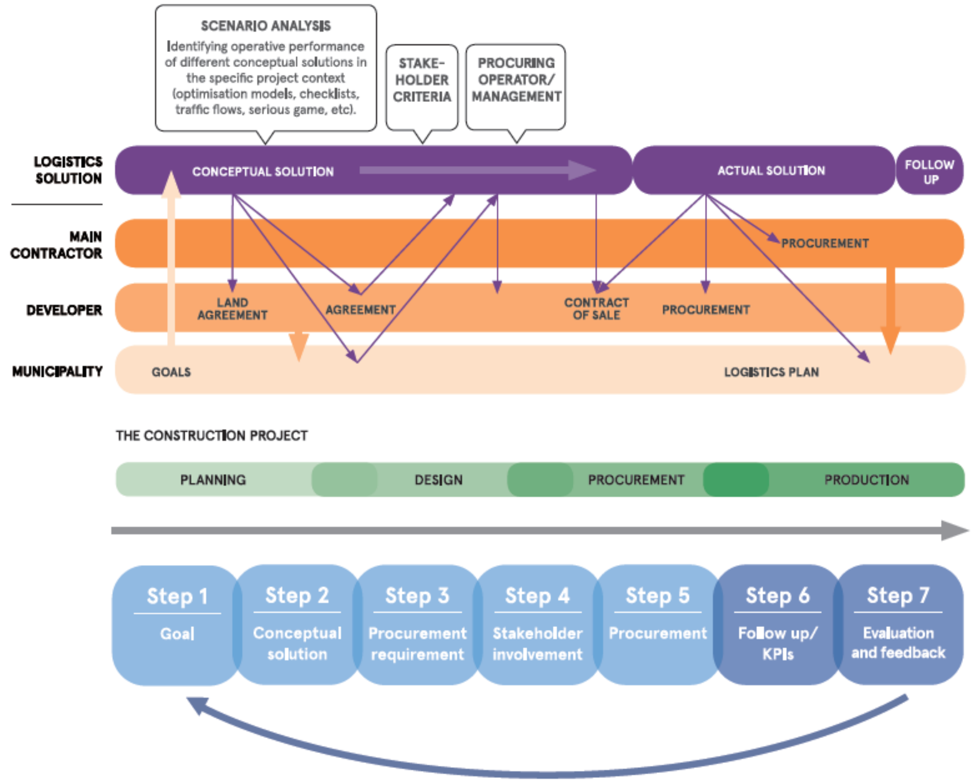

Figure 4.2: Smart governance concept as proposed by Balm et al. (2018, p. 19).

This concept can be used to find solutions to specific problems focusing on construction logistics. It involves all stakeholders affected by the coordinated projects (Balm et al., 2018), which is desirable in a control tower. Furthermore the concept takes a specific area in consideration (Balm et al., 2018), not just one project, again similar to a control tower. This smart governance model only focuses on three roles, municipality, developer and contractor. In a control tower more stakeholders should be incorporated, therefore this model could be more elaborate, especially since wholesalers and logistical service provides have impact on the logistical solutions.

4.1.3 Business Model Canvas

The definition, purpose and described governance model provided insight into what a control tower is. To elaborate further a business model canvas (BMC) is used, as a BMC creates a common language in a visual way (Osterwalder et al., 2005). To do so it uses nine blocks (Osterwalder et al., 2005): value proposition, target customer, distribution channel, relationship, value configuration, core competency, partner network, cost structure and revenue model. These blocks are the main contributors to most business models (Osterwalder & Pigneur, 2010). When combined in an overview these blocks will help to capture, visualise, understand, communicate and share the business logic (Osterwalder et al., 2005). The business model canvas for a construction logistics control tower shown in Figure 4.3 was made using information from section 3.2, subsection 4.1.1, and two articles; Staring (2019), and Alias et al. (2014).

Customer Segments

The customer segments block defines the different groups of people or organisations an enterprise aims to reach and serve (Osterwalder & Pigneur, 2010). A control tower has several customer

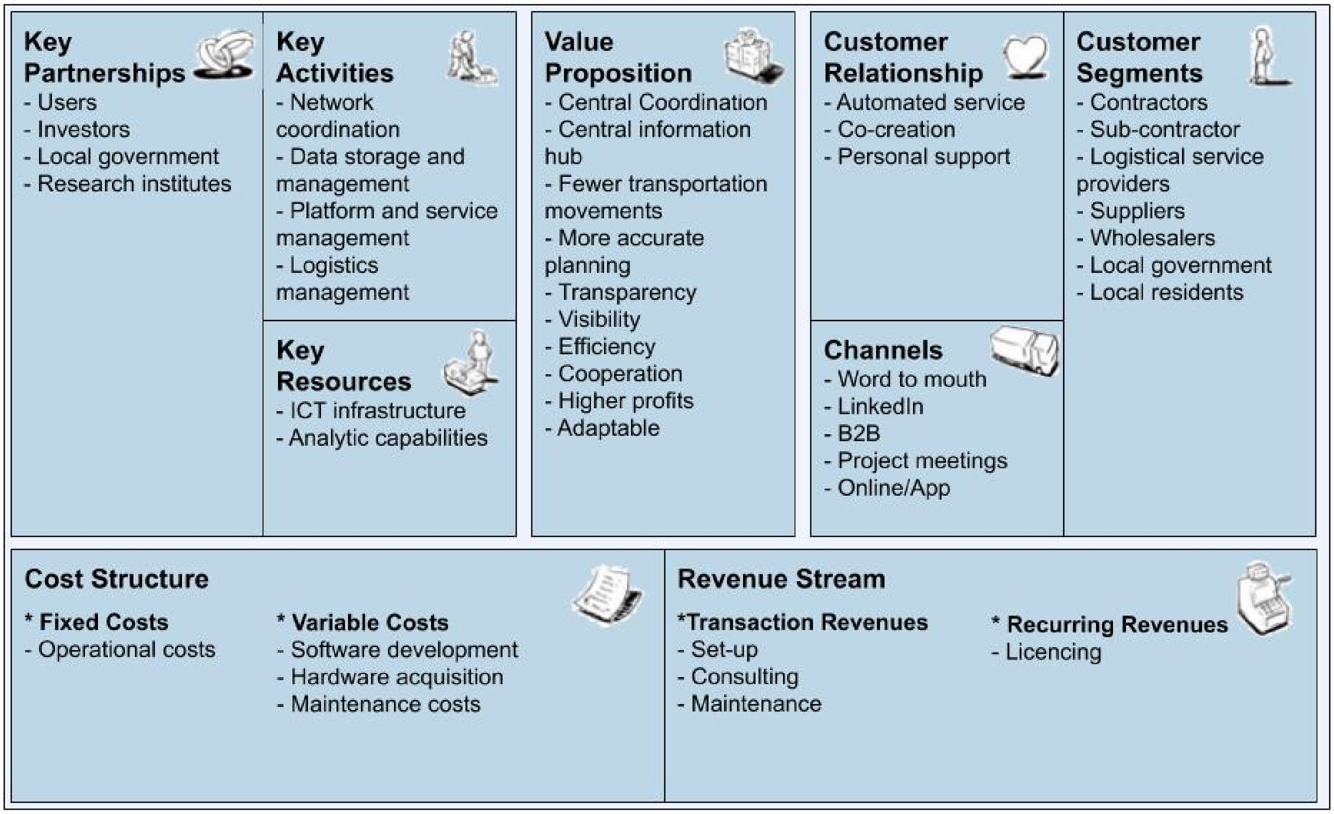

Figure 4.3: Business model canvas for a construction logistics control tower.

segments, ranging from intended users from industry to local government and local residents. Local residents will use the control tower to see what major events will happen in their neighbourhood. They will only use it as an information stream, and are not willing to pay for it.The local government can keep an overview of the projects at hand. With a control tower they can collect information about project duration, traffic flows and see if agreements are honoured. Most important of for the local government is to know how the project affects the livability and environment. The last customer segment are the users from industry, which can be divided into four groups: contractors, subcontractors, logistical service providers and suppliers. The contractors oversee the construction process and ensures the end deliverable meets the clients requirements. Contractors would like to get insight into the current state of the project, mostly in relation to planning. Furthermore they are willing to use a control tower when it helps in fostering collaboration, reducing cost and transportation movements while increasing efficiency. Subcontractors are mostly hired for a specific expertise, they are less interested in how logistics is arranges, as long as their materials are delivered before they need them. The logistical service providers want to know the what, when and where, in order to make their own schedules. Furthermore using a control tower can help to autonomously provide real time estimated time of arrival. The suppliers use a control tower for their planning and sales departments. With a control tower they know when which product must be ready, and therefore they can schedule their make processes.

Value Proposition

A value proposition is the services or products that create value for the described customer segment (Osterwalder & Pigneur, 2010). A control tower should enhance the visibility and transparency within the supply chain. This is done by providing more information about costs, schedules, and desires throughout the entire chain. Efficiency can be increased by making better transportation schedules, which are directly linked to the construction planning. When this is achieved, fewer transportation movements will be made as load can be consolidated, or better planned to achieve higher load factors. To achieve all values information from organisations in the project is required. When this information is shared, schedules can be more efficient and all collaborating organisations can benefit. Lastly all customers can opt which information they want to receive from the control tower. Combining this with the use for all types of projects and situations makes it adaptable to specific desires and contexts.

Channels
In order to communicate the value proposition to the customer segment certain channels can be used (Osterwalder & Pigneur, 2010). These channels mostly are business-to-business (B2B). A specific channel could be an application on a mobile phone or a cloud based platform. Project meetings will always be required to come to agreements and understandings, therefore these can also be used to discuss the input and desires for a control tower. Other channels can be used through which new customers can be attracted. This can be through professional channels such as LinkedIn, or more informal ones such as word to mouth advertisement.

Customer Relationship
The control tower offers an automated service, recognising each customer and their characteristics, customising the service that specific customer desired. In order to make the control tower more user friendly and offer the desired functionalities co-creation is used. With co-creation users help create the product or service, which can create a better relationship between the business and customer. Furthermore the customer has personal support when using a control tower. Each customer is different, therefore personal support is desired as it facilitates better integration of the control tower to the needs of each specific customer.

Revenue Stream
A control tower should not cost much for the customers, especially at the early adoption stage, as this will hamper the use. The costs, however, do need to be paid, else there will not be a control tower to use. The revenue streams can be split into two: transaction revenues, and recurring revenues. The recurring revenues can be licensing revenues, or pay to use. A part of the control tower will be free of charge, as local residents are not willing to pay for knowing what will happen in their neighbourhood. The more modules a customer desires, the more expensive these licences can get. The transaction revenues are once, in return for a specific service. These transactions are the set-up of a control tower, or in other words integration between control tower and a new customer. The maintenance cost could be incorporated into the licensing cost or paid each time maintenance is done, depending on the preferences of the customer. The last revenue stream is consulting. These consults can be during inquiry phase of an organisation willing to use a control tower, or during use by a company facing issues or willing to get more out of the control tower.

Key Resources
The most important assets a control tower requires are a proper ICT infrastructure and analytical capabilities. The ICT infrastructure relates to a stable internet connection, large amounts of data storage and capabilities to gather data from ICT systems used by companies. The infrastructure is also required to provide a reliable service and communication network. The analytical capabilities are required to process and analyse the gathered information. Using the analytics insight into the

relation between construction and logistical planning can be given. Furthermore these capabilities are required for event management and sending of notifications.

Key Activities
The key activities undertaken by a control tower should be network coordination, data storage and management, platform and service management and logistics management. The network of actors, their capabilities and desires need to be managed during a construction project. A control tower relies on vast amounts of data, this data needs to be stored and managed. The information provided by the control tower can be shared though a platform. This platform is part of the service a control tower provides, along with other capabilities. The entire control tower revolves around construction logistics, therefore logistics management is the main key activity.

Key Partnerships
There are several key partnerships that enable a control tower to work properly. First of all the intended users are key as they provide the data required to achieve the value proposition. The partnership goes further than data sharing as users co-create the control tower. A second partnership is made with investors and research institutes. The investors make it possible to start-up a control tower, and the research institutes provide the know how about a control tower. Another partnership is with the local government, as they are involved in making development plans resulting in the projects for which the control tower is used.

Cost Structure
There are two types of cost that are incurred by a control tower: fixed and variable costs. The fixed costs are mainly operational costs, such as electricity, web hosting and personnel costs if applicable. The variable costs can be split up in three components: software development, hardware acquisition and maintenance. Each of these three components will vary in cost depending on how much is needed.

4.2 General Requirements from Literature

The previous section provided an introduction to construction logistical control towers where a definition and purpose were given. This section provides some more specific information about control towers, by presenting general requirements found in the literature. Requirements from interviewed organisations are discussed in section 5.4. Some of the requirements from the literature focus on information systems, while others have a focus on collaboration. Both are relevant as a control tower will incorporate information system and requires collaboration with organisations.

According to Cheng et al. (2010) information infrastructures between members of a supply chain, such as a control tower, must satisfy the following three requirements: accommodation of varying degrees of IT sophistication, have a wide range of functionalities, and allow for changes in suppliers and customers. Not all organisations have the same maturity of ICT systems. Therefore some organisations will be left out if a certain level of IT sophistication is required. If a minimal level is required organisations have to invest, while this is not always beneficial. A control tower should have a wide range of functionalities as different organisations will require different functionalities. This does not only depend on the nature of their business but also on what they have to offer. The functionalities are discused in section 4.3. Finally a control tower should allow for changes of data suppliers and customers. Allowing changes is required at the beginning and ending of each project, as the group of organisations will be different in each new project.

A control tower can be seen as a system suitable for collaboratively managing supply chains, which have the following five desirable characteristics (Cheng et al., 2010; Staring, 2019; Ludema et al., 2016b): low costs, ability to integrate external systems and information, ease of use, ease of integration, and adaptable access to information and applications. When costs are too high organisations tend to hesitate before adopting a new system. Hesitation will also occur when a control tower can not be integrated with systems currently in use. When this is not possible organisations willing to use a control tower need to replace their old systems with new ones that can be integrated, which is undesirable as new systems incur cost. Therefore the ability to integrate systems along with data compatibility is required (Ludema et al., 2016b). When a system is hard to use or has a steep learning curve, people tend not to use them unless demanded to. The adaptable access to information and application can be enabled by using modules. When a control tower is modular different organisations are able to gain access for different purposes (Staring, 2019). The capabilities of a control tower can be split into different modules. These modules can be mixed and matched to the needs of a specific organisation in such a way that it better satisfies their needs. Furthermore these modulus can be divided into publicly accessible and privately accessible, or perhaps paid modules. All functionalities, or modules, must be accessible at all times and with as little delay as possible. This will increase responsiveness and helps towards real time information exchange (Ludema et al., 2016b).

The general requirements for a construction logistics control tower found in the literature can be summarised by the following list.

- Accommodate varying degrees of IT sophistication.
- Have a wide range of functionalities.
- Allow for changes in suppliers and customers.
- Have low costs of operation and set-up.
- Able to integrate external systems and information sources.
- Easy to use.
- Easy to integrate in current business.
- Adaptable access to information and applications depending on the organisation (modular).

4.3 General Functionalities from Literature

The requirements provided a context in which the control tower should operate. A next step in gaining a more complete overview is to define potential functionalities of a control tower. These functionalities present what a control tower could do when it becomes operational. This section only focuses on functionalities from literature, functionalities proposed by interviewed organisations are discussed in section 5.5.

Within the literature there are several functionalities and capabilities discussed of a control tower. According to Trzuskawska-Grzesińska control towers are responsible for *"process monitoring, measurement, assessment, corrective and preventive actions, responding to customer tickets and/or issues as well as reporting to the internal and external partner's organizations to initiate the improvement processes"* (Trzuskawska-Grzesińska, 2017, p. 123). Furthermore the control tower should be focused on balance between supply and demand, in- and outbound logistics, and procurement (Trzuskawska-Grzesińska, 2017).

The main capabilities of a control tower can be described as end-to-end visibility, information hub and digital twin (Staring, 2019). Visibility means capturing of relevant and accurate data and interconnect it timely which will support informed decision making (Bhosle et al., 2011; Staring, 2019). A digital twin can be seen as a virtual version of the physical supply chain. This digital twin therefore includes all information within the supply chain, and thus can be used for planning and execution of activities (Staring, 2019). A control tower also functions as a facilitator of collaboration (van Merrienboer & de Vries, 2016) as it uses the information gathered to make unified schedules.

The found functionalities can be divided in three levels of control: strategic (S), tactical (T) and operational (O). On the strategic level decisions are made about the goals of the company, as well as design of the overall network (Staring, 2019; Bhosle et al., 2011; Ludema et al., 2016b). This level makes decisions for the years or decades to come. The tactical level looks several months or years ahead, and focuses on enabling proactive planning of procurement, operations and distribution, and transport optimisation (Staring, 2019; Bhosle et al., 2011; Ludema et al., 2016b). The last level, operational, concerns day-to-day operations such as transport, order and inventory management, as well as real-time control activities (Staring, 2019; Bhosle et al., 2011; Ludema et al., 2016b). From the literature the following list of possible functionalities of a control tower can be derived (Staring, 2019; Trzuskawska-Grzesińska, 2017; Bhosle et al., 2011; Ludema et al., 2016b; Topan, Eruguz, Ma, van der Heijden, & Dekker, 2019; De Bes et al., 2018):

- Planning and routing:
  - In- and outbound logistics, including waste transportation (T/O)
  - Real time monitoring/tracking, including estimated time of arrival (O)
  - Horizontal transport planning (T)
  - Vertical transport planning (e.g. crane planning) (T/O)
  - Planning of delivery time windows (T/O)
  - Consolidation planning (T/O)
  - Construction planning (S/T)
- Information hubs:
  - Preferred route information (S/T)
  - Collaborative information sharing (S/T/O)
  - Relation between construction and logistical schedules (T/O)
  - Process monitoring (O) (Estimated time of arrival and traffic)
  - Forecasting, including demand and cost (S/T)
  - Scenario calculation (S/T) (traffic flow causing congestion)
  - Periodic performance monitoring, using KPI's (O)
  - Representative digital twin (S/T/O)
  - End-to-end visibility (S/T/O)
  - Inventory management (O)
- Decision making (autonomous):
  - Event management, for events such as disruptions (T/O)
  - Self corrective actions and warnings (T/O)
  - Procurement, of materials and strategic locations (S)
  - Auditing and reporting (T)

- Creating and sending of invoices (T/O)
- Logistical network design (S)

4.4 Designs Known in Literature

The final part searched in the literature is focused on the design of a control tower. This design has to meet the requirements posed, and ensure that the potential functionalities can be enabled. There are three design parts known in the searched literature. These known designs focus on the following parts: control structure (subsection 4.4.1), roles within a control tower (subsection 4.4.2), and levels of operation (subsection 4.4.3).

4.4.1 Control Structure

A first known design part is how a control tower fits the control structure within a supply chain, as shown in Figure 4.4. The figure shows two supply chains (SC1 and SC2), each having three links (L1, L2 and L3) of which L2 is shared by both chains. Due to a shared link the optimisation of one supply chain can result in de-optimisation of the other (Grefen & Dijkman, 2013). The control tower (4C) consists of a chain-level control system (CCS) and a chain-level information system (CIS). The CCS and CIS are used to control and monitor the two separate supply chains and the concurrence of the two (Grefen & Dijkman, 2013). Thereby it helps to optimise resources used in L2, resulting in an optimisation of both supply chains. From Figure 4.4 it can be seen that a control tower interacts with each link in each the supply chain and the environment.

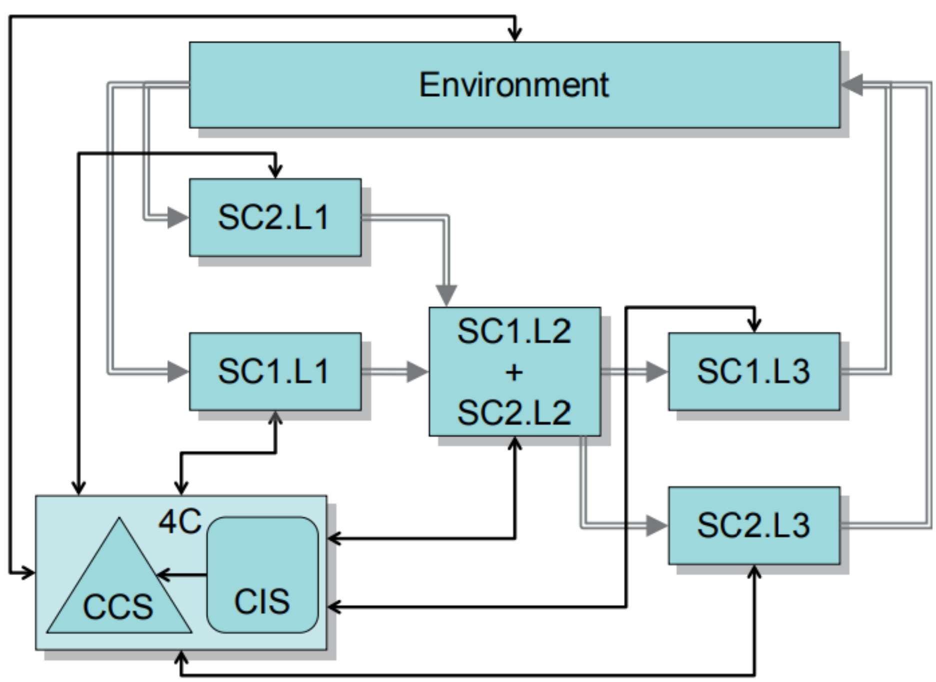

Figure 4.4: Cross chain control centre integration model, as proposed by Grefen and Dijkman (2013, p. 52).

4.4.2 Roles within a Control Tower

Another known design aspect are the roles within a control tower, as shown in Figure 4.5. These roles are discussed briefly. The value chain designer is responsible for the production of one or more value chains to reach particular goals with the available business services. The value chain coordinator coordinates the execution of the selected value chain, which might result in alterations based on real-time information. The coordinator provides decision support to the customer. The business transaction manager has contact with the end user and provides them with reports and instructions. The resource planner optimises the capacity use of used resources. The sensor evaluator evaluates state changes introduced by a sensor, which might result in changes of daily operations. The business service manager specifies and publishes business services by an enterprise, which are stored in the data store. The performance & compliance monitor evaluates value chain performance and analyses potential risks. These roles are formed for a physical control tower. When a control tower becomes more cloud based these roles might be taken over by artificial intelligence.

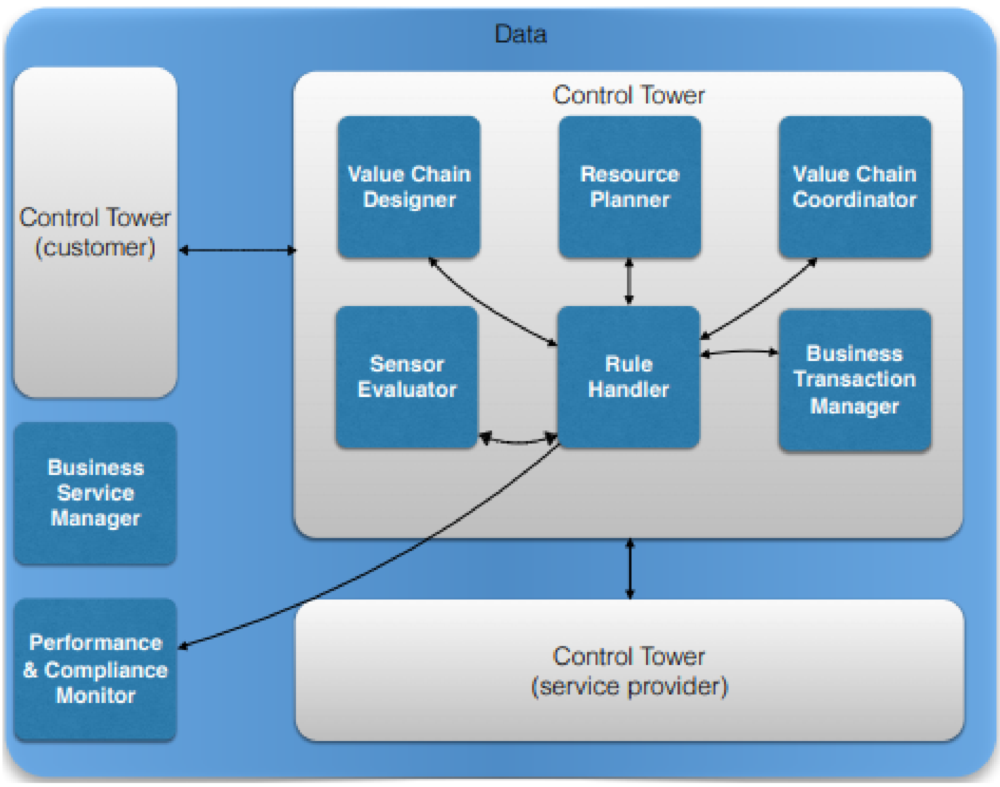

Figure 4.5: System architecture of control tower components, as proposed by Hofman (2014, p. 5).

4.4.3 Levels of Operation

De Bes et al. (2018) provide a schematic representation of a construction logistics control tower. The schematic shows three levels within the control tower; operational for short term insights and forecasts, tactical for synchronisation of six week till six months schedules, and strategical for key numbers and scenario analysis. The paper by De Bes et al. (2018) is not the only one making this division. Their schematic provides information about potential users and how they are linked to a control tower. The information will be provided using customised dashboards per stakeholder, which in this case are: contractors, suppliers, logistical service providers and road managers.

4.4.4 Section Conclusion

These design examples provide an indication of what should be included in the design of a control tower. The part from De Bes et al. (2018) indicates that the design should clarify which level (operational, tactical or strategic) a functionality is designed for. The roles as proposed by Hofman (2014) give an indication of how a control tower interacts with organisations within a supply chain. The design shows a split between service provider and customers, which can be interpreted as a split between a data providing side and a data receiving side. The integration model from Grefen and Dijkman (2013) indicates that there is a difference between the control system and information system. This can be translated to a data providing side and a to be controlled side. Both sides can have a similar set of actors. Furthermore the model shows that all supply chain actors should be linked to the control tower to either collect data or coordinate actions.

What is not shown is a design focusing on the functionalities linked to data residing within stakeholders. A design showing functionalities and the requirements needed to achieve them can be called a functional design. This design could incorporate parts of the three designs shown in this section. First more information is required about requirements for the functional design and about potential functionalities it should include.

4.5 Chapter Conclusion

The goal of this chapter is to provide the state-of-the-art of construction logistics control towers within the literature. Where a construction logistic control tower can be considered as a central node that monitors, plans and coordinates logistical processes for one or more construction projects by integrating relevant information systems and data sources. This definition was followed by the proposition of two governance structures and a business model canvas to provide a visualisation of the propositions a control tower holds. Afterwards requirements were given, which can be summarised as; a control tower should have a wide range of functionalities, which can be adopted modularly, while allowing for various IT sophistication of regularly changing suppliers and customers, which desire ease of use and integration.

These requirements were followed by a set of potential functionalities that were divided into three categories; planning and routing, information hub and decision making. The planning and routing category focuses on how logistics can be scheduled and the routes vehicles should take. Information hub provides a knowledge base used for amongst others forecasting and inventory management. The Decision making category focuses on processing the gathered to make informed decisions.

Finally the known designs elaborated on three points desired to include when designing a control tower. These points or known designs did not show where certain data originates from. Neither did they show what functionalities a control tower should have. Therefore the design part of this thesis is focused on making a functional design. In order to make such a design it needs to be known what functionalities a control should have, what data is required for these functionalities, and where the data can be gathered from. Answers found in the literature have been given in various sections in this chapter. More information can be found through stakeholder engagement, and are presented in chapter 5.

Chapter 5: Empirical Research in Construction Logistics

Chapter 4 concluded with the notion that a functional design was missing and should be made. A literature basis for requirements and functionalities was presented in that same chapter. Further information required for making a functional design is presented in this chapter. To find this information the following research questions are answered in this chapter: *Which coordination and information systems are used by organisations active in construction logistics, and what data resides in these systems?* and *What is a control tower perceived to be by organisations active in construction logistics?* The answers to these questions are found through conducting semi-structured interviews. A network analysis (section 5.1) is conducted to find organisational types that should be interviewed, as the presented case (subsection 2.1.1) did not include specific organisations.

After the network analysis RQ3 is answered by presenting the data availability and willingness to share data (section 5.2). RQ4 is answered in the other sections, where first the visions of a construction logistics control tower are discussed (section 5.3). Next the requirements (section 5.4) and functionalities (section 5.5) found during the interviews are presented. Then the willingness to use a control tower is discussed (section 5.6). Finally potential facilitators are presented (section 5.7) before the chapter conclusion is given (section 5.8).

5.1 Construction Project Network Analysis

Stakeholders are becoming more and more important when solving a problem and implementing solutions (Bryson, 2004). Therefore a network analysis should be conducted to find which stakeholders, or organisational types, should be involved in making a functional design for a control tower to enhance coordination in construction logistics.

Although the exact organisations were not known when this theses was conducted, an analysis could still be carried out by generalisation. Each construction project has a general set of actors (Berden et al., 2019; De Bes et al., 2018): a client/project developer, contractor, subcontractors, wholesalers/suppliers, third party logistics providers, municipality offices, waste processor, local residents and local companies. The network analysis was conducted using these general actors. First the network boundaries are defined by identifying the actors and their values (subsection 5.1.1). Afterwards interrelationships between organisations and shared issues are visualised using a stakeholder-issue interrelationship diagram (subsection 5.1.2). The diagram is followed by a power interest grid to show which organisations are able to change outcomes (subsection 5.1.3). When the interrelationship diagram and power interest grid are combined it is found which organisational types should be included in designing a solution to coordinate construction logistics (subsection 5.1.4).

5.1.1 Organisational Types Involved in Construction Projects

In subsection 2.1.1 it is explained that during this thesis it is not known which organisations will be involved in the mentioned projects. In general most construction projects involve similar sets of organisational types, therefore a network analysis can be conducted. It needs to be known which organisations are involved in a construction project, and what their roles and interests are. When this is known a stakeholder-issue interrelationship diagram can be made, showing the relations between different organisations and shared issues. Table 5.1 shows the organisational types involved in construction projects, their roles and interests. Part of this information has already been provided in subsection 3.2.2.

Table 5.1: Table of organisational types, their role and interests.

Organisation:	**Role:**	**Interests:**
Municipality of Amsterdam[1]	As legislator, and policy maker, it sets the context in which the project will take place. This context is partly covered in the tenders opened by the municipality.	Achieving policy resolutions in terms of accessibility, environment, circularity and sustainable (construction) logistics. Furthermore increased quality of life for citizens, and a good business environment.
Contractor	Responsible for the entire construction process and sees to it that the project is finished on time, upholding the agreed upon quality.	Efficient construction in a sustainable manner for low costs with good working conditions while keeping customers satisfied.
Subcontractor	Contractors outsource different construction activities to specialised subcontractors.	Sufficient materials on site to ensure a continues workflow at low cost, with proper working conditions.
Project developer	The project developer subscribes to the tenders issued by the municipality of Amsterdam. Once a tender has been won, the project developer hires a contractor to partly or fully do the construction works for that particular project. The project developer can be seen as the client will be the owner once a project is finished.	On time delivery of the project with high quality at an affordable price.
Wholesaler/ Supplier	Supplier of construction materials, could also arrange transport of their materials to the construction site.	High quality materials delivered within schedule at a competitive price based on timely and detailed information.
Logistics service provider (LSP)	Arranges transports for construction materials between different wholesalers/suppliers and the construction site. Is employed by supplier/wholesaler or (sub)contractor.	Detailed and timely information supply to ensure reliable transportation at a competitive price, preferably with high load factor. High efficiency in equipment use and transportation movements for higher profits at lower cost.

[1]See Appendix D for the different departments involved in construction projects.

Table 5.1: Table of organisational types, their role and interests.

Organisation:	Role:	Interests:
Waste processor	Provides the collection and disposal of waste streams originating from the construction project.	Efficient routing of vehicles for easy pick-up of waste.
Local companies	none	Continue their business and not be hindered by the construction works. They would like to be informed timely if the project poses problems for them to conduct their business as usual.
Local residents	none	As less hindrance and noise as possible, along with continued safety and livability. They also would like to know what is going to happen in their neighbourhood.

The network analysis is made to see which organisations should be involved in finding a solution to enhance coordination in construction logistics. Some of the organisations described in Table 5.1 are not central, or actively involved in construction projects. Figure 5.1 visualises the involvement of organisational types in construction processes. Those in the middle circle are active on a daily basis, the second circle indicates those with weekly involvements. The more towards the outer ring the less direct involvement with construction projects there is. From Figure 5.1 it can be seen that the local companies and local residents have no regular direct involvement in construction projects. Therefore these will be excluded from further analysis. The others are involved at least on a monthly or weekly basis.

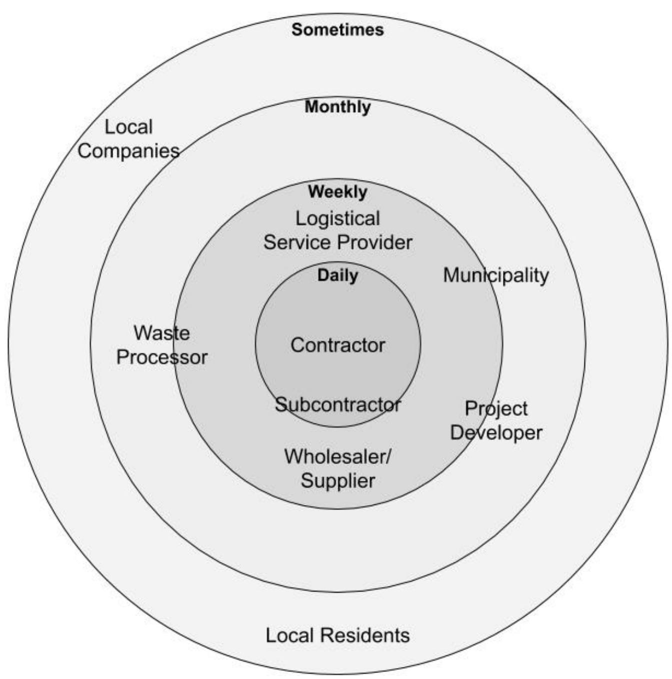

Figure 5.1: Organisations intensity of involvement in construction projects.

5.1.2 Stakeholder Interrelationships

The organisations, their role in the construction process and interests are known. It is however not known how these organisations relate to each other, and what issues they share. A stakeholder-issue interrelationship diagram can be used to visualise just that (Bryson, 2004). This diagram can be used to see which organisations operate in, or have knowledge about, *construction logistics*. In construction projects there are *leading* and following organisations, the leading organisations are those who can enable change in the environment or by direct control over the project. Another issue is *coordination*, not all organisations involved in construction logistics can enable coordination, and not all leading organisations have the knowledge to coordinate construction logistics. In the diagram the organisation boxes have a green fill where issues have a red one, relations are shown by edges. Normal edges denote a direct relationship, whereas the dashed edges denote a weak or indirect relationship.

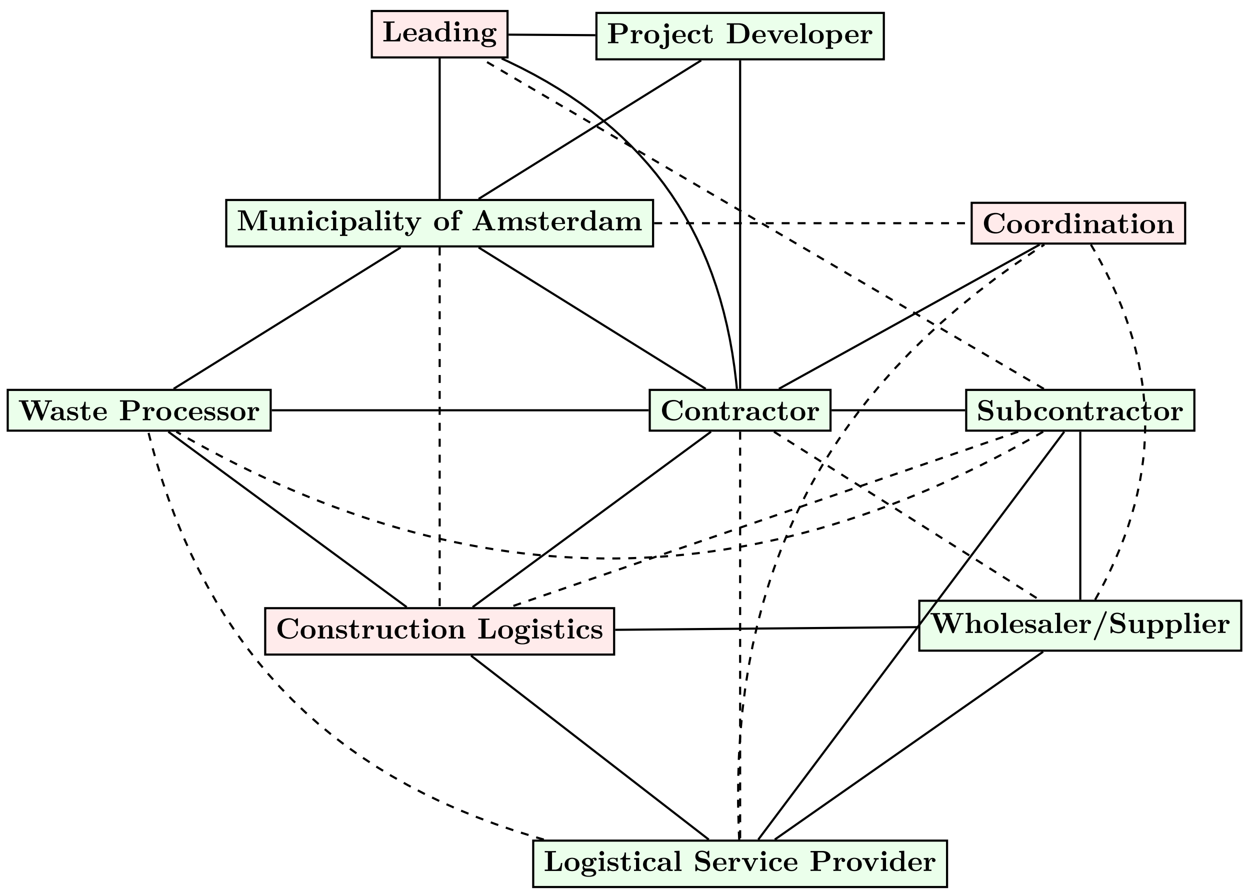

Figure 5.2: Stakeholder-issue interrelationship diagram.

The *leading* organisational types are; the project developer, as he provides the project plans which the others have to execute; the municipality, as they are the ones creating the tender and provide legislative context to which the project has to uphold; the contractor, as he is the one responsible for delivering the end result, and thus the focal point for those working on the project; and the subcontractor is somewhat leading as he orders his materials to be delivered at a certain time slot (in consultation with the contractor).

The contractor is the only stakeholder who has a direct link to *coordination*, as he knows most about the project at hand, has the power to set context and has direct relations with almost all organisations involved. The municipality is linked to coordination as they coordinate the redevelopment of areas. The municipality coordinates on a strategic level which takes decisions for several years into the future. In doing so the municipality coordinates the redevelopment of entire areas, instead of coordinating a project itself. The contractor coordinates the project by making decisions and consulting with other organisations. Both wholesaler/supplier and logistical service provider perform coordination in logistical activities. Their link is more weak as they only coordinate their own logistical activities, not those of others. Furthermore they get hired by different projects to do a certain number of transportation activities, which are not all logistical activities of one project.

The project developer is the only stakeholder not having a relation to *construction logistics*. He does not care about the order, routes, or other logistical issues, as long as the project is finished within budget, on time and in the agreed upon quality. The municipality sets conditions for the environment construction logistics takes place in, such as zone restrictions. The subcontractor also has a weak link with construction logistics as they do not carry out logistical activities apart from their own movements and ordering of material. All other organisations either carry out logistical activities or are involved in making the logistical schedules.

From the Stakeholder-issue interrelationship diagram. it can be seen that the contractor plays a central role as he has links with all issues and organisations. Furthermore it can be seen that both municipality and contractor are leading and involved in construction logistics. Therefore they are the key stakeholders in creating more coordination in the construction supply chain. Figure 5.2 shows that almost all organisations have a direct relationship with construction logistics, making it the central issue to be coordinated. It also shows how the organisations relate to each other, providing insight in the logistical system. Therefore it partly can be seen which organisations need to be coordinated in order to change the entire system. The other part is in knowing which organisations have the power to influence construction logistics processes, and if their interests in construction logistics are high enough to be willing to enact change. When the interests and power are known, a more elaborate answer in who should be involved in finding and implementing the solution can be found. An ideal tool to find the power and interests organisations have in construction logistics is a Power interest grids..

5.1.3 Power and Interests in Coordinating Construction Logistics

A power interest grid shows the interest an organisation has in a certain issue and the power it has to affect that issue (Bryson, 2004). Where power can be defined as the capacity to influence the behaviour of others so that they behaves in line with your wishes (Newell et al., 2009). The grid can be split into four quadrants (Bryson, 2004); *players* having both high interest and power; *subjects* having high interest but little power; *context setters* having high power but little interest; and *the crowd* having little interest and power. The players must be taken into account in order to address the issue at hand, as they have both power and interest. They are the organisations who can encourage others to follow, or if dissatisfied keep the issue from changing. The subjects need to be informed (Mind Tools, 2020) so their interest will not fade. They might not have the power to directly affect the issue, but could help with expertise in solving the issue. The context setters need to be satisfied (Mind Tools, 2020) in order to keep them from protesting, as they have the power to enact change but might not know what the issue exactly is.

From the Stakeholder-issue interrelationship diagram. it was found that the construction logistics is the central issue. Therefore construction logistics is taken as the subject in Figure 5.3a. The figure shows which organisations have the power and interest to help change issues in construction logistics. The second grid (Figure 5.3b) is made with a different issue in mind: coordinating logistics throughout the supply chain. This issue is chosen as it is the central theme of this thesis. By knowing the interests and power of the organisational types in supply chain coordination it can be found which can help in finding solutions and eventually implement them.

(a) Construction Logistics

(b) Supply Chain Coordination

Figure 5.3: Power interest grids.

Figure 5.3a shows the power and interests of the different organisational types in construction logistics. It can be seen that the logistics service providers (LSP) and wholesalers/suppliers have high interests and some power. Since they are the ones executing the logistical movements. The subcontractor has less power, he states the when, what, and where, but other than that he does not have power over logistics. The subcontractor, however, has less interest in how logistics is carried out as long as the right materials get delivered at the right time and place. The municipality has a bit more power than the other three power and has high interests as transportation moves through their city. The municipality poses several policy goals involving logistics within the city. Furthermore the municipality has legislative power which could change the context in which other organisations have to operate. Lastly the contractors have the most interest and power over construction logistics. They have both legitimate and information power[2], and therefore can coordinate the logistical processes. Furthermore their interests is high since they are the ones responsible for the completion of the project, and therefore are interested if all (including logistics) is on schedule and within budget.

Figure 5.3b shows the power and interests of the organisational types in supply chain coordination. When compared with Figure 5.3a it can be seen that almost all organisations have shifted. The project developer has become less powerful and less interested, as supply chain coordination has less direct effect on the project than logistics. A LSP is interested in coordination as it might effect the amount of work they have to carry out, while they might have less power over the change.

[2]Legitimate power is a formal authority accepted by others to control organisational resources (Newell et al., 2009). Information power refers to the access to valuable data, information, or knowledge (Newell et al., 2009).

Wholesalers/suppliers have not shifted as they are interested in how this coordination would take place, and have some power to make demands. The subcontractor is more interested in coordination as it might effect their preferred suppliers, material deliveries and planning. The municipality has less power over supply chain coordination as they can not influence organisations to share information or collaborate. They however are interested in more coordination as it poses benefits for the areas under construction. Contractors might be most interested and powerful in supply chain coordination. They have links to almost all organisations within the supply chain. Furthermore they have the power to pose demands which need to be met for those working on a project.

5.1.4 Section Conclusion

The network analysis was made using general organisational types typically involved in a construction project. The analysis was conducted to show which organisations have a relation with construction logistics. Furthermore the analysis should show which organisations have the interest in supply chain coordination and those having the power to make changes.

Figure 5.2 shows that almost all organisational types are involved in construction logistics. The figure also shows the relations between the organisations themselves. When the list of organisations involved in construction logistics is combined with Figure 5.3a it can be seen that only the waste processor is not considered a player. From Figure 5.3b it can be seen that there are four players when it comes to coordinating the supply chain: contractor, wholesaler/supplier, logistical service provider and municipality. These four are also players in construction logistics, and therefore need to be involved during the empirical research to aid in finding a solution to enhance coordination in construction logistics.

The four organisational types were interviewed to find answers to RQ3 and RQ4. A total of 13 semi-structured interviews were conducted, divided over found organisational types; five contractors, two logistical service providers, two wholesalers and four persons in three municipality departments. A list with names of the interviewed organisations along with their type is given in Table 5.2.

Table 5.2: Interviewed organisations.

Organisation:	**Organisational Type:**
BAM	Contractor
DeNijs	Contractor
Dura Vermeer	Contractor
Van Gelder	Contractor
Rutte Group	Contractor and Logistical Service Provider
Vrijbloed	Logistical Service Provider
Zoev City/PK Waterbouw	Logistical Service Provider
BMN	Wholesaler/Supplier
Van Keulen	Wholesaler/Supplier
Project Engineering Bureau (2x)	Municipality of Amsterdam
Mobility and Public Space	Municipality of Amsterdam
Traffic Management	Municipality of Amsterdam

5.2 Data Availability and Data Sharing

The interviewed organisations all have a wide variety of data available. This data partly resides in systems such as described in section 3.5. Some organisations started using these systems over four years ago while others started using them just recently. Through the conducted interviews it was found that there is a gap between systems described in literature and systems used by the interviewed organisations. The interviewed organisations differ in their preferences when it comes to information sharing. These preferences are discussed per organisation, along with the data available in systems used by organisations. Afterwards some observations about the willingness to share data are stated.

5.2.1 Contractor

The interviewed contractors stated they use the following systems: Kyp, BIM, GIS and Ilips. Data available in these and other systems is presented in Table 5.3. An elaboration of these systems contractors use is given in section E.1.

Table 5.3: Data available in ICT systems used by contractors.

System:	Data:
Kyp	Construction planning
	Construction order
BIM	2D or 3D Model
	Bill of materials
GIS	GPS data of the area
	Traffic information
	Route information & choice
	Risk management of transportation
	2D or 3D Model
	Track and trace of vehicles
Construction Ticket System	Planned arrival times
	Arrival of materials
Other	On site storage times of materials
	Typological characteristics
	CLP or BLVC
	Agreements made (including KPI's)
	Project delivery dates

Some of the contractors stated that information sharing is giving and taking, nothing is shared unless asked for. Another contractor states that they are open to share all information available on construction logistics with others, even if they are not working on the same projects. A third contractor tries to arrange up front information sharing between collaborating organisations. This way they try to share and gather as much information as possible before starting a project. They do so to make a more accurate planning, as they perceive the construction planning to be the most important information that can be shared.

5.2.2 Municipality of Amsterdam

The Municipality of Amsterdam uses several data collection and information systems. Some systems have a large open data pool while others are only available to municipality employees. Table 5.4 provides a summary of the data available in systems the municipality uses. More elaboration on the described systems can be found in section E.2.

Table 5.4: Data available in ICT systems used by the municipality.

System:	**Data:**
Data Point	Lots
MOCO	Real time traffic information
	Traffic model
CORA	Overview of construction projects
MobiMaestro	Real time traffic information per road piece
	Traffic light indication
	Traffic incident information
	Public lighting
	Bridge open/closed
	Weather information
Maps	Planned and current road works
	Incidents & duration
	Maximum speeds
	Signs (commandment and prohibitions)
	Control scenarios from traffic management centres
	Real time highway images
	Bridge open/closed
	Static and dynamic parking data
	Event date
	IVRI data (incl. topology)
	Zone restrictions
	Cycling data
	Preferred routes
	Electric vehicle loading points
	Parking areas
Other	City development plans (incl. hub placement, person responsible for area)
	Agreements (incl. KPI's)
	CLP or BLVC

The Municipality of Amsterdam has lots of information stored in their data point. Measurements and data updates are done when the data is required for a research project. This might result in less up-to-date data. Most of the information gathered by the municipality is already open for the public, and displayed in different maps. The municipality is open to more information sharing in order to make more accurate forecasts and to update key numbers more regularly.

5.2.3 Logistical Service Provider

The interviewed logistical service providers all used different systems. Therefore there is an overlap between the three, as they use their systems to reach similar goals. Table 5.5 provides a summary of the data available in systems logistical service providers use. More elaboration on the described systems can be found in section E.4.

Table 5.5: Data available in ICT systems used by logistical service providers.

System:	**Data:**
Own	Planned delivery times
	Duration of transport
	Transported materials (incl properties)
	Transport Planning
GPS Buddy	Track & Trace of equipment
	Route planning
	Monitoring of daily planning
	Transport planning
OutSmart	Invoices
	Track & Trace of equipment
	Transport Planning
Other	Preferred route
	Route information
	Estimated time of delivery
	Duration of transport
	Loading times
	Transportation cost
	Vehicle properties (incl load factor)
	Transported materials (incl properties)

One of the interviewed logistical service providers stated that all transportation companies collaborate with each other on a certain level. For instance if one needs extra equipment than it can be arranged. This logistical service provider tries to enhance efficient use of equipment by using one truck for several projects, at least when possible. This same organisation did not see a reason to change construction logistics as they fear loss of business. Another logistical service provider was open to share all information and data they have, as change requires openness of information. They would only withhold privacy data and data threatening their business model or investments.

5.2.4 Wholesaler/Supplier

Wholesalers/suppliers make use of warehouse management systems, such as SAP. The two interviewed wholesalers also have vehicles of their own making it possible to arrange transportation of the ordered products. Table 5.6 provides a summary of the data available in systems wholesalers/-suppliers use. More elaboration on the systems presented in the table can be found in section E.3.

Table 5.6: Data available in ICT systems used by wholesalers/suppliers.

System:	Data:
SAP	Material properties
	Materials in stock
	Lead time
Other	Point of destination
	Planned time of arrival
	Invoice
	Material cost
	Transportation cost
	Route information

The interviewed wholesalers/suppliers would like to see more coordination within the chain. When asked about sharing information both organisations stated to already share all relevant information with collaborating organisations. They were not willing to share the split between material price and transportation cost.

5.2.5 Other Information Providers

There are several other organisations that could provide data, which were not interviewed. The information was provided while conducting interviews with other organisations. The three other information sources are summarised in Table 5.7. More elaboration on the described systems can be found in section E.5. These organisations have not been interviewed. Therefore nothing can be said about their willingness to share data.

Table 5.7: Data available in ICT systems used by other organisations.

System:	Data:
Subcontractor	Capabilities personnel
	Required personnel
	Material required
	Estimated time to complete their work
Weather	Current conditions
	Forecasts
Event	Date
	Duration
	Location
	Expected increase in traffic

5.2.6 Observations About Data Sharing

First of all it was found that several organisations throughout the supply chain stated that it is not wise to keep all cards against your chest, especially when collaboration is desired. These organisations were more willing to share information in regards to construction logistics, although several organisations did not want to share all of their information.

In general it was observed that all interviewed organisations stated they are willing to share almost all information concerning construction logistics with third parties. In these same interviews some organisations were less willing to state what all this information exactly is, or withheld information regarding their business model. This was found through comparing answers, from what one organisation stated they desired to receive and what another stated they were willing to share. When asked about this information gap some stated that sharing the information would be an ideal case for the entire chain, however not desired. Almost all organisations had a counter argument why full information sharing would not be desirable, which mainly came down to loss of competitive position or business case. They, however, all shared the same idea that in an theoretically ideal situation information is shared freely with all organisations involved in a project. From this observation it could be said that the construction industry is slowly opening up to more information sharing than is strictly required.

A third observation is that the information sharing and integration of data should be coordinated and facilitated. When something new is being tried in the construction industry it should be either proven or demanded, which can be assigned to the conservative nature of the industry. The interviewed organisations stated that the coordination or facilitation should be provided by an independent, reliable, neutral organisation with a sense of business. They furthermore stated that in case of a platform, it should be open for the entire chain.

5.3 Vision of a Construction Logistics Control Tower

The second part of the interviews focused on a control tower, and started with the perception or vision of a construction logistics control tower. The interviewed organisations all had their own visions of a control tower. These will be discussed per organisation and afterwards concluded on.

5.3.1 Contractors

Several contractors envisioned a control tower as a module based system. One of them thought it to be something shown on a screen while other thought of it as a physical place. One contractor stated that a control tower should be open source, used by all that desire to use it. Not all information should however be visible for all users, which is in line with this idea of a modular system. All contractors talked about the importance of data and data sharing, not just their own but from all organisations involved. There were different ideas about when and how a control tower should be used. Some contractors thought a control tower to be a resource within a firm, overseeing all of their own projects. Some thought a control tower to be most useful in coordinating several projects, or even all projects within one region. One of the contractors had the following explanation of his vision of a control tower. The construction industry is a production (make-to-order) industry and revolves around the construction of a project. The focus does not lie on the entire supply chain. Therefore a control tower should focus on coordinating the supply chain in such a way that it facilitates the projects to run as smoothly as possible.

5.3.2 Municipality of Amsterdam

The municipality of Amsterdam envisions a control tower as a combination of a digital environment and persons making scenarios and calculations. The persons are in close contact with contractors and have the control to take actions when needed. In their vision a control tower should mostly be used to manage and predict traffic flows. The municipality employees thought a control tower to be most useful for large scale developments, not for individual projects.

5.3.3 Logistical Service Providers

Logistical service providers had various visions of a control tower. One of them thought it to be designed to enhance environmental performance and not to enhance efficiency. This organisation did not see a control tower work, as logistical coordination is best done by organisations specialised in a specific logistical field. Another logistical service provider envisioned a control tower as a hierarchical organisation, with at the top level persons coordinating strategic decisions and at the bottom those executing the work. In this vision a control tower coordinates all projects on a city wide level. It therefore coordinates all project related schedules and thus also logistics. A last logistical service provider envisioned a control tower as a central node that coordinates logistics for multiple projects across multiple organisations. The coordination should be focused on maximising logistical efficiency.

5.3.4 Wholesalers/Suppliers

The wholesalers/suppliers agreed that a control tower should be used for multiple, preferably large, construction projects. They did not agree about the form it should take, one of them thought it to be a platform providing an overview of real time logistics. Another wholesaler thought a control tower to be a combination of a cloud based application and human operators, where it should be used as point of contact for the entire chain. Therefore it communicates with all relevant organisations what the best options are.

5.3.5 Section Conclusion

The interviewed organisations all have their own visions of a control tower. Most organisations envisioned a control tower as a central node to coordinate multiple, or at least large scale, construction projects. This could be done either by a platform, application or a combination of human operators and ICT systems. All interviewed organisations posed requirements for their vision of a control tower. These requirements are stated in the following subsection.

5.4 General Requirements from Stakeholders

The requirements given in the interviews are an addition to those found in the literature (section 4.2). The following general requirements for a construction logistics control tower came to light during the conducted interviews. The requirements have not been presented per organisational type as they all stated similar requirements.

The first requirement focuses on what a control tower should do, a control tower should provide insight into costs throughout the entire supply chain. Currently the tender offers do not provide a perfect split into all expenses made, making it hard for contractors to see what the actual costs are. A second requirement is about visibility, project plans should be accessible for the public to a certain extent. The degree of accessibility should be made variable in such a way that organisations not working on a project could still get relevant information. Furthermore it should be ensured that organisations working on the project get all information required to execute their jobs as good as possible. Thirdly the control tower should be compatible with all sorts of ICT systems. This should allow for all organisations to use a control tower without difficulties in for instance data formatting. Another requirement is the ease of use, a steep learning curve will result in lower usage. The fifth requirement is about integrity of data, the control tower must comply with the general data protection regulation (GDPR). This does not only encompasses safe and secure data storage and access, but also deletion of data on request. Furthermore the data must not be sold to third parties, or shared with random organisations. This requirement can be translated to a safe and secure system. A sixth requirement is that is provides timely information of high quality. Timely depends on the functionality as some information must be shared more than 24 hours before a process starts, while other information can be shared just one hour in advance. The provided information must also be of high quality. If the information is not correct, the models will not be correct. This will result in lower use as the perceived added value decreases. Finally the control tower should be impartial and neutral, it should not have preferences over one company compared to another.

The general requirements for a construction logistics control tower provided by the interviewed organisations can be summarised as:

- Provide insight in cost
- Publicly accessible to a certain extent
- Compatible with all sorts of ICT systems
- Ease of use (and access)
- Safe and secure system (Compliance with GDPR)
- Provides timely and correct information (reliable)
- Impartial facilitator
- Neutral facilitator
- Guardian of rules and agreements

Requirements can also be derived from the visions organisations have of a control tower, as presented in section 5.3. Contractors, for instance, envisioned a control tower to be modular. Therefore modularity is considered as a requirement. Another requirement from contractors is that a control tower should allow for data exchange. The municipality envisioned a control tower to manage the traffic flows, which could be a requirement for potential functionalities. The wholesalers envisioned that a control tower should be a point of contact for the entire supply chain. This can be translated into that a control tower should be open for all organisations in the supply chain. The logistical service providers added the requirement that a control tower should focus on maximising logistical efficiency. At the end of section 5.3 it was found that a control tower was envisioned to coordinate multiple or at least large scale construction projects. This could be seen as a requirements of the capabilities of a control tower.

These requirements are summarised by the following list:

- Modularity
- Allow for data exchange
- Manage traffic flow
- Open for all organisations in the supply chain
- Maximise logistical efficiency
- Coordinate multiple or at least large scale construction projects

5.5 General Functionalities from Stakeholders

During the interviews organisations were asked what a control tower should be able to do. These functionalities are presented in a single list as different organisations provided similar answers. There is an overlap of functionalities described in the literature (section 4.3) and those stated by the interviewed organisations. These overlapping functionalities are *italicised*. The functionalities provided by the interviewed organisations are listed using the same categories as the earlier presented functionalities, and with the same annotations: (O) for operational, (T) for tactical, and (S) for strategic.

- Planning and routing:
  - *Real time estimated time of arrival (O)*
  - *Making of integral planning (T)*
  - *Waste/Return transportation schedule (T/O)*
  - What moves where at what time, in which amounts (T/O)
  - *Transportation time window planning (T/O)*
  - *Consolidation planning (T/O)*
- Information hubs:
  - *Process monitoring (O)*
  - *Forecasting and scenario calculation (S/T/O)*
  - Vehicle information (S/T/O)
  - Material properties (S/T/O)
  - *Project information (S/T/O) (construction and logistical planning, costs, load factors, etc.)*
  - Area information (S)
  - Costs of processes (S/T)
  - *Preferred route information (S/T)*
  - *Digital twin (S)*
  - Site layout and management (S/T/O)
- Decision making:
  - Balance supply and demand of materials and equipment between projects (S/T)
  - Aligning projects with each other (S/T)
  - Apply for permits and exemption papers, e.g. zone entry or (un)loading (T/O)
  - *Warning/Alarm messages (O)*
  - Procurement of strategic locations (S)
  - *Event management (T/O)*

5.6 Stakeholders Willingness to Use a Control Tower

The interviewed organisations can be considered as intended users. Therefore organisations were asked about their willingness to use a control tower with the previously described visions, requirements and functionalities in mind. If they were not willing to use a control tower it was asked why and if adaptions could be made to increase their willingness to use. The answers are given per organisational type, followed by a conclusion.

5.6.1 Contractors

Out of all interviewed organisations contractors were the most positive about the idea of a control tower, especially on the tactical and operational level. The interviewed contractors had a clear idea of what a control tower is and what it should be used for. In general the contractors were open to the idea of a control tower. Some would like to use it within their own organisations while others thought it to be a feasible idea to coordinate multiple projects of multiple organisations.

Some contractors stated that a control tower currently is not value adding due to the nature of the construction industry. This has to do with contracting and liability over logistics at the wholesaler/supplier. Others perceive it to be value adding since they can acquire more information, resulting in more efficient processes with a lower impact on the environment.

5.6.2 Logistical Service Providers

One logistical service provider thought a control tower would not be beneficial for them. They already plan their processes quite efficiently and their equipment is used for multiple projects during the same time period. They furthermore stated that each market has its own specialisation and therefore should not be coordinated by another market that does not have the proper capabilities. Another logistical service provider was quite open to the idea of centrally coordinated logistics. This logistical service provider thought a control tower would add most value on the strategic level.

5.6.3 Municipality of Amsterdam

Three different departments of the municipality have been interviewed. These three departments all had a somewhat similar idea about what a control tower is and what it could be used for.

Road managers were willing to use a control tower to gather information regarding traffic intensity and vehicle specifics, such as load factor, emission class and weight. Almost all data gathered by the road managers should be open for public use. Exceptions are only made when there is proper cause for not sharing.

Mobility and Public Space department of the municipality sees most benefit in the tactical and strategic levels of a control tower. They would be willing to use a control tower for several things such as updating key numbers and ensuring mobility. In their opinion a control tower should not be just an IT solution, but combined with gatherings of relevant organisations to discuss key topics. These topics help to regain focus, share information and discuss problems.

Project Engineering Bureau sees a role in a control tower for all organisations involved in construction projects. The municipality could benefit from monitoring logistical processes and if agreements are met. The monitoring of logistics can be used to see if policy goals are achieved or if adjustments are in order.

5.6.4 Wholesalers/Suppliers

The interviewed wholesalers/suppliers thought a control tower to be beneficial for the construction supply chain. One saw potential to get material demand earlier than currently is considered normal. Another saw potential to reduce the number of transport movements. Both were hesitant about horizontal collaboration as this would result in loss of competitive position. One of them stated that when they arrange transportation at least 70% of the load must be theirs before considering consolidation. If the load factor would be less then a logistical service provider should be contacted.

The interviewed wholesalers/suppliers stated that logistical coordination is based on customisation. One said it therefore should be done manually, while the other thought a control tower could be used as a tool to aid them.

5.6.5 Section Conclusion

Contractors were most positive about the idea of a control tower. It seemed that most of them were willing to use a control tower in the future. The interviewed logistical service providers differ too much in vision about a control tower to give a statement about their willingness to use. Wholesalers/suppliers see a role for a control tower within the supply chain in coordination of logistics. Whether they want to play a role in it depends on the organisation. The municipality sees benefit in a control tower, and would use it as a monitoring and strategic decision making tool.

In general it seems that there is some hesitation in using a control tower. This is mainly caused by uncertainty about the concept of control towers and what it could do for the organisation itself and for logistical coordination in general. Most interviewed organisations were positive about the potential of a control tower. It, however, seems that further developments are required before organisations are fully willing to use a control tower. For now more information about data requirements, functionalities and further design and implementation are required.

5.7 Potential Facilitators Proposed by Stakeholders

During the conducted interviews certain qualifications for a facilitator were given. The facilitator should not have preferences over users or projects that are in- or excluded without having grounded reasons. The facilitator should have a sense of business, not just about the control tower but more importantly about construction logistics as this is the field a control tower operates in. Without sense of business it is harder to negotiate with users about functionalities and data requirements. Collaborating organisations should therefore trust the capabilities of the facilitator. There were four potential facilitators mentioned by the interviewed organisations: contractor, municipality, wholesaler and A new organisation. These four potential facilitators are discussed in the same order, after which a conclusion is given.

5.7.1 Contractor

The contractor was mentioned most frequently as potential facilitator of a control tower. They were, however, seen unfit by some of the interviewed organisations as they are perceived to be most concerned with their own projects. Therefore a control tower facilitated by a contractor might result in enhanced coordination for their own projects. Although this could pose benefits for construction logistics, it is not in line with the definition of a control tower provided in subsection 4.1.1, where a control tower was defined to focus on an area, not the projects of a single organisations. Contractors were seen fit to facilitate a control tower as they are the focal organisation for a construction project. Furthermore contractors have contact with organisations throughout the supply chain, and therefore could be able to coordinate them all. Finally, in the network analysis (section 5.1) it was found that contractors have the power to influence construction supply chains and construction logistics.

5.7.2 Municipality of Amsterdam

The Municipality of Amsterdam is perceived to be a key player influencing operational context. The municipality was, however, seen unfit to be the facilitator in a control tower by some of the interviewed organisations. The main reason is that they are perceived to lack knowledge about construction logistics processes. The municipality was seen fit as they have power to make demands about the operating context in the form of tenders, policy and perhaps legislation. Interviewed organisations stated that the municipality should make the use of a control tower beneficial. However, it was also stated that obligation to use a control tower would not be desirable. The benefits should not only consist of financial support in the set-up of a control tower, but also in tender procedures. Lastly the municipality could be a facilitator as they have contact with most organisations involved in multiple projects, and therefore are perceived as central stakeholder.

5.7.3 Wholesaler

Wholesalers could be a third option for facilitation of a control tower. In the current supply chain wholesalers arrange transportation for part of their own products, and have an overview of the material needs for several projects. They, however, do not have the complete overview since multiple wholesaler are involved in a single construction project. Wholesalers furthermore demand that, when they arrange transportation, at least 70% of goods transported needs to be their own. Nevertheless they can be a good option as they have knowledge about material requirements and logistical planning. Furthermore wholesalers have relationships with multiple organisations within the supply chain. Using the same line of reasoning a logistical service provider could therefore also facilitate a control tower. The advantage is that logistical service providers do not demand a percentage of goods from one specific wholesaler. Both wholesaler and logistical service provider have the disadvantage that they are not neutral, and might be considered as dependent. Their expertise lies with materials and transportation not with the on site construction process. Therefore they might lack the knowledge to facilitate construction related functionalities of a control tower.

5.7.4 New Organisation

There could be a fourth option, a new organisation purely dedicated to the control tower itself. This new organisation has no previous involvement with other organisations, which is both a benefit and downside. The benefit is that it is neutral as it does not have previous bad experiences. The downside is that there it is new and therefore not yet proven to be trustworthy. This new organisation could be composed in such a way that it meets all previously mentioned requirements. The formation could even be negotiated with several organisations involved in multiple projects throughout the operational area. The only question then is; What are the area boundaries the control tower will operate in? Depending on the area other stakeholders need to be involved as different projects are undertaken.

5.7.5 Section Conclusion

During the interviews no clear preference was stated over one of the four potential facilitators. The wholesaler was only mentioned once, while others were mentioned multiple times. There was doubt by the interviewed organisations if they are the right fit to facilitate a control tower on their own. Depending on the person asked benefits and downsides were given for certain options. All did agree that the facilitator should be neutral and independent. From this perspective a new organisation might be the best fit. A new organisation does, however, have downsides as trust needs to be build and competence needs to be shown.

A clear vision and definition shared by all stakeholders is required before the facilitating role should be chosen. Without this shared vision and definition, all stakeholders will have different ideas about a control tower and therefore different ideas about facilitation.

5.8 Chapter Conclusion

The chapter discussed the data availability of organisations involved in a control tower (section 5.2). The four organisations found in the conducted Construction Project Network Analysis were elaborated on more extensively than others. It was found that there is a wide variety of information available. Some of the information resides in multiple organisations, some information is open source and other parts of the available information reside in a singular organisation and is not open. Furthermore, it was found that the interviewed organisations only recently started using information and coordination systems, which differ per organisation. The organisations with higher maturity of ICT are incorporating more and more into one central system. It was stated that the logistical planning is most difficult to incorporate in this central system.

Section 5.2 furthermore elaborated on the willingness to share data. It was concluded that most interviewed organisations were willing to share data. What organisations wanted to share differed greatly, as some were open to share all data, and others the bare minimum. In general it was found that the construction industry is slowly opening up to share more and more data with its partners.

Later sections focused on the concept of control towers. The interviewed organisations all have their own visions about a control tower (see section 5.3). Most organisations envisioned a control tower as a central node to coordinate multiple, or at least large scale, construction projects. This central node could either be in the cloud or a physical place. The found requirements from interviews, as elaborated on in section 5.4, can be summarised in the following sentence; A control tower should be impartial, neutral, reliable, safe and secure, publicly accessible to a certain extent, while allowing for ease of use and access by its users. The requirements were followed by a list of functionalities (see section 5.5), of which some were also found in literature.

In section 5.6 it was found that the interviewed organisations were seemingly willing to use a control tower. For now a control tower is too conceptual that it is not perceived as value adding by most organisations. Further developments in the direction of data requirements, functionalities and implementation are required before a more clear answer can be given on willingness to use. The implementation also depends on the facilitating organisation. It was found in section 5.7 that there are four potential facilitators, all having benefits and downsides: contractor, municipality, wholesaler, or a new organisation. There was a slight preference for a new organisation as it is perceived most neutral and independent. First a shared vision and definition amongst stakeholders is required before a more strong advice can be given.

A functional design could aid to create a shared vision and definition. Furthermore this design could make it more clear what a control tower encompasses and what value it could add.

Chapter 6: Functional Design of a Construction Logistics Control Tower

In section 4.5 it was found that there a functional design of a control tower is not yet described within the literature. A functional design aids in gaining a more clear vision of a control tower, and its value, which is required following section 5.8. This chapter focuses on making and evaluating this functional design, which corresponds to the following research objectives: *Making a functional design for a construction logistics control tower for city development.* and *Evaluating the proposed functional design.* These objectives are met by discussing information gathered from the literature (chapter 3 and chapter 4) and information found during the conducted interviews (chapter 5).

The first step in making a functional design is finding the requirements for a construction logistical control tower and its design (section 6.1). A second step is making a list of functionalities a control tower should have (section 6.2). Afterwards data requirements for these functionalities are found (section 6.3). The required data needs to be provided by a range of sources and organisations, which already were found in section 5.2. The design is made following these two steps, afterwards it is shown in section 6.4, followed by a proof of concept (section 6.5). Then the proposed design is reflected on in section 6.6. Finally conclusions drawn from this chapter are presented (section 6.7).

6.1 In- and Excluded Requirements

Requirements for a control tower and the functional design can be found in five sections of this thesis report. The general requirements for a control tower from the literature have been discussed in section 4.2 and those from interviewed organisations in section 5.4. Additional requirements can be formulated from the definition and purpose section (section 4.1). The designs described in literature (section 4.4) hold requirements as well. Finally the visions for a control tower by stakeholders (section 5.3) contributed to the list.

First the requirements for the development of the design are elaborated on. Requirements that are not considered further are discussed afterwards. All requirements are provided with the section number from which they originate.

6.1.1 Included Requirements

The included requirements can be divided into functional requirements, and design requirements. An elaboration on the choices is given after the requirements are presented. Those excluded are elaborated on in the next subsection.

Functional requirements focus on what a control tower should do, and are summarised in the following list:

1. Can be used as hub for visibility, decision-making and action (section 4.1)
2. Facilitates network coordination (section 4.1)
3. Coordinates multiple, or at least large scale, construction projects (section 4.1 and section 5.3)
4. Monitors, plans and coordinates logistical processes (section 4.1)
5. Incorporates construction and transportation planning (section 4.1)

6. Facilitates logistical management (section 4.1)
7. Reduces transportation movements (section 4.1)
8. Allows for data storage (section 4.1)
9. Allows for data exchange (section 4.1 and section 5.3)
10. Guardian of rules and agreements (section 5.4)
11. Has a wide range of functionalities (section 4.2)
12. Manages traffic flow (section 5.3)
13. Maximises logistical efficiency (section 5.3)
14. Provides insight into costs (section 5.4)

All requirements found in section 4.1 Introduction to Construction Logistics Control Towers have been included in the list. These requirements must be met as they follow directly from the definition and purpose of a construction logistics control tower, if these requirements are not met then it is not a control tower. Requirement ten is included as a control tower has knowledge of most processes within a project and the made agreements. Therefore it should be able to guard the rules and agreements. Requirement eleven is included as a control tower with few functionalities poses less benefits to the supply chain, and therefore would be used less. Requirement twelve is considered as a construction logistics control tower should be able to manage at least all traffic induced by construction logistics. Related to this is the ability to maximise logistical efficiency as the control tower is focused on construction logistics. The decisions and actions made by a control tower should maximise the efficiency of construction logistical processes. Several of the interviewed organisations stated that they would like to receive more insight into the costs of logistical processes. Since this was mentioned more than twice it is included as a requirement.

Design requirements are the non functional requirements that should be met by the design.

1. Integrates information and data sources (section 4.2 and section 5.4)
2. Accommodates varying degrees of IT sophistication (section 4.2 and section 5.4)
3. Is modular (section 4.2 and section 5.3)
4. Open for all organisations in the supply chain (subsection 4.4.1 and section 5.3)
5. Open for external organisations and the public (section 5.4)
6. Allows for changes in data suppliers and customers (section 4.2)
7. Functionalities divided into strategic, tactical and operational level (subsection 4.4.3)
8. Split between service provider and customer (subsection 4.4.2)
9. Split between data providers and to be controlled organisations (subsection 4.4.1)

Functionalities rely on data from different information and data sources, which therefore should be able to be integrated. It should not matter what degree of IT sophistication these sources have, as long as relevant information can be subtracted. During the conducted interviews it was found that all organisations desire different functionalities and information from a control tower, therefore it should be modular. A control tower should not be designed to aid one specific type of organisation, therefore it should be open to all organisations in the supply chain. It should furthermore be open for external organisations and the public as these could both gain and provide valuable information. Including these groups could reduce perceived nuisance as they are aware before it occurs. The last four requirements are found through the known designs, and are included as they provide a basis on which can be build to an integral design.

6.1.2 Excluded Requirements

Certain requirements have been presented during the thesis that are not included. These requirements are:

1. Low costs of operation and set-up (section 4.2)
2. Easy to use (section 4.2 and section 5.4)
3. Easy to integrate in current business (section 4.2)
4. Delivers timely and correct information (section 5.4)
5. Comply with GDPR (section 5.4)
6. Impartial facilitator (section 5.4)
7. Neutral facilitator (section 5.4)

The first requirement is not considered as it does not have an influence on the design, but on how a control tower is set-up and used. The second and third requirement also depends on the operational phase. The delivery of timely and correct information has to do with the technical design aspects, rather than the functional design aspects. Compliance with GDPR is mandatory, this requirement applies for the technical design, not the functional design. The sixth and seventh requirements are for a facilitator, which should be used in implementation and facilitation, not during the functional design phase.

6.2 Minimal and Desired Functionalities

The functional design visualises the functionalities a control tower should have. Therefore it needs to be known which functionalities should be included in the design. Functionalities found in the literature are discussed in section 4.3, and those given during interviews in section 5.5. From these two a list of minimal and desired functionalities can be derived. The functionalities only having strategic purpose are left out, as they are outside of the thesis scope. The functionalities are presented in the following list, with an indication in which section they originate from. Functionalities originating from both sections have been *italicised*.

- Planning and routing:
  - *In- and outbound logistics, including waste transportation (T/O)*
  - *Real time monitoring/tracking, including estimated time of arrival (O)*
  - *Horizontal transport planning (T)*
  - *Planning of delivery time windows (T/O)*
  - *Consolidation planning (T/O)*
  - *Construction planning (S/T)*
  - Vertical transport planning (e.g. crane planning) (T/O) (section 4.3)
  - What moves where at what time, in which amounts (T/O) (section 5.5)
- Information hubs:
  - *Preferred route information (S/T)*
  - *Process and performance monitoring (O)*
  - *Forecasting and scenario calculation (S/T)*
  - *Digital twin (S/T/O)*
  - Collaborative information sharing (S/T/O) (section 4.3)
  - Relation between construction and logistical schedules (T/O) (section 4.3)
  - End-to-end visibility (S/T/O) (section 4.3)

  - Inventory management (O) (section 4.3)
  - Vehicle information (S/T/O) (section 5.5)
  - Material properties (S/T/O) (section 5.5)
  - Area information (S) (section 5.5)
  - Costs of processes (S/T) (section 5.5)
  - Site layout and management (S/T/O) (section 5.5)
- Decision making:
  - *Event management (T/O)*
  - *Self corrective actions and warnings (T/O)*
  - Auditing and reporting (T) (section 4.3)
  - Creating and sending of invoices (T/O) (section 4.3)
  - Balance supply and demand of materials and equipment between projects (S/T) (section 5.5)
  - Aligning projects with each other (S/T) (section 5.5)
  - Apply for permits and exemption papers, e.g. zone entry or (un)loading (T/O) (section 5.5)

All functionalities mentioned by both literature and interviews are incorporated in the minimal set of functionalities, as these are important from both perspectives. Further decisions on including or excluding functionalities are elaborated on the following subsections. These decisions are based on the BMC (Figure 4.3) and other characteristics provided in section 4.1 and section 5.3. A visualisation of the minimal and desirable functionalities is given in Figure 6.1. The coloured functionalities represent the minimal set and the black ones represent the desirable or extra functionalities.

6.2.1 Planning and Routing

All potential functionalities from the planning and routing category have been incorporated either as minimal or as desirable functionality. The planning and routing functionalities concern what moves where at what time and in which amounts. The first functionalities therefore are horizontal and vertical transport planning. In order to make these the construction planning is required along with in- and outbound logistics, waste removal, preferred route planning and planning of delivery time windows. Adaptions to the transport planning can be made using real time monitoring, or tracking, of equipment.

A *desirable* functionality could be the incorporation of the consolidation planning. This consolidation could first be done for one project, which is quite desirable. When consolidation is achieved for multiple projects within one region, it could have major benefits for all parties involved. It would, however, mean adjustments in scheduling construction activities over all projects so that logistics could be optimised.

6.2.2 Information Hub

A control tower also functions as a hub where information is stored, shared and analysed. An example of this information is the bill of materials. One of the minimal functionalities is monitoring of processes, such as construction activities and deliveries. The monitored processes can relate to the KPI's or other agreements made before starting a project. The relation between construction

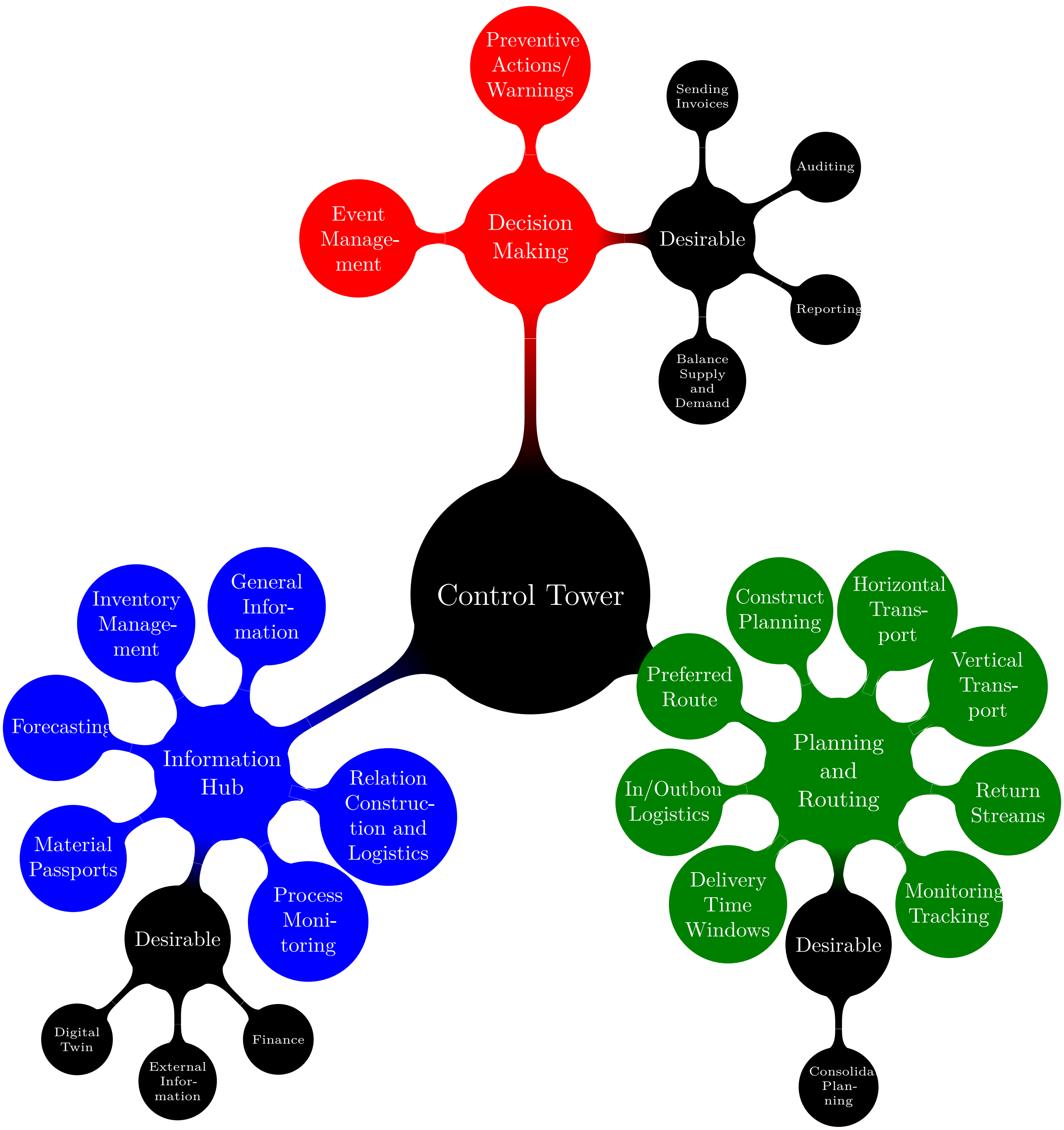

Figure 6.1: Functionalities per Category

and logistical planning, along with changes will also displayed. Furthermore using analytics these schedules can be adjusted accordingly when required. The control tower also needs some sort of forecasting abilities to see whether adjustments are desired. To make forecasts more data is needed than already described above. For transport monitoring traffic information is needed, and weather information might be useful for construction processes. Another informational function has to do with inventory as it needs to be known if all materials required to continue working are on site, on route or delayed. The last functionality regarding information is the material passport of the to be removed materials and the construction project. All projects start by either demolition or other sorts of site preparation. When it is known what is already there it might be reused in other projects, instead of demolished to be used as landfill.

A *desirable* functionality for the information hub is more collaborative information sharing. The above functionalities are mostly focused on logistics. There, however, resides more information inside companies besides their logistical activities and construction planning. Examples of this information are vehicle properties and area restrictions. Furthermore a control tower would become more effective when information is shared with other organisations operating in the same area on different projects. A second additional functionality is incorporating finances so that visibility can be increased. These finances include the costs of processes. Finally a digital twin can be desirable as it helps to calculate and forecast scenarios more accurately.

Not included in both sets is end-to-end visibility as it can be considered a goal, not a specific functionality. Functionalities can be used to achieve goals, but are not considered as goals on their own. Another functionality this is not included is the site layout and management. The site layout is already included in the inventory management, as this requires to known what is stored where. Therefore a separate functionality would be redundant. Site management consists of more than just inventory management, as it also includes site safety and other arrangements. Site management is location specific and can not be combined with other sites, therefore site management could be better carried out by personnel on site instead of by a control tower.

6.2.3 Decision Making

The last category of functionalities is decision making. Some decisions are already mentioned such as adapting the construction and logistical planning in specific cases. This can also be described as event management, reacting accordingly to deviations by using predictive and prescriptive analytics. The event management can result in two types of decisions: autonomous preventive actions or warning signals. The warning signals are send when the control tower analyses the data and sees that a deviation is going to occur. This message is send to the organisation responsible to resolve the deviation, it is accompanied with all relevant information and might include a suggested correction. The autonomous preventive action can be done instead of sending a warning signal. The system itself resolves the issue and notifies the involved organisations accordingly.

Desirable decision making functionalities could be the sending of invoices, at least when finances are incorporated. In the same line of work auditing and reporting could be incorporated. Another type of decision making is the balancing of supply and demand between projects. This could for instance be supplying demolished or residual materials to meet the demand of other projects in the region. It is however not included as it requires more information than gathered during this thesis.

Functionalities that are *not included* are: aligning projects with each other, and applying for permits and exemption papers. The alignment of projects is not taken as a separate functionality as it results from other functionalities. For instance if the horizontal transportation schedule for multiple projects is made, then they could be aligned to maximise logistical efficiency. Therefore it could be considered a secondary functionality resulting from executing the minimal functionalities. Applying for permits and exemption papers is not included as the focus in this thesis lies on construction logistics instead of implications or processes to ensure a vehicle is allowed to make a delivery. If a control tower becomes operational and is going to arrange logistics, then it could be desirable to let the control tower arrange the paperwork as well.

6.2.4 Meeting Requirements

The presented functionalities should meet the requirements posed in section 6.1 before they are incorporated in the functional design. The design requirements will not be taken into account as these do not pose requirements for the functionalities themselves. The functional requirements will be discussed individually.

The functionalities are split-up in different categories, of which decision making is one (requirement 1). The others provide visibility on several aspects such as inventory and other information, planning and routing. Network coordination (requirement 2) is facilitated through event management, transportation planning and return streams. Further network coordination depends on the governance model and potential additional functionalities. The third requirement depends on the kinds of projects incorporated in the control tower, not on the functionalities it has. The requirement can therefore be met during implementation and use, not while making a functional design. There could be some discussion about the wide range of functionalities (requirement 11) as there are three general categories. However, these categories have a total of 16 different functionalities. The first category, planning and routing, satisfies the fourth (monitors, plans and coordinates logistical processes), fifth (incorporates construction and transportation planning), sixth (facilitates logistical management) and twelfth (manages traffic flow) requirement, as these requirements have all been translated into multiple functionalities. The functionalities do not directly show if there would be a reduction of transportation movements (requirement 7). The minimal functionalities allow for data storage (requirement 8) as forecasts can not be made without stored data. Data exchange is required to gather the information enabling the functionalities, and to provide the output of these functionalities to the users. Therefore requirement 9 is met. The guardian of rules and agreements (requirement 10) is not immediately clear by the functionalities displayed, as rules and agreements are not necessarily taken into consideration. Therefore this requirement should be discussed further in subsection 6.6.1. The maximisation of logistical efficiency (requirement 13) depends on the capabilities of the software systems used or the personnel hired in the control tower. The insight in cost (requirement 14) have not been provided in the functionalities, but could result from the data provided and should therefore be discussed further in subsection 6.6.1.

The minimal set of functionalities meets most of the posed requirements. Requirement 3, 7 and 13 depend on implementation and use of a control tower. Requirement 10 and 14 should be discussed after the design is proposed, as these depend on more on the design than the minimal functionalities.

6.3 Desired Data per Functionality

The minimal set of functionalities defined in section 6.2 are elaborated on further in this section. The elaboration is given per functionality along with the data requirements to enable the functionality. First planning and routing functionalities are discussed (subsection 6.3.1), followed by information hub (subsection 6.3.2), ending with decision making (subsection 6.3.3).

6.3.1 Planning and Routing

Construction projects require planning and routing to make logistics more efficient. The following functionalities placed in the planning and routing category are presented in Figure 6.2, and elaborated on per functionality.

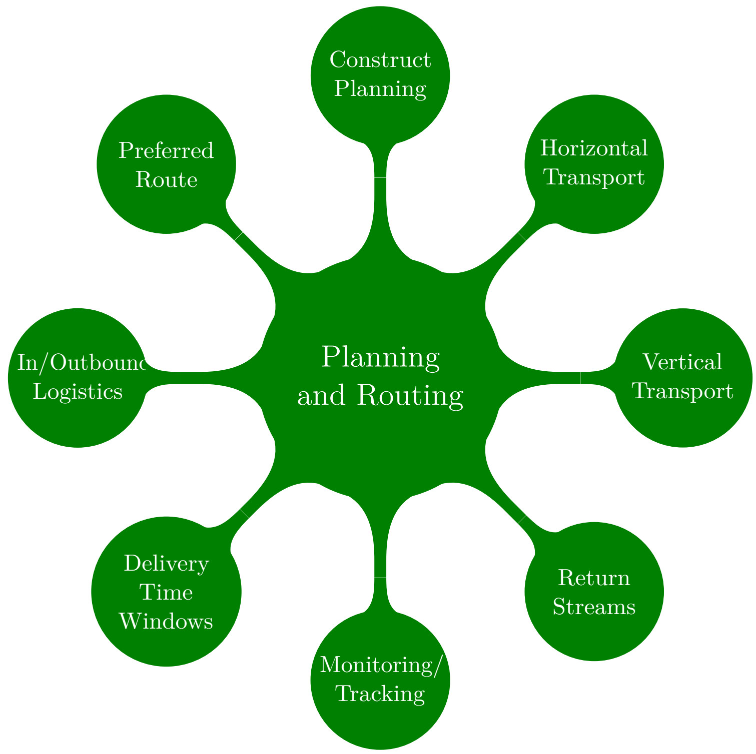

Figure 6.2: Planning and Routing Functionalities

Construction Planning (T)
The construction planning states what is going to be build at what time and in which order. To make this planning a 3D model is needed along with a bill of materials. This model can be used to determine the order in which to construct, although there is a standard general order of constructing (see subsection 3.1.3 for the construction phases). Most of the time contractors make a general, six week and one week planning. The general planning shows how far along the project should be. The six week planning is already more detailed, and the one week planning is at a day to day detail level. In order to make the six and one week planning it needs to be known what the capabilities of the subcontractor are. In other words what amount of work can they deliver per hour or day. In the general planning the rough material calculations are known. These can be adjusted to the work pace in the six and one week planning. Weather conditions might effect the one week planning as construction works are not allowed to continue in certain weather conditions. Lastly the project delivery date needs to be known to schedule all works along with some buffer time.

Horizontal Transport Planning (T)
Horizontal transport planning is the planning of transportation from the supplier/wholesaler to the construction site. In order to make this planning information is required from the supplier/wholesaler, transportation provider, contractor and subcontractor. Before a transportation planning can be made it needs to be known what needs to be transported, where it originates from, and when and where it needs to be delivered. The what can be taken from 3D drawing applications such as

BIM. These applications can create a bill of materials, which lists all relevant parameters of the required materials, such as volume weight and dimensions. The when can be translated from the construction planning, but can be adjusted to real time feedback from the construction site. The where also depends on the construction planning, but not fully. It also depends on the logistical structure, meaning if the materials get stored on site or in a hub nearby site. Either way a site layout needs to be known to assign storage space for the materials if they are not used directly. The point of origin depends partly on cheapest price and partly on preferred supplier/wholesaler of the subcontractor. When these are all known a planning can be made. There are two more things that have an effect on the horizontal transportation planning: preferred route and cost. In order to make a planning it is wise to know which routes will be taken. When the routes are known transportation time can be calculated and with that information delivery windows can be chosen. Certain routes or operators are more cheaply than others, having effects on the cost of transportation.

Vertical Transport Planning (e.g. crane planning) (T/O)
In utility and housing construction projects a vertical transport planning is required as materials need to be hoisted to the right floor. In road construction a vertical planning can be used to lift heavy parts in to place. Making a vertical transport planning is similar to a horizontal transport planning as it needs to be known what needs to be transported where at what time. Not only for the vertical transportation but also what needs to be delivered when at ground level, so it can be hoisted to the right place at the right time. Therefore the relation between horizontal and vertical transport planning is required (De Bes et al., 2018). Furthermore time windows of deliveries are needed. There is a dependence on what needs to be moved for the equipment used to do the vertical transportation, as there is a difference between a bag of sand, prefabricated walls or concrete.

Return Streams (O)
In construction projects there are three types of return streams: waste, damaged goods and packaging. Waste is seen as used and left over product which is not considered usable any more. Damaged goods and packaging need to be returned to the supplier to get reimbursed. Return streams can be seen as a part of the transport planning on the operational level as damaged goods and waste are hard to predict. The packaging can be calculated beforehand, to do so it needs to be known what is ordered by which supplier. Some suppliers have their own packaging and thus need to be returned to that specific supplier, while euro pallets are general and thus can be switched around.

Real Time Monitoring/Tracking of Equipment (O)
For contractors and the municipality it is not always known where what equipment is, where it comes from or where it needs to go next. Not all is interesting for them, but it might come in handy. Tracking and monitoring of equipment can provide estimated times of arrival and traffic predictions. The current location is known by using GPS data of the vehicle, abstracted from GIS. Route information such as number of stops before arrival, loading times at those stops and traffic information also play a role in monitoring. The traffic information consists of current traffic and forecasted traffic. These are both required to make an accurate estimated time of arrival. The estimate also depends on road works or other blockages, which therefore also need to be known. These roadblocks might be caused by other construction projects, in which case they might already be known in the control tower.

Planning of Delivery Time Windows (T/O)
Delivery time windows are time slots of a certain duration in which a specified delivery or pick-up is planned. Logistical service providers or wholesalers/suppliers can claim a time slot for their deliveries to plan their logistical operations in an efficient manner. To plan these delivery time windows certain things need to be known. The first of which depends on the area as it might pose entry or other logistics related restrictions. If there are no restrictions materials could even be delivered outside of normal working hours for more flexibility. Secondly the construction planning, more specifically what is required when, needs to be known to ensure a continues work flow. The third are the (un)loading times per delivery as these have influence on the amount of deliveries that can be made in a certain time period. These are very important as there is limited (un)loading capacity at a construction site. All other vehicles have to wait for an empty slot before they can be (un)loaded. The waiting can be done on a vehicle holding area. Delivery time windows prevent too many vehicles arriving at the same time. One time slot might be assigned to multiple deliveries making it wise to know estimated times of arrival. This might give a vehicle priority over another to reduce on site downtime. There are tools on the market that are proven to be reliable in making a delivery time window planning. If possible these tools should be incorporated as a whole instead of the different data requirements.

In- and Outbound Logistics (T/O)
The in- and outbound logistics provide insight into how crowded the area will be. Furthermore it helps with streamlining delivery time windows and return streams. The inbound part consists of horizontal transport planning together with the personnel arriving at the site. The outbound part depends on conversion rate of material or amount of waste created along with other return streams. The personnel also leaves after a days work as do vehicles after their delivery is completed. The time at which a vehicle leaves depends on their arrival time (time window) and the (un)loading time.

Preferred Route Planning (T)
Preferred routes can be used to calculate scenarios and forecast the amount of traffic caused by a specific project. The first dependence of preferred routes is the CLP (or BLVC), as this states the to be avoided places affecting route choice. It includes locations which increase the risk of accidents such as schools and hospitals. There are other restrictions which might not be posed in a CLP such as zone entry restrictions (7.5 ton zones, bridges, emission, etc). Traffic and other route information affect the route as it might be cheaper or faster to reroute. Lastly most of the time the cheapest route will be taken, after safety and other restrictions are taken into account. Cheapest might also mean fastest as reduced time might result in more deliveries per day, increasing the profit per vehicle.

6.3.2 Information Hub

A control tower stores all kinds of information for different purposes. A large part of this information is used for planning and routing, as these are quite important for logistics. Another part of the information can be used for other things, such as process monitoring, forecasting and inventory management. This category of functionalities is less focused on the logistical process itself, but more on information gathering and information sharing. The functionalities elaborated on in this category are shown in Figure 6.3.

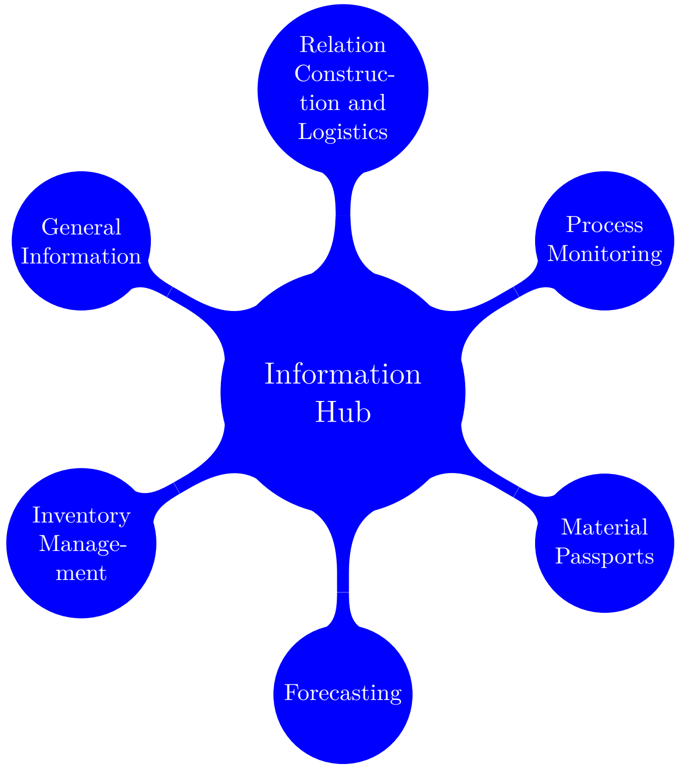

Figure 6.3: Information Hub Functionalities

Relation between Construction and Logistical Schedules (T/O)
The relation between the construction and logistical schedules makes it possible to see immediate effects on one when the other changes. This helps in calculating scenarios and predicting delays and their effects. The relation provides valuable insights if the planning can be achieved or if certain aspects need to be adapted. The relation helps enhance logistical coordination by adjustments while construction progresses.

Process Monitoring (T/O)
Monitoring of KPI's provide insights in the performance of the project. For a full list of the KPI's to be monitored see Appendix B. Monitoring KPI's has a second function, verifying logistical key numbers (De Bes et al., 2018). These key numbers can be used for calculating scenarios and their effects. In every construction project there are agreements made about cost, environmental aspects and other up front made choices. These agreements can be monitored, although it is difficult for this thesis to envision those beyond the stated KPI's.

Material Passports (S/T)
Generation and updating of material passports could be a functionality of a control tower. This is particularly useful when buildings get to be demolished, as these passports show the recycle potential. This helps in creating a more circular economy. Furthermore demolition could be done more easily when it is known beforehand what materials there are in a building. During the construction phase a material passport is most easy to make as the required knowledge about the materials is present at the construction site. If it is made afterwards some changes made during the process might already been forgotten, resulting in a less accurate material passport.

Forecasting (S/T)
Forecasts can be made for different reasons, for instance: material demand, supply of materials, traffic, or weather conditions.

Material demand is not always perfectly known before a project starts. It is however useful to make forecasts about the material demand in order to calculate costs and make logistical schedules. The demand might be met by supply from other projects. This supply can come from demolished buildings for instance recycled concrete, or reuse floor tiles in public spaces. Forecasts can be made for the supply of recyclable materials, or surplus materials. Some suppliers only allow materials to be purchased in predefined order quantities. If the material demand will not be equal to the defined ordered quantities there will be a surplus, which might be useful for other projects.

In certain weather conditions it is not allowed to continue working outside. Another reason for incorporating weather conditions is that in certain weather conditions some operations will take longer or are more difficult to carry out, such as hoisting with heavy wind or pouring concrete in extreme rainfall. When this is known in advance the construction planning can be shifted to suit the weather conditions. A seven day weather forecast is 80% accurate, while a ten day forecast is 50% accurate (Cappucci, 2019). It can be said that the more a weather forecast looks ahead the less accurate it becomes (Cappucci, 2019; SciJinks, 2020). If construction is going to be adjusted to the forecast it will only be done days in advance.

Traffic conditions can be monitored and forecasted to adjust the estimated time of arrival. Which can lead to other vehicles being (un)loaded before or after the original time window. Furthermore the traffic conditions can also be used to adjust vehicle routes. A forecast of the traffic caused by a single construction project can be made using the predicted material demand. This forecast can be used to see the impact on traffic in the neighbourhood and greenhouse gas emissions.

Inventory Management (O)
Due to the converging nature of construction projects there is a lot of material flowing towards the construction site. These materials need temporary storage until they are going to be used. Therefore the available storage space needs to be known before the first delivery arrives. It is useful to know what is stored where and why. If it is not known what is stored new materials will be ordered while they are not needed. If it is not known why something is stored it might be considered waste while it should be returned due to defects. In order to manage inventory it needs to be known what will arrive when. After arrival it needs to be noted where things are temporarily stored. Furthermore when materials or equipment are used it also needs to be known, since this might clear space for new material arrivals. Waste, overflow or damaged goods need to have a storage space as well until they are picked-up. The storage duration of equipment and materials is required, since the space it occupies cannot be used in the mean time. Inventory management can be done using a warehouse management system, which is especially useful in combination with a construction hub. Furthermore RFID-chips can be used to track whereabouts of materials and equipment.

General Information (S/T/O)
A control tower can provide information relevant for others, such as the public or organisations working on other construction projects. This information is amongst others: the typological features/characteristics (as explained by Ludema, Rinsma, and de Vries (2016a)), road blocks (due to special deliveries/cranes), project throughput times, current project phase, general construction planning, and point of contact information.

6.3.3 Decision Making

Decisions can be made, partly autonomous, using predictive and prescriptive analytics, and forecasts. These decisions require information flow and certain knowledge of the logistical processes. Without information flow it can not be known what the current state of processes are and therefore if action is required. Decisions can have undesired effects without knowledge of the processes. There are many processes which, depending on the circumstances, require different types of decisions. To fully elaborate them all could be a thesis on itself, therefore the two minimal functionalities (shown in Figure 6.4) are not elaborated on in depth.

Figure 6.4: Decision Making Functionalities

Event Management (T/O)
Event management are the actions required when activities deviate too much from the original plans in such a way that it could result in more deviations. For event management it needs to be known what the original plans and activities are. Furthermore boundaries in which activities can operate in are required. For instance if a delivery is five minutes late it probably is not a problem. However, if the crane planning is made per minute it could result in larger delays. If an event is to occur then either the system must react and adjust activities itself to prevent the deviation, or mediate its effects. A message could also be sent to the right persons to make them aware of the event and its effects. This can be seen as a preventive actions or warning, which is the second step in event management. It has been taken as a separate decision and will be discussed later. The events can be categorised into logistical related disruptions and construction related disruptions.

The *logistical related disruptions* are amongst others delayed deliveries. When a delivery is delayed it could have consequences for other deliveries during the same day, and potentially for the construction schedule if materials are not delivered before they are needed. The time window planning and estimated arrival times are required to know if a delivery is on time or not. More information is required before it can be said if a delayed delivery will result in a disruption. The consecutive planned deliveries and their estimated times of arrival need to be known. If this delay causes further delays then it can be considered a disruption. The event can be handled by moving this consecutive delivery forward in the schedule, at least when possible. Another way a delayed delivery can cause disruptions is when the consecutive steps it has to take are compromised due to the delay. Examples of consecutive steps are movement to temporary storage and vertical transportation.

Construction related disruptions are, amongst others, delays resulting from slower working pace then anticipated or logistical disruptions. Delays in construction have implications for almost all other processes, as construction is a sequential process. Not only are other construction activities delayed, but the logistical schedule needs to be adjusted as well. When a delay occurs it must be known what the delay is and if it would affect other activities. If it does affect other activities then it must be known how long it would take to make up for the delay. When this is known an alternative schedule can be made taking into account this time shift. Afterwards all impacted organisations need to be informed, not just organisations working on site but also suppliers and other logistical organisations.

Preventive Actions and Warnings (T/O)
As said before preventive actions and warnings are the second step in event management. It needs to be known that something is going wrong before an action can be taken.

Preventive actions require more than knowing something is wrong or about to go wrong. It needs to be known what the normal state is, and what the boundaries are which can be operated in. Something about to go wrong will be near the operational boundaries. When it goes over the boundaries it causes a problem. In order to take preventive actions it needs to be known what can be done to keep within the boundaries, which differs per situation. These situations need to be defined before hand. Strict rules need to be made about what to do in each of these situations. Only then preventive actions can be taken autonomously. What these rules are is difficult to say without having intimate knowledge of the processes which can benefit from these preventive actions.

Warnings can be given more easily. Warnings can be send in different occasions with different purposes. Most warnings that occur are differences from the forecasted or planned situation. Not all of these occasions desire a warning, as some would not cause further differences. If no further differences are caused a warning might not be necessary. If further differences occur from the situation then a warning is in order. This warning should consist of at least the cause for the difference, and perhaps a proposed actions to negate the differences. When a warning should or should not be send along with the exact implications needs further investigation. During this thesis not enough knowledge was gathered about the processes and effects of message sending.

6.4 Functional Design

All information required to make the functional design has been elaborated on. The design focused on where data resides (presented in section 5.2), what functionalities a control tower should have (provided in section 6.2), and what data is required for those functionalities (as elaborated on in section 6.3). The functional design, as shown in Figure 6.5, consists of two parts, a data proving part and a data requiring part. These two parts are elaborated on in subsection 6.4.2 and subsection 6.4.3 respectively. First some general information about the design is given (subsection 6.4.1).

6.4.1 General Design Information

The focus does not lie on technical design or internal system requirements. Therefore the control tower has been presented as a black box. There are two concerns that must be noted about the internal system. The first is that systems proven to be reliable should be used as whole, not just the produced data. These proven systems already provide some of the desired functionalities of a control tower, and therefore it would not be wise to do the same thing twice. The second concern is about data quality and reliability, which has not been investigated during this thesis. There are different cases in which data quality and reliability play a role. For instance when two data providers have different information about the same subject. Who holds the correct data? Other questions are, how can it be ensured that data is correct, or correctly acted upon? Who owns the data after it is shared with a control tower, the original owner or the control tower? There are more examples from the field of data science that need further investigation before a control tower can be put into practice.

The design only shows one stakeholder of each type, which is not correct. Each construction project involves at least 20 subcontractors and multiple suppliers (ECLLP, 2013; Emrath, 2015). These have not all been incorporated in the design as they generally hold the same information. A construction hub is connected with a dotted line as one will not always be present or used in projects. The data availability has been simplified and generalised to a certain extent. For instance the bill of materials will differ per construction phase, but one is always present. It is not required to show all these four bills of materials as they all are, in principle, a bill of material.

The construction phases have not been included in the design, but the differences are elaborated on here. The data availability and data requirements are slightly different during the four construction phases. During site preparation and substructure construction a construction hub is less likely to be used than during shell and final construction. Furthermore the material requirements are different during the first phases. Site preparation and substructure construction require large volumes of similar heavy material and heavy equipment, such as sand and concrete (The Constructor, 2009; OECD, 2001). The shell construction still uses a lot of concrete or prefabricated parts, but is already more diverse in material demand (Geertsma, 2014). Final construction requires relatively light and diverse materials (Niels, 2019). Some of the functionalities such as a construction planning are required before starting the first phase of construction, although it will be updated regularly.

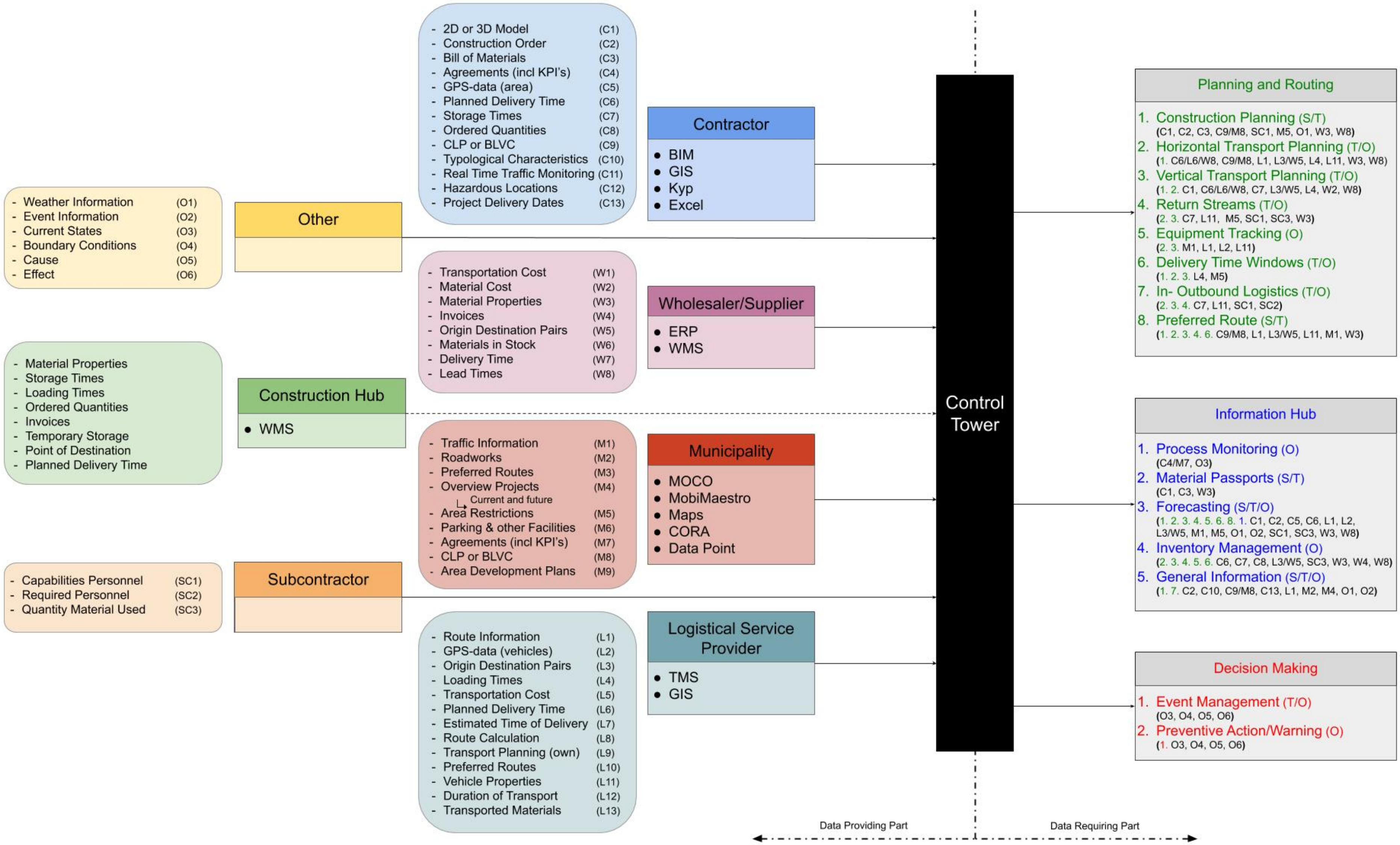

Figure 6.5: Functional design of a construction logistics control tower.

6.4.2 Data Providing Part

The data providing part lists the stakeholders and other organisations that provide data to a control tower. This part of the design incorporates the data availability by each of these providers, visualised on the left side in Figure 6.5. Furthermore it shows which ICT systems these providers use, as stated in section 5.2, or could be using. The systems were found by conducting stakeholder interviews. During these interviews it was asked what purpose these systems were used for. This led to the list of ICT systems described along with a part of the data availability. Another part of the data available was found by asking about an ideal state, along with what data is desired to receive from other organisations. When interviewing organisation it was asked about the previously stated data desirability. More specifically it was asked if the data resided within the organisation and if they were willing to share this data with the data requesting organisation. The rest of the information was found through desk research. The systems given in the interviews are either described in scientific literature or have a vendor which provides information about the system.

6.4.3 Data Requiring Part

The second part of the design shows what functionalities a control tower should have. These functionalities were found through literature review (section 4.3) and interviews (section 5.5). A selection of minimal and desirable functionalities was selected from these two sets (see section 6.2). The minimal functionalities have been elaborated on further in section 6.3, in which the data requirements per functionality were discussed. It was chosen to only present the minimal functionalities in the design, as can be seen on right side of Figure 6.5. The design uses the same three categories and colour notation as used earlier in the thesis.

The data requirements per functionality are indicated below the functionality by a letter number combination. Annotations are used resembling the origin of the data: contractor (C), wholesaler/-supplier (W), municipality (M), logistical service provider (L), other (O), and subcontractor (SC). The combination below functionalities corresponds to the same combination behind data described in the left side of the design. For instance C1 under the functionality construction planning corresponds to 2D or 3D Model (C1) behind the contractor. Several combinations separated by a dash sign are the same data hold by different organisations. For instance C9/M8 are both construction logistics plans (CLP) or BLVC, one resides at the contractor the other at the municipality. Some functionalities are considered as a requirement for other functionalities. These are indicated by a coloured number below the chosen functionality, corresponding to the required functionality. The green one below functionality horizontal transport planning indicates that this functionality requires functionality 1. construction planning.

An example: The data requirements for the horizontal transport planning are: the construction planning (1.), planned delivery time (C6/L6/W8), CLP or BLVC (C9/M8), route information (L1), origin destination pairs (L3/W5), loading times (L4), vehicle properties (L11), material cost (W2), and lead times (W8).

6.5 Proof of Concept

In this section a proof of concept is presented. Firstly a description of a traditional situation in the construction supply chain is given in line with section 3.2. This description uses clusters of projects presented in the Case Introduction. Secondly the situation using a control tower is presented. The situation using a control tower elaborates on how functionalities are used. Finally a comparison is made between both situations to show whether a control tower adds value.

6.5.1 Description of Traditional Situation

A description of the traditional way a project is undertaken has been elaborated on in section 3.2. More specifically the planning, ordering and delivery has been shown in Figure 3.3. A brief summary is given along with a visualisation of information and material flow (Figure 6.6).

Half a year before construction starts contractors make an overview of all projects, followed by a calculation of the material demand for each of these projects. The individual contractors then communicate their total material requirements to their preferred wholesalers/suppliers, and make agreements about the delivery of these materials. The wholesalers/suppliers in their turn make schedules to meet the demand posed by the contractor. These schedules are the wholesalers sourcing of materials, such as production at the factory or purchase at other suppliers, and arrangements for the deliveries. The information and material flow between contractors and wholesalers is presented in Figure 6.6.

What is not presented by the information from section 3.2, is that the wholesaler/supplier tries to meet the demands of each individual project or contractor. Thereby it could be the case that on Monday half a truckload bricks is transported to a project site, and on Wednesday another half truckload of bricks is transported to a nearby project site. This occurs more often when different wholesalers are contacted by separate contractors, and can be seen by the multiple lines in Figure 6.6.

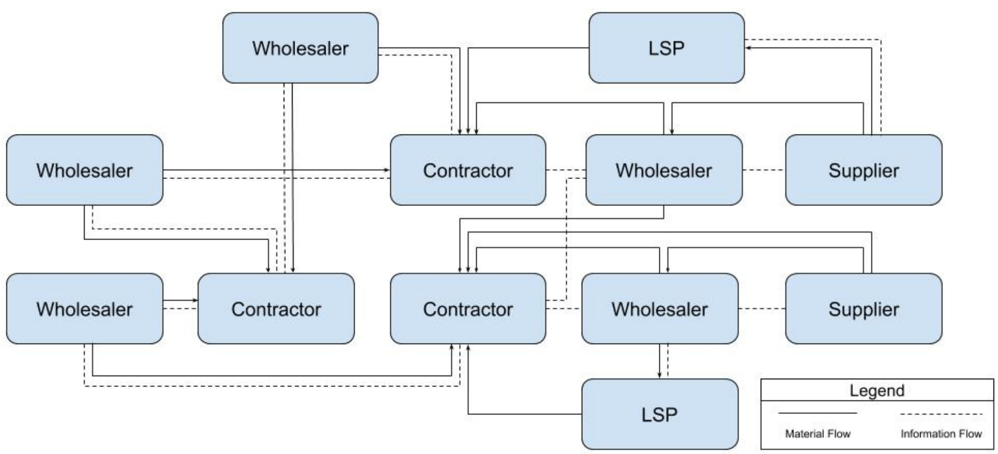

Figure 6.6: Normal situation of information and material flow.

In the presented case (see subsection 2.1.1) it can be seen that there are several similar projects to be undertaken in a similar time span. These projects can be divided in two types: infrastructure projects, and housing or utility projects. The specifics of these projects have been elaborated on in subsection 3.1.3. Projects of the same type have similar material demands as long as they are in the same project phase. There are six housing or utility projects planned in the same time frame (2018-2024), these projects are denoted as P2, P3, P5, P10, UP1 and UP4 in Figure 2.1, and elaborated on further in Appendix A. The infrastructure projects are denoted in the same figure and appendix as P7, P11, UP3 and UP7. These projects start after 2015 and are supposed to be finished in 2022.

6.5.2 Description including a Control Tower

The design proposed in Figure 6.5 presents a wide range of functionalities for a control tower. In this section it is explained how some of these functionalities are enabled during the above described normal situation. Figure 6.7 visualises this situation including a control tower. A control tower acts as a central point of contact for all organisations, independent of the amount of projects undertaken. All stored information can be shared with users depending on which groups of information and functionalities, or modules, they desire (the filtered information flow in Figure 6.7). The project specific information flow is similar to what is communicated with other organisations in the traditional situation.

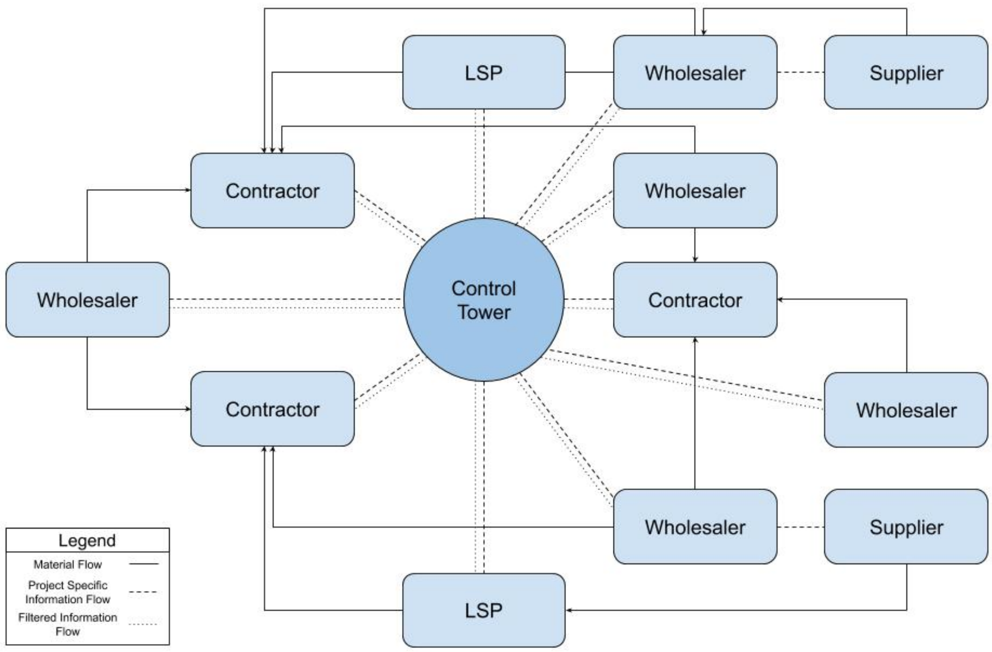

Figure 6.7: Information and material flow with a construction logistics control tower.

The control tower holds an overview of all projects in an area, which is communicated to the individual contractors. The contractors make the construction schedules for each of their projects to calculate the material demand. Both the schedule and corresponding material demand are communicated to the control tower. Thereby a complete overview of the project and their material demand over a specified time is known. From this overview it can be seen if material demand of different projects is similar in a certain time period, or if it differs greatly. This demand is coordinated with all contractors to streamline the different construction schedules, and lower potential traffic intensity. Traffic intensity can be lowered by either spreading the calculated traffic, or by combining transport of similar material flows. Two examples are given, one for either option:

Example one: Two of the infrastructure projects require large amounts of landfill in a certain week. This requires lots of large and heavy vehicles going through the neighbourhood. When timed poorly these could cause high traffic intensity on the surrounding roads. Therefore it could be beneficial to spread the arrival of these landfill deliveries over multiple days or weeks. This way a more continues stream of deliveries is created, lowering the peak intensity.

Example two: During the shell construction two housing construction projects require bricks. One expects a delivery of 1/4 truckload on Monday and the other a 2/3 truckload on Wednesday. It then could be beneficial to combine both deliveries on for instance Tuesday, to decrease the amount of vehicles required to make the delivery.

The calculated material demand of all projects is communicated to the desired wholesalers. The control tower then arranges the horizontal transportation to meet the material demand of the contractor in accordance with the wholesalers. This way the control tower could take over the risks involved in transportation while ensuring a flow of orders for the wholesaler and the steady supply to the contractor. Information about point of delivery, such as hard to reach locations, zone restrictions, and BLVC, is already incorporated in the control tower. Therefore it has a complete overview of all aspects involved in transportation. Furthermore the wholesaler supplies the control tower with material properties, lead times and other information required for transportation and to meet the demand of the contractor.

Next the control tower can focus to maximise efficiency of all transport within one area, as all required information is already known. Efficiency could be maximised through the provided examples of shifted deliveries and consolidation, or by combining delivery with return streams. Most projects have return streams such as faulty products, packaging and waste. After delivery vehicles have space to accommodate for these return streams. Logistical operations is further optimised by including route specific information, such as road blockages. The control tower knows when roads will be closed or partly blocked due to roadworks or special deliveries, as it knows the construction schedules. Using this information alternative routes can be chosen or schedules can be altered.

All the above processes can be monitored using up front agreed upon KPI's. These KPI's can be used to update key numbers for making forecasts and calculating scenarios. The forecasts could be made for the previously mentioned traffic information and material demands, as elaborated on in subsection 6.3.2. The forecasts use information gathered from the different construction sites and from different organisations connected with the control tower.

Decisions about delayed transport can be assessed using the tracking of equipment, monitoring of processes and the forecasts about traffic. For instance, if a vehicle is to arrive 10 min later than planned. This can be calculated using traffic forecasts, and the location and route of the vehicle. It can be assessed if this would result in further delays by looking at the boundary conditions, such as arrival times of other vehicles, vertical transport planning and construction progress. If there are other vehicles that could be unloaded in the delayed time, then there is no problem. Similarly if the materials are not required immediately or transported later (which can be seen in the vertical transport planning), then there is no problem either. Action should be taken if there would be a problem as one of these results in further delays. The action could be through message sending to the relevant people on site, or by rescheduling other processes to accommodate for the delay.

6.5.3 Evaluation of Differences

Figure 6.7 shows that the control tower plays a central role, and that it communicates with all involved organisations. In Figure 6.6 only three contractors are shown while there will be more in the presented case, making the system even more complex. Therefore a single point of contact is valuable as it decreases complexity and provides a more clear and complete overview. Since the control tower takes over the contact between all organisations less time is lost finding all the required information, as there is one place to look. All information available is GDPR compliant, and will not include data if the original data owner has grounded arguments why it should not be shared. Otherwise the control tower should have all information regarding the construction project and construction logistics. The users can opt to receive only the information they desire through choosing for a specific module, increasing information density. A central and all inclusive point of contact can be beneficial especially in an area such as the presented case. There is a hospital in the case area (Amsterdam Amstel III) which needs to be accessible at all times. Individual contractors might partly close different roads to unload vehicles supplying construction materials. In a normal situation these blockage times could overlap, resulting in a significant decrease of accessibility. This has as secondary effect that critical time is lost by ambulances going to the hospital. A control tower could coordinate the road blockages in such a way that accessibility is guaranteed.

Further value is added by the decrease in traffic intensity. This decrease is achieved through higher load factors, less vehicles and shifted transportation schedules. The decrease in traffic leads to lower nuisance and lower greenhouse gas emissions. The following list provides an overview of the most important benefits presented in the proof of concept.

- Single point of contact
- Central information flow
- Choice in information sharing through modules
- Guaranteed access to information
- Coordinated construction logistics for the entire area
- Coordinated road blocks
- Decrease in traffic intensity
- Higher load factors
- Lower nuisance and greenhouse gas emissions

There could be a potential downside to using a control tower. For instance if a preferred wholesaler has less than half a truckload of materials, and another wholesaler also has half a truckload. If one of them supplies both projects it would add to a full truckload. According to a control tower logic, it would be more beneficial to let one wholesaler arrange the supply, instead of two deliveries by different wholesalers. Therefore it could occur that a contractor is not supplied by a preferred wholesaler. There are other factors in play in choice of wholesaler by the control tower such as distance, or minimisation of carbon and nitrogen footprint. This example does not mean that all materials for one project will be supplied by one wholesaler, there could be multiple wholesalers/suppliers as long as logistics is optimised.

6.6 Reflection on the Design

There are several ways to reflect on the proposed design. The first is to see if the proposed design meets the posed requirements (subsection 6.6.1). A second way is to find out if all information is correct (subsection 6.6.2); Do the organisations have the presented data? Are the data requirements for functionalities complete? A third reflection is on the robustness of the design (subsection 6.6.3); Who should be incorporated in order to ensure the functionalities can be achieved? A last way the design is reflected on is by means of benefit (subsection 6.6.4); Do the data providing organisations benefit from sharing their data?

6.6.1 Meeting Requirements

Does the proposed design meet the requirements presented in section 6.1. It has already been stated if the functional requirements are met by the design functionalities (see subsection 6.2.4). Two of these requirements were forfeited to this section, as they depended on the proposed design: guardian of rules and agreements (requirement 10), and providing insight in cost (requirement 14). The proposed design does include agreements as data input. It does however not show whether a control tower guards them. This depends on the potential facilitator and other kinds of functionalities that need to be decided on. Therefore guardian of rules and agreements as a requirement is not met. The second forfeited requirement could be met, as some of the data providers have information about costs. However, in section 5.2 it was found that organisations were not willing to share the cost of all processes. Therefore it can be said that the proposed design does not provide insight into cost, but the option is available. If the design requirements from subsection 6.1.1 are presented again in the following list, and are discussed afterwards.

1. Integrates information and data sources
2. Accommodates varying degrees of IT sophistication
3. Is modular
4. Open for all organisations in the supply chain
5. Open for external organisations and the public
6. Allows for changes in data suppliers and customers
7. Functionalities divided into strategic, tactical and operational
8. Split between service provider and customer
9. Split between data providers and to be controlled organisations

The design integrated multiple information and data sources (requirement 1). Each organisation uses different systems, or sources, ranges from Microsoft Excel to SAP (ERP/WMS systems). Therefore it can be said that a control tower accommodates varying degrees of IT sophistication (requirement 2). The design could be made modular (requirement 3) depending on the business model of a control tower. The business model also decides whether information is open for external organisations and the public (requirement 5). The design already showed that several stakeholders in the supply chain should be incorporated (requirement 4). The proposed design does not show if a control tower allows for changes in data suppliers and customers (requirement 6). The proposed design does show the levels (strategic, tactical and operational) of the functionalities (requirement 7). The design has a data providing and a data requiring side (requirement 8). The data providers are, however, also considered as customers of a control tower, making it hard to clearly present the split between them. This same reasoning can be applied to the split between data providers and to be controlled organisations (requirement 9). From the design perspective these are the same organisations.

Overall most of the requirements are met. Some of the requirements depend on the business model (requirement 3 and 5). Requirement 6 depends on the implementation and use of a control tower. The last two requirements (8 and 9) are not met as the split is harder to make when both ends are the same group of organisations.

6.6.2 Validation of the Design

Reflection on the design by means of validation focuses on available data within organisations, which in combined with limited time resulted in less validation of requirements and functionalities. The available data shown in the proposed design was validated through conducting semi-structured interviews. During these interviews the data providing part was shown to the interviewees. First it was asked if the data shown at their own organisational type was correct. Then it was asked whether information was missing. A third question focused on the correctness and completeness of data residing in other organisations.

During the validation it was found that data does not always reside in a specific information system. The required data could be on paper, or be general knowledge for a certain organisation member. Some examples from the perspective of a contractor are presented:

The agreements made about the project are currently made and signed on paper, and not transferred into a digital format. Another example is the bill of materials, as it is not made automatically by ICT systems. It could be made after a project is completed by checking all invoices, which takes a lot of work and effort for something that preferably is known before construction starts. Planned time of delivery is given within a range of multiple hours or at a given day, not within a specific hour. Storage times are currently not known. These could be calculated if RFID-chips are integrated in all parts in order to measure when a material is used. Construction deliveries are not in an ideal state where the exact ordered and delivered quantities are known. This makes it harder to know when what has arrived, which also needs to be known to calculate storage times. Currently the day materials are required could be roughly estimated, but not exactly known. Finally updates on the final project delivery date are not always made or communicated, as these updates rely on many factors including weather and human factors such as workflow.

A part of the data in the proposed design is currently not shared between organisations. A portion of this unshared data will probably remain private for at least a couple of years. An example is the split between material cost and transportation cost. Since not all data will be shared it could even be asked if it is wise to desire all available data in a control tower. If too much is shared a control tower might become information heavy and be less valuable. Furthermore not all available information is required to execute the functionalities. Demands should not be made about data that is not required for the functionalities, as it might result in reluctance to participate. Taking these points in consideration all data is still visualised. This is done for two reasons; firstly to provide a more complete overview of the data availability, and secondly there might be additional functionalities that do require the data.

6.6.3 Robustness of Data Input

The design needs to be robust as it requires certain data to function properly. Therefore it needs to be known what happens to the functionalities when less or no data from a specific organisation is provided. When these weaknesses are known measures can be taken to ensure that the required data is made available. This can be translated into showstoppers for the data providing part of a control tower, and is discussed per organisational type.

Contractor

The contractor is involved in all phases and most activities of the construction project. Furthermore during the network analysis (section 5.1) they were found to be an enabling organisation for coordinating construction logistics. This can be confirmed by the list of data they provide and the functionalities they either desire or enable. All data they can provide comes from their own sources. Therefore the contractor is an enabler of a control tower, but more importantly a showstopper when not involved.

Logistical Service Provider

Logistical service providers ask certain questions when they are hired to optimise their services and internal processes. By doing so they receive information about what, where and when. Logistical service providers arrange their logistical processes to maximise the efficiency of each of their vehicles. When their part of the information is not shared it would effect the functionalities: forecasting, in- and outbound logistics, preferred route and equipment tracking. The other functionalities can be considered a boundary context in which the logistical service provider operates. Some of the data can be received if the organisation hiring a logistical service provider asks for it. Examples are type of vehicle used, amount of vehicles used, and loading times. This would leave information about cost, routes, equipment tracking, and partly forecasting. The residual information is desirable to have but not of essence to enable functionalities. Therefore it can not be said that a logistical service provider is considered a showstopper, or enabler. The process of data collection would become easier if they do provide data directly to a control tower. Moreover, there would be more information available which aids the possibilities and functionalities for a control tower.

Wholesaler/Supplier

Currently wholesalers/suppliers are responsible to arrange logistics, therefore they hold similar information as logistical service providers. The most important information a wholesaler/supplier has are material properties. Logistics will become harder to plan and carry out without knowing these material properties, as this determines: type of vehicle, number of required vehicles, and route choice. Order or waiting times of a material can also be considered necessary for construction projects and construction logistics. Most of this necessary information is given in a quotation. Therefore it can be said that either a logistical service provider or wholesaler/supplier must provide data to a control tower. When neither provide data it becomes more difficult to get information about transportation and materials. If one of them provides data then most functionalities can be enabled. It would still be ideal if both provide data as both supplier and logistical service provider have information desirable for certain functionalities.

Other Data Providers

Most data from **the municipality** and part of the other information sources can be considered as open data, and therefore publicly accessible. Since this data is publicly accessible they can not be considered showstoppers from a data point of view.

The **subcontractor** delivers a small part of the data which most of the time can be roughly estimated by a contractor. This can be done as contractors have lots of experience with projects, and therefore have a general idea of the average capabilities and personnel required. With this in mind it can be said that a subcontractor is not necessarily a showstopper.

It is not known if a **construction hub** will be used in the case area. Data available in a hub is however not essential for a control tower to function properly. Using a construction hub can enhance data availability and coordination.

Intermediate Conclusion

To conclude, some data is provided by several organisations or by an open source, while other data is provided by a single private source. These singular private sources need to be incorporated since their data is required. The multiple or open sources can all be incorporated, but it is most important to include at least one source for each piece of required data. More sources provide a more sound base of information and could enable more options, as each source always has more data available than minimally required. Therefore a contractor, and logistical service provider or wholesaler/supplier must be included. The municipality and other data sources are preferably included but not necessarily required.

6.6.4 Benefit of Sharing Data with a Control Tower

Most of the required information resides in four data providers: contractor, logistical service provider, municipality and wholesaler/supplier. What do they stand to gain from providing their data to a control tower? This depends per organisation as they all have different desires.

Contractor

The contractor contributes a large part of the required data. Most of the functionalities of a control tower are, in one way or another, normally performed by the contractor. Therefore it can be said that a contractor does not gain much by a control tower. A control tower however provides all required data from a single point, instead of multiple. This makes it easier for a contractor to gather the required information, which potentially can get even more data than required. The control tower could furthermore be used as a tool to carry out functionalities they normally do on their own, reducing contractors workload. There are some extra functionalities to a control tower due to the extra data it could gather, such as the preferred route and some of the forecasts. The preferred route might not be interesting as long as the deliveries are made on time. Some forecast abilities such as the estimated times of arrival are more interesting as these enhance process coordination. Using a control tower to enhance coordination could result in higher efficiency of logistics. In return higher efficiency helps in winning tenders, as tenders could be won on higher load factors and fewer transportation movements.

Logistical Service Provider

Logistical service providers are used to plan all details of transportation, customised to the clients wishes. They already receive all information required to carry out the service they are hired for. With the received information they plan their logistical processes to optimise equipment use. Some logistical service providers adapted their business model to the lack of coordination and last minute requests by the industry. These organisations do not benefit from using a control tower since this enhances coordination and therefore undermines their business model. The benefit for logistical service providers is in higher load factors, as their service can be combined over more projects than normal. This could be done by letting the control tower coordinate all logistics, or by subscribing to full-fill specific services. Either way it does require a change of business model. It is not known if logistical service providers are willing to do so. Further research is required to give an answer about preferred solution for the logistical service providers. For now it seems that the benefits for a logistical service provider do not outweigh the cost.

Municipality

Most of the data the municipality shares is considered open. A large part of the data is from real time monitoring systems or from previous measurements, only a small part results from forecasting. This part of forecasted data is what the municipality stands to gain by collaborating with a control tower. Furthermore a control tower can aid in reaching policy goals, such as less nuisance during construction and less traffic. A control tower aids as it forecasts the traffic generated by a project or group of projects. This could help the municipality coordinate logistical streams, and coordinate their own maintenance activities. Besides coordination the municipality could gain insight in transport movements and their specifics. This can be done using the horizontal planning combined with material properties and equipment tracking. Therefore it can be known what routes are travelled, what is transported, weight carried and potentially load factors.

Wholesaler/Supplier

Wholesaler/supplier provide information about material properties and delivery or ordering times. Some of the wholesalers also provide logistical services with the ordered materials. A control tower poses benefits of more coordinated logistics with higher load factors, since demand of multiple projects can be met. Part of the value proposition of wholesalers is in their ability to provide a logistical service tailored to customer needs. Therefore it could result in lower differentiation amongst wholesalers. This could outweigh the cost, depending on the amount of orders received by a control tower.

Intermediate Conclusion

To conclude, the four main data providing organisations do not all stand to benefit by a control tower. The municipality and contractors stand to gain most by adopting a control tower. The benefits are: more coordination and control, less transportation movements and more efficient scheduling. For a logistical service provider the benefits do not outweigh the cost, and therefore they are less willing to participate in a control tower. The wholesalers/suppliers have loss of value proposition, but gain in higher load factors, and potentially more demand. Currently it seems the benefits outweigh the cost, this could however shift when the concept of control towers is further developed. The benefits and downsides for organisations involved in a control tower should be kept in mind during further development to maximise benefits for data providing organisations.

6.7 Chapter Conclusion

In this chapter a functional design has been proposed following two steps. The first step was to define potential functionalities for a control tower, shown by Figure 6.1. The second step was finding the data requirements for these functionalities (section 6.3). These parts were combined in the design, as shown in Figure 6.5. The data availability shown on the left side of the design was based on earlier findings in section 5.2.

The design was reflected on in terms of meeting requirements, validity, robustness and benefit. The posed requirements were almost all met, as discussed in subsection 6.2.4 and subsection 6.6.1. The validity focused mostly on verifying data availability within organisations (see subsection 6.6.2). The main findings were that the data presented to reside in organisations is correct. However, not all data shall be shared, and that not all data is required for the presented functionalities. Robustness focused on finding showstoppers from the data input perspective (see subsection 6.6.3). It was found that the contractor is the main data providing organisation. The other organisations should be included when possible, while they are not always essential. This has two reasons; their data is open source, or their data also resides in other organisations. After the robustness benefits of sharing data with a control tower were shortly addressed (subsection 6.6.4). The conclusion was that for now it seems that the benefits outweigh the downsides. The balance could shift when the control tower is developed further. Therefore organisations should continuously be kept involved during the development to maximise potential benefits.

Chapter 7: Conclusions and Recommendations

This thesis focused on enhancing coordination in construction logistics through a construction logistics control tower. Here a construction logistics control tower was defined as a central node that monitors, plans and coordinates logistical processes for one or more construction projects by integrating relevant information systems and data sources. The thesis focused specifically on making a functional design for this control tower while involving stakeholders.

The findings of this thesis are presented in section 7.1, and are followed by a recommendation section (section 7.2). Afterwards limitations of the thesis are discussed together with future directions (section 7.3). Finally a reflection on the thesis is presented (section 7.4).

7.1 Findings

The findings of the thesis are discussed in this section. Each research question or objective is discussed separately.

7.1.1 Coordinating Construction Logistics State-of-the-Art

The first research question was aimed to find the current state of coordination in construction logistics (see chapter 3). By doing so a problem area could be defined, corresponding to the first design step: awareness of the problem. The first research question was posed as:

RQ1: What is the state-of-the-art in coordinating construction logistics?

Through conducting a literature review it was found that the construction industry can be considered as fragmented, complex, converging, typified as make-to-order, and project driven. In construction there is a shift visible from greenfield development towards brownfield development, along with an increase in off-site prefabricated parts. These two trends pose additional challenges for construction logistics. These challenges are amongst others: lack of sense of urgency of logistics, lack of data sharing, and decreasing construction sites. In general there is a large demand for construction materials, equipment and personnel that needs to be delivered on time, at the right location. When combined with the challenges, it can be seen that coordination needs to be enhanced.

Collaboration and coordination is currently done in small amounts, mostly with trusted partners. There is, however, a lot of room for both vertical and horizontal collaboration. Construction organisations and processes could be coordinated using information and coordination systems. Multiple of these systems have been described, all designed to enhance coordination in particular ways. Most of the described systems are not designed to coordinate an entire supply chain, let alone multiple supply chains. A concept build around coordinating complex environments is a construction logistics control towers.

7.1.2 Construction Logistics Control Towers Literature Perspective

The second research question was answered in chapter 4, through conducting a literature review. Stakeholders perspectives on construction logistics control towers are taken into account in research question 4 (see subsection 7.1.4 for conclusions). The second research question was posed as:

RQ2: What is known about construction logistics control towers within the literature?

A control tower is designed to oversee and coordinate logistics for one or multiple, preferably large, construction projects within one area. It was defined as a central node that monitors, plans and coordinates logistical processes for one or more construction projects by integrating relevant information systems and data sources. There was no agreement in the literature if a control tower is a physical place, fully virtual/cloud based, or a combination of both. Its main purpose is to enhance coordination between logistics chains and construction projects. In order to do so it requires information from different information and coordination systems used by organisations active in construction logistics. There are two governance models suitable for a construction logistics control tower: network topography governance and smart governance concept (see subsection 4.1.2). The governance model of a control tower should be supported by contractual agreements. A business model canvas (subsection 4.1.3) was used to further describe the value proposition of a construction logistics control tower.

Eight general requirements for control towers have been described in section 4.2, and the general functionalities have been described in Figure 6.1. These functionalities were divided into three categories: planning and routing, information hub and decision making. An annotation was used to describe which level the functionalities operate in: strategical (S), tactical (T) and operational (O).

Finally the chapter described what is known about the design of a control tower. One known design indicated that it should clarify which level (operational, tactical or strategic) a functionality is designed for. Another design focused on the roles within a control tower. The last design presented a difference between a data providing side and a to be controlled side. These points or known designs did not show where data originates from. Neither did they show what functionalities a control tower should have. Therefore the thesis further focused on making a functional design. Stakeholders should be involved in realising this functional design. A network analysis was conducted to see which organisational types should be involved (see section 5.1).

The network analysis was conducted with general stakeholders as it was not known which organisations will be active in the case area. Through a stakeholder-issue interrelationship diagram (subsection 5.1.2) and power interest grids (subsection 5.1.3) it was found that four organisational types should be included for the remainder of the thesis. These four are: contractors, the municipality, logistical service providers and wholesalers/suppliers. These organisations were interviewed to find answers for research questions three and four.

7.1.3 Stakeholder Data Availability

The third research question focuses on the data availability of stakeholders. This research question was formulated as:

RQ3: Which coordination and information systems are used by organisations active in construction logistics, and what data resides in these systems?

The answer to this question was found in section 5.2. The answer was found through conducting semi-structured interviews, and desk research. These interviews were conducted with the four organisational types found during the network analysis. The answers were presented in tables per organisation: Table 5.3 data available in ICT systems used by contractors; Table 5.4 data available in ICT systems used by the municipality; Table 5.5 data available in ICT systems used by logistical service providers; Table 5.6 data available in ICT systems used by wholesalers/suppliers; and Table 5.7 data available in ICT systems used by other organisations.

It was observed that all interviewed organisations, in general, are willing to share most information about construction logistics with third parties. The interviewed organisations all shared the idea that in a theoretically ideal situation information is shared freely with all organisations involved in a project. From this observation it could be said that the construction industry is slowly opening up to more information sharing. A second observation was that the information sharing and integration of data should be coordinated and facilitated. When something is being tried in the construction industry it should either be proven or demanded, because of the conservative nature of the industry.

7.1.4 Stakeholder Perception of a Control Tower

The fourth research question was answered in section 5.3, based on semi-structured interviews. This question was posed as:

RQ4: What is a control tower perceived to be by organisations active in construction logistics?

The vision of a control tower varied between the interviewed organisations. It was perceived as an app; as purely physical place with screens; and as a hierarchical organisation. Some thought it to be a combination of software and a human operated system. It was found that organisations agreed a control tower is most useful for coordinating multiple, or at least large scale, construction projects. Still it would be useful to create a shared vision and purpose between stakeholders. The organisations' visions of a control tower were accompanied by eight requirements see section 5.4.

Potential functionalities were found during the conducted interviews. These were divided in the same three categories (planning and routing, information hub, and decision making) and provided with the same annotations to indicate the level, strategic (S), tactical (T) and operational (O), as used in answering RQ2. The functionalities were given in section 4.3.

The willingness to use a control tower was also discussed. In general, it was found that there is some hesitation in using a control tower. This is mainly caused by uncertainty about the concept of control towers, and what it could do for the organisation itself and for logistical coordination in general. Most interviewed organisations were positive about the potential of a control tower. However, it seemed that further developments are required before organisations are fully willing to use a control tower.

7.1.5 The Proposed Functional Design

The first research objective was met in chapter 6. This objective focused on the functional design, and was formulated as follows:

RO1: Making a functional design for a construction logistics control tower for city development.

The design was made by first presenting requirements (section 6.1), which consisted of the combination of requirements from literature and from the empirical research. These requirements were divided in two: functional requirements and design requirements. The second step was finding the functionalities for the design, which were found through combining functionalities found in literature and those provided by the interviewed organisations. A selection was made using the business model canvas (subsection 4.1.3), the definition and purpose (section 4.1), and the vision of interviewed organisations (section 5.3). The selected functionalities were shown per category in Figure 6.1. Afterwards it was checked to see if the functionalities met the requirements. It was found that the minimal set of functionalities meets most of the posed requirements. Those not met were tested again after the design was presented, where it was found that they were not met.

The functional design was proposed in section 6.4 using the functionalities on one side. The other side describes the organisations that should be involved as data source for a control tower, along with their information and coordination systems and the data that resides in them. This is similar to the information provided by answering RQ3, which is shown in section 5.2. The functional design was presented in Figure 6.5.

7.1.6 Evaluating the Proposed Design

The second research objective focused on:

RO2: Evaluating the proposed functional design.

The design was evaluated on four points (see section 6.6): meeting requirements, validation, robustness of data input, and benefits of data sharing. It was found that the design meets the proposed requirements. Some requirements depend on the business model and facilitation of a control tower, and therefore could not be validated as this was not the focus of the thesis. The data availability was considered accurate by the interviewed organisations. However, not all presented data is available in ICT systems, and some data will not be shared easily. It was found that at least the contractor should be included along with either logistical service provider or wholesaler/supplier. The other data providing organisations should preferably be incorporated, but are not seen as necessary to carry out the functionalities. It was furthermore found that municipality and contractor stand most to gain from a control tower. Logistical service provider and wholesaler/supplier might perceive that the cost outweigh the benefits.

7.2 Recommendations

The recommendations derived from the thesis are divided in three parts: those for the construction industry, those for the municipality, and those for development and implementation.

7.2.1 Recommendations for the Construction Industry

The control tower operates in the construction logistics, therefore recommendations are posed for the surrounding environment: the construction industry. Several characteristics of the construction industry came to light while conducting the thesis. This was not limited to the conservative nature. For instance that the concept of just-in-time has a different definition per organisation, which all do not correspond to the meaning of just-in-time. Their interpretation is not delivery shortly before materials are required, it tends more towards delivery several days or weeks before materials are required. There could be lots to gain if just-in-time is implemented correctly, such as decreased inventory on site and more accurate material requirements as delivery time is closer to use.

Another concept that could be further developed in the construction industry is consolidation. Currently load factors of 50% are considered acceptable by organisations, while higher load factors could easily be achieved when consolidating. Some organisations try to accomplish consolidation or efficient use of equipment, which is not always desired by the collaborating organisation. Therefore it can be said that a start is being made, but there is still much to gain.

Most importantly there should be a change in behaviour within the construction industry. Currently the construction industry tries to keep the old proven ways. There are other methods that are proven in different industries, such as the food industry, or retail. Logistical schedules are more precise and without large failures in these industries. The construction industry should be more open towards new ideas, instead of waiting to see if others succeed. If all organisations adopt the wait and see strategy then the industry will remain the same, while new ideas can bring lots of benefits.

7.2.2 Recommendations for the Municipality of Amsterdam

This thesis was commissioned by the Municipality of Amsterdam, therefore there are recommendations for them specifically. First of all it must be said that the Municipality of Amsterdam stands to gain by using a control tower. A control tower is designed to enhance coordination in construction logistics, and thereby poses the following benefits for the municipality:

- Lower peak traffic intensity
- Less construction vehicles through the city
- Lower carbon and nitrogen emissions
- Increased liveability
- One central information stream
  - As single point of contact for a region
  - To see whether goals are met
  - As guardian of rules and agreements

The municipality could aid in awareness about control towers. Commercial organisations often wait until the municipality acts before making changes. Therefore the municipality should take a leading role when the control tower is ready to be implemented, at least when no other organisation is pursuing implementation. A control tower should be implemented as it poses lots of benefits to all actors involved. The municipality should not lead alone, but collaborate with contractors and wholesalers as they have further contacts, and are going to use the control tower on a more regular basis. The municipality should, however, not become the facilitating organisation for a control tower, as there are several organisations that perceive them to lack the know-how of construction logistics.

This recommendation is given as multiple organisations mentioned that lots of construction organisations wait until the municipality creates an incentive. These incentives could be obligation by legislation, but also by including the use of a control tower in the EMVI conditions. Other incentives could be the ease of getting logistical permits, or perhaps even financial aid. Furthermore, it was mentioned that the municipality should collaborate with other organisations while implementing new solutions. Organisations desire to decrease costs and project duration, while the municipality desires lower emissions, traffic intensity and nuisance. Both these desires can be met using a construction logistics control tower.

The key in the further development is collaboration between municipality, research institutes and organisations active in construction projects. The municipality and organisations are the end users. However, they have different view of what a control tower should do. In further development numbers from actual projects are required to first test in a simulation. Later projects can be used as experiments to see whether a control tower is beneficial in real life. Both municipality and the organisations active in an area should collaborate to let the experiment run its course, and yield valuable results. The development upon test phases should be done by research institutes. These institutes should keep close contact with the municipality and other organisations to see whether all desirable features are included.

To conclude, further development should be done in cooperation with research institutes and organisations active in construction logistics. The municipality should aid in the implementation of a control tower through collaboration, without becoming the owner. Implementation could be aided by legislative, financial or non monetary benefits. Facilitation and ownership should, preferable, be done by a new organisation that has knowledge about all aspects of construction and construction logistics, and is perceived to be capable, neutral and trustworthy.

7.2.3 Recommendations for Development and Implementation of a Control Tower

Recommendations for further development or implementation of a control tower are presented in this subsection. The first is make a common vision known throughout construction supply chains. Currently the visions of what a control tower is, what its functionalities are, and what benefits it has are not aligned amongst different organisations. Steps could be taken towards implementation when this common vision is spread and accepted throughout the supply chain. The implementation could be best done by a neutral, independent and new organisation. This organisation needs knowledge of logistical processes and construction projects. Furthermore knowledge about ICT systems is required, as a control tower integrates different ICT systems. It should be a new organisation as there would not be agreement about which organisation will be best suited to implement a control tower. All organisations involved in construction logistics have their benefits and downsides.

A control tower should furthermore be made modular. Each organisation should be able to choose the functionalities it requires. This does not only apply to organisations, but also to the public as some information might be desirable for them. It should, however, be ensured that organisations do share their data to ensure more functionalities can be enabled than available in their module.

A recommendation for further development would be to look into the field of data and information science, as this field poses many implications for a control tower. Data integrity and quality are most important, but also who is responsible if data is incorrect or missing. Further development must be accompanied by continues involvement of the target user group. This thesis proposed a functional design from interviews, but as time progresses some functionalities and requirements might shift. Moreover, it was found that some potential users did not see the benefit yet. When users are continuously involved they help shape the end result, and thereby could become more interested.

In short, for further development and implementation it is required to first create a common vision. A construction logistics control tower shall be harder to implement without the common vision about what a control tower is and what value it adds. More information should be gathered about a potential facilitator. Not just who it should be, but also what it exactly is going to do. From the common vision a technical design can be made while involving the facilitator and potential users.

7.3 Limitations and Future Directions

During a master thesis there is no room to pursue all directions possible. Choices have to be made, resulting in directions for further research. The focus of this thesis lied on making a functional design, leaving out the technical specifications of a control tower. Therefore certain aspects such as how different ICT systems need to be integrated, or how data exactly is shared are left out. These and other information and data related questions should be investigated during further research. Some of these limitations have already been mentioned such as information quality and integrity. In addition it should be investigated if a control tower could be possible from a technical perspective.

The thesis had a focus on the tactical and operational level, leaving out the strategic level. This level might be most interesting to contractors and municipalities, as up front agreements and decisions have a large impact on the remainder of the construction project. Therefore the strategic level needs to be taken into account in further research. Another future direction could be to include more information sources and functionalities. In this thesis four organisational types were interviewed, while there are many more. A control tower could even be used for emergency services or include more information about the area. Examples could be forecasted flood plains or location of electrical wires in the ground.

Further research could be done in when it is desired to use a control tower. Not all situations could be suitable for a control tower, think of small size projects, or too many projects. This was not found in the searched literature. Interviewed organisations stated that it should either be large scale or multiple projects. The entire magnitude was not discussed. During this future research calculations of total volume transported could be made, which also is beneficial for municipalities.

Another future direction could be the alignment of supply and demand, not just of materials but also of personnel and equipment. Currently equipment and personnel stationed in Amsterdam drives to Rotterdam to conduct work, while there is a similar flow in the other direction. This results in unnecessary travelling causing loss of time and higher greenhouse gas emissions.

A final future direction came to light during the conducted interviews. This was the optimisation of electrical heavy duty equipment use, such as asphalt rollers. This equipment most of the time is highly specialised, but required for multiple projects. Using electrical equipment has large benefits for the working environment and nature, but can not be operational all day long due to battery life. Therefore optimisation of loading and use times is required. This equipment could be owned by a white label to ease the use by different organisations.

7.4 Reflection

In this section a short reflection is given from a scientific and personal perspective. The scientific perspective focuses on the gathering of knowledge and shows the contribution to the scientific literature. The personal perspectives focuses on what could have be done differently to make the thesis go more smoothly.

7.4.1 Scientific Reflection

The subject of construction logistics control towers is relatively new, which is reflected in the literature, as there was not a lot of literature about the subject of control towers in the field of construction logistics. Most of the literature about control towers is from the aviation industry, which is a different concept. Nevertheless there was enough literature to provide a good knowledge base. The conducted interviews furthermore provided a clear view of why the thesis was relevant, and gave a sense of direction.

The proposed design describes the systems used by organisations and the data available in these organisations. The design also shows potential functionalities for a control tower along with their data requirements. These potential functionalities aid towards creating a business case for a control tower, which was not yet clearly defined in the literature. Moreover, through stakeholder involvement it was found that there was no common vision of what a control tower encompasses amongst intended users. Therefore it can be said that the artefact designed during this thesis adds to the literature and has social relevance.

7.4.2 Personal Reflection

If I would have to start all over again, I would start exactly the same. Search the literature to gather as much knowledge about a construction logistics control tower as possible. What I would do differently is to categorise the literature and make annotations about what is in the articles, instead of copying large pieces of text that might seem relevant. It turned out that three quarters of my original relevant text was not important. The conducted interviews helped me in gaining a clearer view of how the construction industry operates. It furthermore helped me to see the relevance of my thesis, and create a clearer picture of what a control tower encompasses. During the interviews I sometimes did not get a clear answer. Therefore, if I would start over, I would summarise the answer and ask if that is correct or not. Moreover, I would ask if they would see potential in a control tower, who should facilitate one, and what drawbacks might be. These questions came to light during later conducted interviews. Nevertheless I would not change the large lines in which the thesis was conducted, as the process shaped the end result. Therefore if this thesis would start again the end result might be different as the process shapes the end result.

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Appendix A: List of Projects in Amstel III

Current and future projects in the case area can be found in two websites from the municipality of Amsterdam. The first website is the implementation program 2020, which shows all projects to be started in 2020. The second website shows all projects currently ongoing or to be started in Amstel III. The projects shown on this second website might have an overlap with projects from the implementation program as 2020 is progressing while this thesis is written. The information provided in Table A.1 is all the information that is publicly accessible. For further information the project client needs to be contacted. The information from the table and figure gives an idea about the area and the redevelopment plans.

Table A.1: Elaboration current and future projects Amsterdam Amstel III (Municipality Amsterdam, n.d.-g, 2020a).

P#:	Project Name:	What:	Scheduled:
P1	Werkerf III	Redecorate public space, improve traffic safety (parking spaces) and elevate social safety (clean and very safe)	13 Jan 2020 - 17 Dec 2021
P2	SPOT	Realisation new neighbourhood: Completing 1100 houses and redecorate public space	1 Jun 2020 - 31 Dec 2023
P3	Hettenheuvelweg: living and working in a green environment	Demolition office building and construction residential tower	2021 - 2023
P4	KARSP: residential tower in Bullewijk	Adapting two office buildings into residential towers	Mar 2019 - 2022
P5	Hessenbergweg area: ready for the future	Area transformation into a living city area with a.o. around 2000 new houses, a school, a church and 40.000 m2 working space	2021 - unknown
P6	Paasheuvelweg 17: from office building to housing	Transformation of office building into a residential tower	2020 - 2021
P7	Pietersbergweg en Paalbergweg: street redesign	Redesign to 30 km/h zone, bike parking spaces, underground waste container and sustainable lighting	2020 - 2021 (8 weeks)
P8	Trinity: island inhabitants in Amstel III	Transformation Trinity buildings from office buildings to residential towers	Apr 2020 - Sep 2021
P9	Train track park: green carpet along the train tracks	Turning the green area into a city park with biking lane	Jul 2020 - 2021
P10	OurDomain: living and relaxing for students, starters and status holders	Constructing three residential buildings with a public park in between	2018 - 2021

Table A.1: Elaboration current and future projects Amsterdam Amstel III (Municipality Amsterdam, n.d.-g, 2020a).

P#:	Project Name:	What:	Scheduled:
P11	Square station HOLENDRECHT, AMC side and bus station	Demolition dry running, removal of biking lane and walking bridge, elevating biking lane and pedestrian area, and redesign square	29 Okt 2018 - 1 Jan 2021
P12	Meibergdreef zone: from divider to connector	Renewal public space	2020 - 2023
P13	Entry area AMC: green oasis	Redesign entry area Amsterdam UMC, location AMC, from concrete to green environment	2020 - 2021
UP1	De Loper / De Passage, Kavel 15	Site preparation and construction of office buildings	6 Jul 2020 - 19 Jul 2022
UP2	JC Arena	Renovation and restoration facades (3 phases) for expansion Johan Cruyff Arena	2 Sep 2020 - 9 Aug 2023
UP3	Trailer parking	Realisation of 40 lorry parking spaces	1 Feb 2021 - 14 Jun 2022
UP4	Urban Interactive District	Site preparation, construction parking garage and constructing 4 residential towers	6 Jul 2020 - 9 Sep 2024
UP5	Haaksbergweg / Entry	Site preparation for first part underground access tunnel to parking garage on adjacent building plot UID.	6 Jul 2020 - 7 Sep 2021
UP6	Dreefkwartier	Site preparation ground, sheet piling, constructing tower and arrange public space	6 Jan 2020 - 4 Jul 2022
UP7	A9 Gaasperdammerweg and A2 junction Holendrecht North and South	Widen to 2x5 lanes and alternating strip including constructing a tunnel in context of program Schiphol-Amsterdam-Almere	1 Jun 2015 - 31 Dec 2020

Appendix B: List of Construction Project KPI's

Table B.1 uses the same categories as described by Supply Chain Council (2010) for the SCOR-method. Each category has several indicators to measure how each category scores. The numbers behind the indicators are linked to Figure B.1 to provide a visualisation. These indicators can be measured in different parts of the supply chain: at the supplier (S), from supplier to construction site (S-CS), from supplier to hub (S-H), at the construction hub (H), from hub to construction site (H-CS), on construction site (CS), or during the return stream (R). The indicators can be measured during certain phases, during shell construction (Sc), making the structure wind and water tight (Wp), during final construction (Fc) and while finishing the interior (In), although some can be measured in all phases. The measured indicators have an effect on the supply chain itself, internal effect (I), or an effect on the surroundings, external effect (E).

Table B.1: Key Performance Indicators, as proposed by Vrijhoef and van Dijkhuizen (2015, p. 3-4).

Category:	Indicators:	Chain:	Phase:	Effects:
Reliability	Percentage deliveries on time (1)	S-CS, H-CS	all	I
	Percentage orders meeting requirements (2)	S-CS, H-CS	all	I
	Waiting times caused by fail orders	CS	all	I
Responsiveness	Unloading times at site (3)	CS	all	I, E
	Waiting times for transportation (4)	CS	all	I
	Transport speed hub to site	H-CS	all	I
	Unloading times hub	H	Wp, Fc, In	I
	Loading times hub	H	Wp, Fc, In	I
	Waiting times hub	H	Wp, Fc	I
Agility	Throughput times call hub (5)	H	Wp, Fc, In	I
	Throughput times supplier (6)	S	Sc, Wp	I
Costs	Number of transport movements	S-CS, S-H, H-CS	all	I, E
	Number of avoided movements	S-CS	all	I, E
	Distance (km) transported (7)	S-CS, S-H, H-CS	all	I, E
	Avoided distance (km) transported (8)	S-CS	all	I, E
	Waiting times transport, construction, hub (9)	S-CS, S-H, H-CS	all	I, E
	Logistical costs per m^3/kg material	S-CS, S-H, H-CS	all	I
	Costs/Benefits hub	H	Wp, Fc, In	I
	Site productivity (18)	B	Wp, Fc, In	I
Assets	Consolidation degree hub (10)	H	Wp, Fc, In	I
	Occupancy rate	H	Wp, Fc, n	I

Table B.1: Key Performance Indicators, as proposed by Vrijhoef and van Dijkhuizen (2015, p. 3-4).

Category:	Indicators:	Chain:	Phase:	Effects:
	Stock level hub (11)	H	Wp, Fc, In	I
	Load factor weight (12)	S-CS, S-H, H-CS	Sc, Wp	I
	Load factor volume (13)	S-CS, S-H, H-CS	Wp, Fc, In	I
	Load factor distance	S-CS, S-H, H-CS	all	I
Environment	CO2 emissions (14)	S-CS, S-H, H-CS	all	E
	NOx emissions	S-CS, S-H, H-CS	all	E
	PM10 emission, fine dust	S-CS, S-H, H-CS	all	E
	Waste reduction (15)	S-CS, S-H, H-CS, CS	Wp, Fc, In	E
	Recycling degree	S-CS, S-H, CS	Fn, In	E
	Nuisance involving construction traffic to site (16)	S-CS, S-H, CS	all	E
	Incidents involving construction traffic to site	S-CS, S-H, CS	all	E
	Accidents involving construction traffic to site	S-CS, S-H, CS	all	E

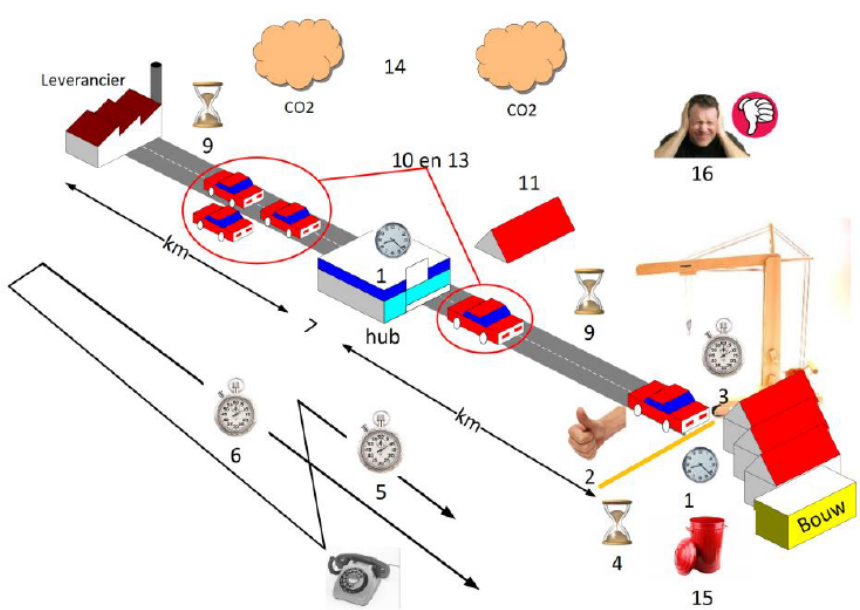

Figure B.1: Key performance indicators visualisation, as proposed by Vrijhoef and van Dijkhuizen (2015, p. 4).

Appendix C: More Coordination Systems from literature

Different ICT systems have been described in the main body of this thesis (see section 3.5). These were not all systems found in literature. The following systems were found but were not used by companies (section 5.2) or incorporated in the design (section 6.4). These systems are noteworthy as they could be used in the construction industry.

Manufacturing Resource Planning

Manufacturing resource planning (MRP) is used to align demand and supply for manufacturing. This is done by forecasting the demand and adjusting the production and distribution to supply the forecasted demand. Using the forecast all other schedules are made, thereby adjusting processes so the supply will be as close as can be to the forecast. These forecasts thus are made to plan the resources needed for manufacturing. Using MRP can lead to reduction of inventory, improved service and enhanced efficiency (Shehab et al., 2004).

Material Requirement Planning

Material requirement planning (MRP-II) was first used when MRP systems expanded from planning resources needed for manufacturing to planning resources for the entire firm (Shehab et al., 2004). MRP-II not only plans material needs but also the required personnel and machine capacity (Shehab et al., 2004). According to Stadtler and Kilger MRP and MRP-II systems are most of the time integrated in current ERP systems (Stadtler & Kilger, 2008).

Collaborative Planning, Forecasting and Replenishment

With collaborative planning, forecasting and replenishment (CPFR) supply chain partners exchange more than just orders and shipment notices, sales plans and production forecasts are also shared (Davenport & Brooks, 2004). By doing so supply chain partners can synchronise their processes more fully which result in higher efficiency. CPFR is a collaborative initiative intended to improve relationships through joint planning (Hollmann et al., 2015). It incorporates sharing of information, risk, benefits, cost and forecasts, aiming to optimise supply chain performance and efficiency. According to Hollmann et al. CPFR results in *"first, improved service level while simultaneously reducing inventory and costs; second, promotion of greater integration, visibility and cooperation among partners; and third, a holistic approach to SC management"*(Hollmann et al., 2015, p. 975). The article by Hollmann et al. also includes a list of barriers to CPFR, which are summarised as: *"investments in technology, a lack of internal integration/collaboration, a lack of a clear understanding of collaborations and SCC's impact from long-term partnerships on profit earnings, information security and confidentiality, system incompatibility, over-dependence on technology when implementing CPFR, lack of ability to differentiate between with whom to collaborate and in what order and security protocols"* (Hollmann et al., 2015, p. 981).

Delivery Management System

Delivery management systems (DMS) manages the movement of vehicles going in and leaving from the construction site (Lundesjö, 2015). A DMS functions in the operational field, creating value for daily operations. It is used to give site managers control over delivery schedules, provides notifications of arrival times and helps site managers appoint the right place to the right product (Lundesjö, 2015). This is all done according to prior made plans, which are gathered in a DMS. These plans include delivery points, site lay-outs and scheduling for waste removal. According to Lundesjö current users mostly are larger companies developing larger construction sites that are often located in urban areas with traffic congestion problems (Lundesjö, 2015).

Appendix D: Municipality Departments

The municipality of Amsterdam consist of different departments having their own role and purpose within the municipality. When a construction project is to be undertaken the following departments might be involved, depending on the nature of the project. These departments are explained along with their connection to construction projects or construction logistics.

Project Engineering Bureau

The project engineering bureau Amsterdam is an independent advice and engineering company within the municipality of Amsterdam. They have expertise in the fields of structural engineering, infrastructure, traffic, environment, city greenery and public space (Municipality Amsterdam, n.d.-e). It acts as independent advisor at large and important construction projects, such as the North/South line and IJburg. the engineering bureau developed a calculation model for construction logistics which visualises the impact of a project on its environment.

City Management Office

The city management office supports the coordination system "Road Construction" and advises the city director (Municipality Amsterdam, n.d.-b). Together they are committed to keeping the city accessible, liveable and safe during construction works. Together with the city director they try to align projects to reduce nuisance and costs.

Mobility and Public Space

The department of mobility and public space concerns itself with accessibility, safety, design and quality of the public space within Amsterdam (Municipality Amsterdam, n.d.-j). They contribute to all levels of accessibility and mobility: international, national, regional, city level and local.

City Development

City Development shapes the growth and development of Amsterdam to realise policy goals in housing and area development. Their core activities are: site preparation of municipal ground along with leasing the grounds, management of properties, and financial and economical aid and management of spatial projects (Municipality Amsterdam, n.d.-d).

Planning and Sustainability

The planning and sustainability department concerns itself with sustainable spatial planning. They try to design the scarce space of the city with the growing number of inhabitants in mind, while ensuring the quality and sustainability of the projects at hand (Municipality Amsterdam, n.d.-i).

Project Management Bureau

The project management bureau provides the project management for complex multidisciplinary and integral projects in the social, physical and economical domain (Municipality Amsterdam, n.d.-h). The bureau collaborates with and can be commissioned by other departments, in order to develop new knowledge and ways of working that suit the issues of today and tomorrow. Their core activities are: project-, process- and program management, construction management, planning and structural consulting, and project consulting and support.

Coordination System

The coordination system focuses on projects taking place in the public space of Amsterdam. These projects have to follow the code of conduct described in the system. The coordination system is not a single but alliance of different departments within the municipality (Balm et al., 2018). This system has as goal to minimise nuisance and cost by optimisation of the CLP aspects and by making work with work (Municipality Amsterdam, n.d.-f). Making work with work can be considered as doing some extra work while the main activity is carried out. Part of their activities is to monitor the number of projects taking place, and to combine or adjust planning schedules when needed (Balm et al., 2018).

Appendix E: Systems used by Interviewed Organisations

E.1 Contractor

An overview of the data from a contractor was presented in Table 5.3. The systems provided in that table are elaborated on further in this section.

Kyp

Kyp originated from a desire to communicate better with all parties involved within one project (Kyp, 2014). Using Kyp should facilitate a more LEAN planning on the construction site and chain wide integration by communicating progress made of the project (Kyp, 2014). It is designed to introduce and keep track of the construction planning and its activities during the construction process (van Merrienboer & Ludema, 2016).

BIM

Building information model or BIM has been elaborated on in subsection 3.5.6. Most of the interviewed contractors stated that BIM is used for its 3D representation of projects, with an ambition to move towards 4D and hopefully 5D. Some contractors stated that BIM is used to start calculating material requirements. There are some problems, one of them is that BIM sees some parts as one piece, instead of a composition. One example is a window frame, BIM sees it as one part, instead of a composition of four wooden beams. This does not help in making the bill of materials, as it can not be translated one on one.

GIS

In subsection 3.5.4 it was described what geographical information systems (GIS) are. Some of the interviewed organisations use GIS for multiple purposes, of which real time traffic monitoring is one. The traffic information is used for optimal route calculations. Besides traffic, safety is one of the considerations of route choice. GIS also provides an overview of education locations, hospitals and other places where safety matters most. This helps in finding the optimal route for transportation. Furthermore opting for the safest routes is one of the prerequisites in a CLP/BLVC (Croydon, 2015). GIS, however, requires input from other traffic management systems to calculate optimal routes. This information can be provided by traffic information towers or models used by the municipality (see subsection 5.2.2. Besides optimal route choice GIS can be used for 2D drawings of a project. The interviewed company stated that they are investigating the integration of 3D drawings in GIS. One of the interviewed contractors uses GIS to track and trace their vehicles. This data is then used to make adjustments in road construction planning to time the arrival of new product optimally. Furthermore GIS is used for day to day (operational) planning.

Construction Ticket System

A construction ticket system is used to plan arrival times of vehicles either delivering or picking up materials and equipment. Time slots are claimed by a transportation company to meet demands posed by the project. When a time slot is claimed information about the materials to be delivered need to be given as well. This way contractors have insight in what will be delivered when in order to assign temporary storage places and make a horizontal transportation schedule. This construction ticket system can be considered as plug and play, as each construction project can have one while a transportation company can log in to both.

E.2 Municipality of Amsterdam

An overview of the data from the Municipality of Amsterdam was presented in Table 5.4. The systems provided in that table are elaborated on further in this section.

Data Point

The data point is a central information storage, consisting of all kinds of information available to the public. The goal is to speed-up the data-innovation within Amsterdam (Municipality Amsterdam, n.d.-k). The information stored in the data point can be connected systems by using API's.

MOCO

The monitoring project (MOCO) is used to measure traffic intensity on corridors of Amsterdam. This is done using camera's that scan number plates and store them along with a time stamp (Lie, 2012). The data that is collected by MOCO is used by the traffic model Amsterdam. This traffic model is used for strategic road and public transport research (Municipality Amsterdam, 2020b).

CORA

CORA is a website used by the municipality in which all construction activities are indicated, ranging from minor road repairs to large development projects. This website is currently not publicly accessible. CORA holds all sorts of information for construction projects, and therefore can be used to coordinate construction activities on a strategic level. The input for CORA is most of the time provided before a project starts, and therefore it has less value on the tactical and operational level.

MobiMaestro

MobiMaestro is a network wide traffic management coordination system made by Technolution (Technolution, 2020). It has an open architecture and is constructed modularly, which makes it possible to only incorporate what is needed. The different modules are shown in Figure E.1. Road managers of local governments, including Municipality of Amsterdam, use MobiMaestro to get real time information about several topics including traffic and incidents. Using MobiMaestro gives the ability to, amongst others, adjust road signs and reroute part of the traffic.

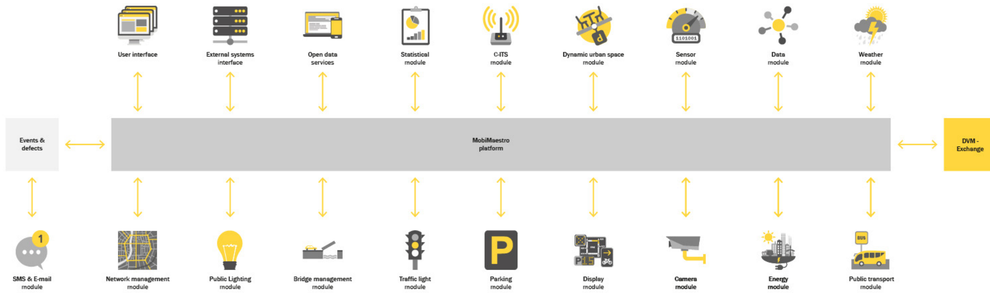

Figure E.1: MobiMaestro modules as proposed by Technolution (2020).

Maps

The municipality of Amsterdam has several maps with different purposes, the four maps discussed are open source. Two of these show the projects currently in progress and those planned within the near future (Municipality Amsterdam, 2020a, n.d.-g). Another map is designed to show the top 15 data categories[1] required to further digitalise Dutch infrastructure (matrixianpublic, n.d.-b). Currently the map shows restrictions on weight, length, width, and height, preferred routes, entry time windows, environmental zones, hazardous substance routes, (un)loading areas, parking places and parking restrictions (matrixianpublic, n.d.-a). A fourth map can be used for all kinds of purposes, such as charging points for electric vehicles, zone restrictions and preferred routes[2]. There is a certain overlap with the data top 15 map. The data top 15 map, however is more detailed, while the other map has a more diverse range of use.

E.3 Wholesaler/Supplier

An overview of the data from a wholesaler/supplier was presented in Table 5.6. The systems provided in that table are elaborated on further in this section.

SAP

SAP started as an ERP system but evolved in *"end-to-end enterprise application software"* (SAP, n.d.). It can be considered as a combination of different systems as it combines ERP, CRM, WMS, finance and other applications into one system. One of the interviewed organisations stated they mainly use SAP as WMS and link to the sales department. WMS systems have been elaborated on earlier in the report in subsection 3.5.5.

[1] Planned and current road works, incidents, duration of incidents, maximum speeds, signs (commandment and prohibitions), control scenarios from traffic management centres, real time highway images, if a bridge is opening, static and dynamic parking data, event date, iVRI data (incl. topology), data for logistics (including environmental zones, (un)loading areas, clearance heights), and cycling data (matrixianpublic, n.d.-b).

[2] All categories are: real estate, area classification, height, parking, energy, historical maps, public transport network, environmental zones, charging points, parking spaces, traffic - routes, municipal notices, waste containers, safety and nuisance, cultural heritage, events, shopping areas, establishments, cab, logistics, substrate, soil quality, explosives, sound zones, Schiphol, risk zones, panorama images, and land exploitation (Municipality Amsterdam, n.d.-c)

Other

Logistical planning by hand as it is tailored to the customer needs. Therefore no systems are used to do logistical planning. There is a system that keeps an overview of all manually made transport movements. This system includes information about what is transported, point of destination and planned time of arrival.

E.4 Logistical Service Provider

An overview of the data from a logistical service provider was presented in Table 5.5. The systems provided in that table are elaborated on further in this section.

Own systems

An interviewed logistical service provider stated that they build their own planning software. They use the information provided by contractors to make their schedules. The information required to make the schedules is; information about the material/goods to be transported in order to choose the right equipment for the job, secondly information about time is needed thus when is the equipment needed and how long is it required. The planning can be adjusted one hour in advance. Furthermore the personnel tries to ensure each vehicle is used as best as possible, which sometimes results in one vehicle being used for multiple projects during the same day.

GPS Buddy

GPS Buddy offers solutions to reduce administrative overhead, cost optimisation, and insight & monitoring (GPSBuddy, 2020). It is mostly used for fleet management and can be incorporated to TMS, ERP or other planning systems. The interviewed organisation uses GPS Buddy to track their fleet, route planning, monitoring of daily planning and as general a planning tool.

OutSmart

OutSmart is an optimisation app for work processes and has the following functionalities: purchase order management, planning and tracking, CRM, offers, invoices, contracts, project management, forms, internal management, time registration, and Customer portal (OutSmart, 2019). The interviewed organisation mainly uses outsmart for CRM, planning, and tracking.

E.5 Other Information Providers

An overview of the data from a other information providers was presented in Table 5.7. The systems provided in that table are elaborated on further in this section.

Subcontractor

Subcontracts have information about the amount of work they can perform in a certain time period. Furthermore they have practical information about the materials needed to do certain work and can give a cost estimate for their labour and materials. These can be provided over the phone or via email. Some contractors could also provide the capabilities of the subcontractor through experience.

Weather

Weather information can be found in all sorts of websites and weather stations. These give insight into current and forecasted wind speeds, rainfall and temperature. There is a problem with forecasts as long term weather forecasts are less accurate than short term forecasts (Cappucci, 2019; SciJinks, 2020). A seven day weather forecast is 80% accurate, while a ten day forecast is 50% accurate (Cappucci, 2019).

Event Information

Finally information about large events is available. This could be football matches, Pride Amsterdam (the canal parade) or other similar large events. These events have an effect on the amount of people moving through the city, traffic and availability of public space. Therefore these events can have an effect on construction logistics and construction safety. These events have information available about location, date, duration, expected number of people, and expected number of vehicles.