BIM or BIM data supporting construction logistics in a Construction Project Logistics System (CPLS) within an inner-city project context

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Abstract

Inner-city construction logistics causes several challenges from both the perspectives of municipalities regarding city-mobility as well as contractors in regards to reaching projects goals in terms of time and costs. Scholars devoted substantial effort to improve construction logistics and pointed out the opportunities of BIM-application within this context in providing best-practices. This study provides for a modular logistics system to obtain an effective Construction Logistics Management (CLM) organisation for inner-city projects. This, by adopting those best practices that are relevant for the context of the project. Qualitative research is conducted by using an in-depth case study on a large inner-city project to collect field notes for four months on a full-time base. Archival research is performed within the same period and eleven semi-structured interviews are conducted.

The inner-city context requires an explicit level of control as there is little room for deviations. Therefore, a Construction Project Logistics System (CPLS-framework) is developed emphasising logistical process control including three dimensions: A governance strategy for project-based CLM in which a strategic, tactical, and an operational level are defined, an element of production control which is provided by Last Planner Systems (LPS), and an element of production system improvement by introducing the Plan-Do-Study-Act (PDSA)-cycle of Deming. This framework is used to capture the planned and the operational logistics process on the case-project. Subsequently, a gap analysis is performed for which a set of People, Process, Technology and Contracts and liabilities (PPTC-framework) conditions are used. The results of the gap analysis provides a list of 23 barriers for the adoption of a BIM-based CPLS.

It is concluded that the CPLS-framework can be used as a tool to design and obtain effective CLM on inner-city construction projects. The framework provides great flexibility in the design of a logistics system which can be tailored to the context of the project it is applied to. Besides, three enabling conditions have been derived for an effective implementation of a BIM-based CPLS using the comprehensive list of barriers, which are: knowledge requirements, process and procedures, and contracts and liabilities.

Frontispiece

"An efficient IT system will bring together the processes and the people who use it"
Sommerville and Craig

"The difficulty lies not so much in developing new ideas as in escaping from old ones."
John Maynard Keynes

"If you always do what you've always done, you'll always get what you've always got."
Henry Ford

"Everyone has a plan until they get punched in the face"
Mike Tyson

"Uncontrolled variation is the enemy of quality"
Edwards Deming

Management summary

Key words: *Construction Logistics Management, BIM, logistic BIM-applications, Construction Project Logistics System (CPLS), Last Planner Systems, enabling conditions*

Purpose – Both scholars and practitioners from the industry indicate a significant need to change how construction logistics is organised, primarily in an inner-city context. Current practices affect both city-mobility aspects and are found to be a barrier in reaching construction project goals in terms of time and costs. This thesis seeks to use Building Information Modelling (BIM) and logistical BIM-applications holistically to obtain an efficient construction logistics management process in inner-city construction projects. As a consequence, the results should benefit the general contractor in setting and maintaining a Construction Project Logistics System (CPLS) and therefore support construction logistics management on inner-city projects.

Methodology – A single case study approach is used to collect qualitative data of an operational construction project logistics system. Field research has been conducted on a large construction project for four months between October 2019 till February 2020 by using observations, taking interviews, and performing archival research.

Design and Theoretical Approach – A theoretical foundation is used to conduct the study by developing a CPLS-framework. This by defining a construction logistics governance strategy and subsequently integrating Deming's PDSA-cycle for continuous production process improvement using Last Planner® principles. This framework emphasises logistical control and defines the organisational aspects of a logistics system on construction projects. Logistical Components (LC) are introduced to allow the development of a CPLS-layout, which provides for information exchange between LC and enables a logistical process. The role of BIM and logistical BIM-applications are subsequently found to be promising LC. Additionally, the importance of People, Process, Technology, and Contract and liabilities (PPTC) is studied to outline a set of PPTC-framework categories and conditions to assist in defining enabling conditions for an effective BIM-based CPLS-layout implementation.

Findings – The abilities of BIM and logistics BIM-applications is recognised as BIM enables to improve CLM on the three aspects: process management, logistical plan-making, and progress monitoring and control. Also, the CPLS-framework is found to be an effective tool as it emphasises logistical control which is considered essential in an inner-city context. The framework can assist in a flexible/tailored manner to obtain a holistic approach for CLM on construction projects considering various LC based on best practices in the industry. It guides in reaching logistics related objectives tailored to the project context, being the project objectives and resources. Moreover, a set of three enabling conditions is found for and effective implementation of a BIM-based CPLS. These are the conditions knowledge requirements of BIM, process and procedures, and contracts and liabilities.

Originality / Value – The findings of this thesis adds to the existing knowledge base on construction logistics management, and BIM for logistics, since it provides for a holistic approach that supports to develop a CPLS tailored to a project context. The presented framework confronts the problem in a different way. Existing literature promotes good logistics but seeks to focus on specific aspects of CLM and does not explicitly emphasises logistics control which is required in an inner-city context.

Conclusion –. This thesis has indicated how an effective BIM-based CLM process can be obtained in inner-city construction projects by using the CPLS-framework. The framework allows to design a CPLS-layout tailored to the project and provides a holistic approach for CLM on projects. Furthermore, it has indicated three enabling conditions being knowledge requirements of BIM, process and procedures, and contracts and liabilities that should be satisfied to allow and effective implementation of a BIM-based CPLS-layout.

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List of Abbreviations

3D-SLP	Site layout planning in 3D
4D-SLP	Site layout planning in 4D (including a time aspect)
AI	Artificial intelligence
AR	Augmented reality
BIM	Building information modelling
CCC	Construction consolidation centre
CLM	Construction logistics management
CPLS	Construction project logistics system
DMS	Delivery management system
ETO	Engineer to order
GC	General contractor
GHG	Greenhous gas
GIS	Geographic information system
IOT	Internet of things
IT	Information technology
JIT	Just in time
LC	Logistical components
LMT	Logistical management techniques
LPS	Last planner systems
MEP	Mechanical, electrical, plumbing
PDCA	Plan, do, check, act
PDSA	Plan, do, study, act
PPT	People, process, technology
PPTC	People, process, technology, and contracts and liabilities
RFID	Radio-frequency identification
VCM	Virtual construction model

Chapter 1 – Introduction

There is a significant need to change the way construction logistics is organised, primarily in dense urban areas, as will be discussed in this chapter. Furthermore, a brief introduction to Construction Logistics Management (CLM) is provided and several developments are introduced to improve practices in construction logistics. Next, the role of BIM in construction logistics is discussed, and a gap in literature regarding the use of BIM in CLM is indicated. Finally, the objective, research method, and the research questions are provided.

1.1. The challenges in inner-city construction logistics

The need to improve construction logistics in an inner-city context is indicated in this sub-section from the perspective of municipalities regarding city mobility and the quality of life in cities and from the perspective of the construction industry itself.

1.1.1. The importance of logistics from a city perspective

Cities heavily depend on their logistical system as it impacts their attractiveness to various corporate groups as well as the quality of life for residents (Ploos van Amstel, 2016; Quak et al., 2011; Dijkmans et al., 2014; Janné et al., 2018). However, many cities cope with logistical challenges due to an increasing number of vehicle movements over the last decades. The construction industry has a significant share in the number of vehicle movements, and transport related pollutions (Ploos van Amstel, 2016; den Boer *et al.*, 2017; Janné *et al.*, 2018). Future predictions show an ever growing impact of construction logistics on city mobility caused by sustainability targets (Krumme, 2019), and an expected increasing number of city inhabitants (Zijm and Klumpp, 2016).

The current housing stock requires net-zero retrofitting and reductions in the level of Greenhouse Gas (GHG) emissions (BZK, 2014; Saheb et al., 2015), which increases the demand for renovation projects. Additionally, an ever-increasing world population is expected which results in higher demands for housing, food, transport, et cetera in general, on a global level (Kovacs and Kot, 2016; Ploos van Amstel, 2016; Zijm and Klumpp, 2016; Janné *et al.*, 2018). Worldwide urbanisation boosts these demands in cities even more, causing increasing demands for construction projects and services in cities and more construction related logistical movements (Janné, 2018; United Nations, 2018).

1.1.2. The importance of logistics from a contractor's perspective

However, many contractors do not realise the importance of logistics, causing logistics to be undervalued in the industry (Fadiya, 2012; Robbins, 2015), even though 80% of construction activities are related to logistics (Lundesjö, 2015b). A lack of transparency in logistical costs makes it challenging to show the benefits of efficient logistics in practice (Sullivan, Barthorpe and Robbins, 2010; Browne, 2015), and therefore hard to justify investments to improve practices (Sommerville and Craig, 2006; Sloot *et al.*, 2017). However, literature indicates that a more efficient logistical organisation can result in time as well as cost savings, by reducing failure costs and increasing the productivity on construction sites (Sullivan, Barthorpe and Robbins, 2010; Methanivesana, 2012; Ekeskär and Rudberg, 2016; den Boer *et al.*, 2017; Dixit *et al.*, 2017; Janné *et al.*, 2018; Dubois, Hulthén and Sundquist, 2019).

Therefore, there is a lot to gain in construction logistics (Lange and Schilling, 2015; Lundesjö, 2015b). Especially in inner-city projects, where space on construction sites is often limited and the surrounding environment provides for additional challenges. Numerous stakeholders are often involved which should all be considered, making it hard to deviate from plans (Kooragamage, 2015). These challenges should be carefully considered in optimising construction logistics within this specific context.

1.2. Tools and methods to support Construction Logistics Management

Construction Logistics Management (CLM) can be divided into supply-logistics and site-logistics (Silva and Cardoso, 1999; Sundquist, Gadde and Hulthén, 2018). Sloot et al. (2017) described construction logistics as a process in which both the physical flow as well as the information flow are considered through planning, organisation, management, and the control of resources. This logistics information flow is leading in this research as it aims to manage construction logistics on projects, the physical flow is therefore subordinated (Browne, 2015; Lange and Schilling, 2015). Logistics Management Techniques (LMT) are often based on lean principles, such as Just In Time (JIT) (Altintas, 2013), demand smoothing and reverse logistics (Waddell, 2015), and the use of prefabrication (Dakhli and Lafhaj, 2018).

Additionally, the implementation of BIM had its impact on CLM, especially in the last decade. BIM is seen as the main enabler to control and support CLM as BIM data provides essential logistical relevant information such as quantities, volumes, locations, and it enables transparency and interoperability (Eastman, 2011; Sloot, 2018; Whitlock *et al.*, 2018). Besides, the maturity in the use of BIM is constantly growing (Jayasena and Chitra, 2013; MHC, 2014), providing new opportunities for logistics as well. Therefore, digital technologies, often BIM-based or BIM supported, to improve construction logistics, which are discussed widely in literature (Pérez, Fernandes and Costa, 2016; Whitlock *et al.*, 2018).

1.3. The need for a project specific approach for CLM

The logistical management approaches, logistical concepts and the logistical BIM-applications can be defined as Logistical Components (LC). They are stand-alone solutions serving different elements of CLM, such as customer service, transport management, inventory management, material management, policies and procedures, facilities and equipment, and many others as indicated by Rudberg and Maxwell (2019).

BIM is interesting to support CLM, since different BIM-applications can serve different elements of CLM. BIM can for instance support sustainable strategic distribution planning by the use of a BIM plug-in (Chen and Nguyen, 2018), material management by using 4D sequence analysing (Wang et al., 2014), facilities and equipment by the use of a 3D-SLP (Le, Dao and Chaabane, 2019) or a 4D-SLP (Bortolini, Shigaki and Formoso, 2015), transport management by the use of RFID and IOT in BIM (Li et al., 2018), et cetera. Therefore, Whitlock et al. (2018) addressed the synergy between BIM and CLM, which is why BIM has a central role in this study.

Nevertheless, Rudberg and Maxwell (2019, p. 534) found that logistics strategies should be tailored to the context of the projects they are applied to. Therefore, the logistics strategy of a project is based on "*a reconfigurable 'modular' approach, meaning that elements of the strategy are defined and then a range of solutions within these elements are defined for selection based upon the nature of the specific project's context when logistic plans are developed*". This study builds on the study of Rudberg and Maxwell (2019). It is doing so by defining a modular logistics system for challenging inner-city construction projects that allows tailoring the logistics system to the project context. Emphasis will be put on logistical control since deviations from logistical plans may hardly be possible due to the inner-city context.

1.4. The objective of the research

The objective of this study is to develop a modular logistics system to obtain an effective tailor-made logistics management process on inner-city construction projects and to discuss how BIM can play a role in such a system. This objective includes three aspects. First, to develop a Construction Project Logistics System (CPLS) and to identify how logistical components can be applied holistically in a CPLS. Second, to discuss how BIM can be adopted as a logistical component. Third, to indicate various enabling conditions that need to be satisfied to ensure the effectiveness of a BIM-based CPLS in inner-city construction projects.

1.5. The research questions of the study

A CPLS needs to support the flow of logistical information to facilitate CLM and enable an effective, modular, and controllable logistical organisation that suits the needs of different construction projects. The different digital technologies (BIM), tools, and methods that are available to enable this information flow should be integrated. Furthermore, enabling conditions should be indicated to provide for an effective use of a BIM-based CPLS on inner-city construction projects. The main question to answer is:

How to obtain an efficient construction logistics management process supported by BIM or BIM data in inner-city construction projects?

This main question is answered by means of four sub-questions:

1. What should a Construction Project Logistics System (CPLS) look like?
   1.1. What are the dimensions of a governance strategy for CLM on construction projects?
   1.2. How to obtain production control in a CPLS?
   1.3. How to obtain continuous improvements in a CPLS?
2. How to establish an information flow and therefore a process within a CPLS?
3. What is the potential role of BIM within a CPLS?
4. What are enabling conditions for effective implementation of BIM in a CPLS?

1.6. The research method

A large and challenging inner-city project is used as a single-case study where field notes have been taken for four months, archival research is performed, and several interviews have been conducted. This in-depth case study approach allowed to outline a CPLS in a contemporary construction project context and to indicate what LC are used and how they are interrelated in the logistic system. The analysis of the CPLS focuses on CLM on this case, supported by BIM or BIM data. Any barriers in the operational logistics process are addressed by focusing on People, Process, Technology and Contracts and liabilities (PPTC) conditions. These barriers are subsequently used to define enabling conditions for an effective BIM-based CPLS.

1.7. The outlook of the thesis

As this chapter has introduced the relevance of the problem and has defined the objective and research questions of this thesis. Chapter 2 formulates the theoretical foundation of this study. This includes a conceptual framework for a CPLS design, the establishment of an (BIM-based) information flow within a CPLS, and a set of PPTC-framework conditions for effective implementation of a CPLS. Both used for the analysis of the field research. Chapter 3 describes the research strategy, the research design and outlines the methods that are used to capture and analyse field data. Chapter 4 introduces the case-project and Chapter 5 draws upon the empirical findings that help to answer the research questions. This is done by first presenting the results of a gap analysis that is performed between the planned and the operational logistical process on the case-project. This analysis is performed by using the PPTC-framework and indicates several barriers in the implementation of a BIM-based CPLS-layout. In Chapter 6 the results will be discussed, and a more thorough understanding of the findings will be given by aligning the findings to academic literature. Conclusions, contributions and opportunities for future research are presented in Chapter 7. Chapter 8 proposes opportunities to obtain a more effective organisation of the CPLS for the case-project.

Chapter 2 - Theoretical framework

This chapter includes three sections. Section §2.1 describes a conceptual model of a CPLS, based on the following three dimensions to ensure logistics control:

- a governance strategy for project-based CLM;
- an element of production control;
- continuous production system improvement.

Logistical Components (LC) are introduced in section §0, supporting specific elements of CLM. The LC are placed in a CPLS-framework to create a CPLS-layout which is required to establish an information flow and therefore a logistical process. Besides, the role of BIM and several logistics related BIM-applications are pointed out as they can play a significant role as LC.

Conditions to ensure an effective implementation of a BIM-based CPLS are defined in section §2.3, based on the conditions People, Process, Technology and Contracts and liabilities (PPTC). These conditions are used to define barriers in the operating CPLS-layout on the case-project and to propose enabling conditions later in this study.

A literature review has been conducted to explore the developments in construction logistics and to outline the theoretical concepts for this research as is presented in this chapter. The literature study helps to obtain a clear idea about the variables that have been used to develop this theoretical framework. Therefore, this chapter indicates how different concepts in literature relate to each other in the context of CLM on construction projects and why this relation is relevant for this study (Sekaran and Bougie, 2016).

Academic search engines such as Google Scholar, Web of Science, Scopus, and the Library of the University of Twente LISA[1] were used to find the relevant literature. Appendix D provides an overview of the search terms that are used to find the relevant literature for this theoretical framework. This appendix allows future studies to replicate the research in order to validate the findings (Eisenhardt, 1989; Sekaran and Bougie, 2016).

2.1. The structure of a Construction Project Logistics System (CPLS)

This section describes a conceptual CPLS-framework. A *governance strategy* is introduced first based on the three levels of decision making, a strategic, a tactical and an operational level. Last Planner Systems (LPS) is introduced subsequently as an element of *production control* after which the Plan-Do-Study-Act cycle of Deming is introduced to allow an element of *production system improvement.* The actual CPLS-framework is developed at last, by aligning the governance strategy with the Deming cycle. This alignment is guided by the principles of LPS.

2.1.1. Governance strategy for project-based CLM

A governance strategy for logistics can in general be translated into three different levels of decision making namely, strategic, tactical and operational (SteadieSeifi, 2011; Janné and Fredriksson, 2019). Such a three-level hierarchy in logistics decision making is recurring in academic literature as various studies indicate several similarities on this topic (Schmidt and Wilhelm, 2000; Ploos Van Amstel, 2002; Riopel, Langevin and Campbell, 2005; Boissinot and Paché, 2011).

A strategic level is said to include long-term decisions varying from a year to over two years. Decisions on a tactical level are considered to have an impact varying from “the upcoming weeks” till several months, and on an operational level on a weekly or daily base (Schmidt and Wilhelm, 2000; Boissinot and Paché, 2011; SteadieSeifi, 2011). Translated to CLM within a project organisation, it can be stated that strategic decisions have an impact on the duration of the project, tactical decisions to approximately six to twelve weeks (which are common lengths for lookahead schedules), and operational decisions on a daily or weekly base (Ballard, 2000).

[1] https://www.utwente.nl/en/lisa/library/

Ploos van Amstel (2002) indicated that the basic rules for logistics control are defined on a strategic level. Decisions on this level will therefore primarily indicate the project strategy and objectives (Riopel, Langevin and Campbell, 2005; Janné and Fredriksson, 2019). Furthermore, the project resources that will be provided to the different departments in the organisation, the main programme, and the overall BIM strategy.

Logistical plans should be made on a tactical level, including material flows, management policies, production, inventory levels, transport, resource planning and batch sizes, Site Layout Planning (SLP), etcetera. This level operates within the boundaries set by strategic decisions (Schmidt and Wilhelm, 2000; Ploos Van Amstel, 2002; Boissinot and Paché, 2011; Janné and Fredriksson, 2019). The tools provided from the strategic level in terms of for example project resources, the available software applications, and available labour-power are applied on this level to develop a process for managing logistics.

Responsibilities on an operational level include plan execution and progress control (Janné and Fredriksson, 2019). This means that supervisors should adapt to daily problems such as bad weather or a lack of labour (Schmidt and Wilhelm, 2000; Ploos Van Amstel, 2002; Boissinot and Paché, 2011). Besides, Ballard (2000) and Koskela (1999) argued that supervisors and foreman should prepare tasks for execution and develop weekly lookaheads based on the tasks that are prepared, which is discussed in the next section.

Furthermore, Borrmann *et al.*, (2018) describe the responsibilities of the BIM manager, BIM coordinator and BIM modeller on three comparable levels. Table 1 provides an overview of the time frames, the scope of decisions and responsibilities, BIM roles, and BIM responsibilities within each level of the governance strategy for project-based CLM.

Table 1. Governance levels of CLM on projects

	Strategic	**Tactical**	**Operational**
Time frame	Duration of the project	Week to six weeks	Weekly to daily
Responsible persons	Top management	Middle manager	Supervisors and foreman
Scope of decisions and responsibilities	Project objectives Master programme /strategy Overall BIM strategy Investments Available software Available manhours	Lookahead / backlog Logistics plan making Stock management Management policies Batch sizes Product design (ETO) Site layout planning	Weekly lookahead Prepare tasks Execute the plans Coordinate logistics React to deviations Settle daily problems
BIM roles	BIM Manager	BIM coordinator	BIM modeler
BIM responsibilities	Corporate objectives Research Process + workflow Standards Implementation Training	Execution plan Model audit Model coordination Content creation	Modelling Drawing production

Table 1. Governance of CLM on projects including three levels of decision making (Schmidt and Wilhelm, 2000; Ploos Van Amstel, 2002; Riopel, Langevin and Campbell, 2005; Boissinot and Paché, 2011; SteadieSeifi, 2011; Trindade *et al.*, 2016; Borrmann *et al.*, 2018)

However, both the responsibilities within the different levels of the hierarchy, as well as the responsibilities within the different BIM roles are interrelated. (SteadieSeifi, 2011; Borrmann *et al.*, 2018). This indicates that there are no hard borders in both decisions to be made or responsibilities to be taken by employees, as there is a certain overlap between the three levels.

2.1.2. Last Planner Systems for production control

The governance strategy allows to control logistical processes on three levels of decision making. This allows to adjust plans to the dynamic character of the industry since the scope and impact of the decisions made within these three levels is narrowed down the hierarchy. Daily or even hourly decisions can, therefore, be made at an operational level to be able to steer the process to last-minute unforeseen changes, which are rooted in the construction industry (Sullivan, Barthorpe and Robbins, 2010; Woodcock, 2015). Unforeseen events that cause variability are for instance bad weather, traffic accidents, a production that is behind schedule, not enough labour power available (Underwood and Isikdag, 2009; Lange and Schilling, 2015). Nevertheless, such events affect the logistical plans that are made on a tactical level for the next couple of days or weeks. Consequently, the lookaheads need to be adjusted based on the decisions made at the operational level if things do not go according to plan (Kymmell, 2008).

Koskela (1999) found several aspects to deal with this variability and to mitigate its impact, which include *production control* and *production system improvement*. The goal of production control is to avoid variability by pro-actively eliminating anything that can disturb the process.

Koskela (1999), advocates Last Planner Systems (LPS) in mitigating the level of variability in a system. LPS is based on the idea that unique plans are made by employees or teams if the plan indicates what is being done today or tomorrow because "*[these plans] drive direct work rather than the production of other plans*" (Ballard, 2000, p.3-1). The employees or teams who make these plans are called "last planners" (Ballard, 2000).

LPS considers three hierarchic levels of planning to allow process control which are a master planning, lookahead programs, and a commitment or weekly works plan (Ballard and Howell, 1998; Ballard, 2000). Even though lookahead programmes are more common in the construction industry, they comprise more functions in LPS than solely indicating what should be done. Ballard (2000) indicates several functions of a lookahead planning in LPS, which include amongst others the development of methods that enable the execution of the tasks and maintaining a backlog of "ready to execute" tasks, which are important for logistics management (Mossman, 2007). Besides, these aspects are part of the five principles of LPS that were defined by Koskela (1999) and essential for *production control*. These principles are leading throughout this study and essential in shaping the CPLS-framework (see Table 2). The five principles of LPS are:

- tasks cannot start until everything that is required to execute is ready: the prerequisites are sound;
- the conformance of the task is monitored after execution;
- non-conformances are identified and causes of non-conformances are removed to improve the process;
- a backlog (buffer) of tasks should be maintained for which all the requirements for completion are available;
- the prerequisites to execute a task should be actively made ready in the lookahead programs. Prerequisite work includes making a logistics plan for each planning task.

2.1.3. The PDSA cycle for continuous process improvements

Koskela (1999) found that production control can be achieved by these five principles. He also indicates that there is an element of *production system improvement* in these five principles to constantly improve practices and create commitment to the plans that are made. This is often established by using the Plan-Do-Check-Act (PDCA) cycle that was introduced in lean thinking by Deming to improve quality (Ballard, 2000; Morgan and Liker, 2006). The Plan-Do-Study-Act (PDSA)-cycle is an overall strategy to improve processes, see Figure 1. The phase Check is replaced by Study as new knowledge should be obtained in this phase to predict the outcome of proposed adjustments in the process (Moen and Norman, 2006).

Feliz *et al.*,(2014, p.1308) state that "*the last planner system puts the Deming cycle into action*" in striving to continuous improvements of the process. The Deming cycle will be used to guide the process in monitoring the conformance to logistic plans.

Figure 1, PDSA / Deming - cycle

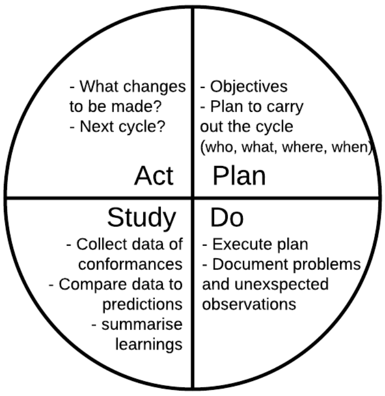

Figure 1.Plan-Do-Study-Act (PDSA)-cycle Based on Moen and Norman (2006).

The alignment of the PDSA-cycle to LPS is addressed by Feliz *et al.*, (2014) who showed how activities in LPS relate to the four phases in the PDSA-cycle based on Ballard (2000) and Koskela (1999). He defined two cycles, see Figure 2. The first representing the make-ready-planning which entails actively preparing prerequisite work. The second cycle represents the weekly-production-process. These two cycles are part of the foundation of the CPLS-framework that is configured in the next section as the activities are recurring in Table 2.

Figure 2. PDSA-cycles based on LPS

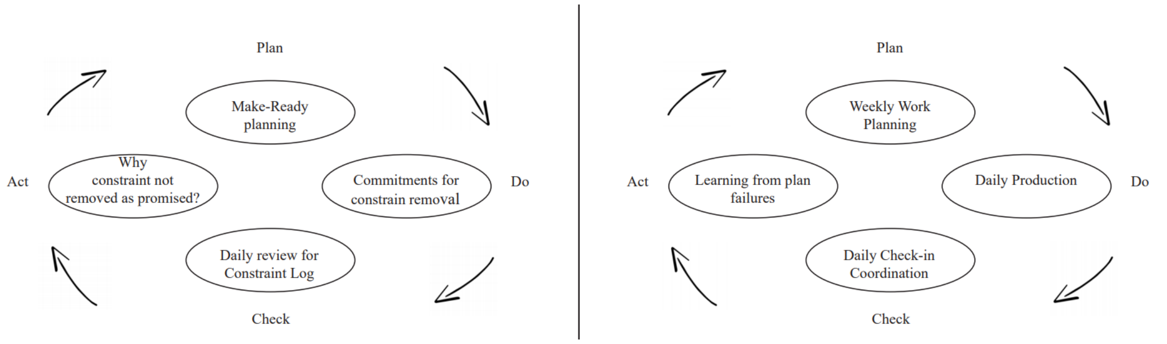

Figure 2. Deming cycles as an embodiment of a make-ready-planning and a weekly production process (Feliz *et al.*, 2014)

In sum, three dimensions are discussed in the previous sections that provide the foundation of a logistics system. A *governance strategy* in which three hierarchic decision-making levels are defined, Last Planner systems is introduced to support *production control*, and the PDSA-cycle is introduced for continuous *production system improvement*. The following section elaborated on the integration of these three elements to develop the CPLS-framework.

2.1.4. Shaping the CPLS-framework

This section integrates the three dimensions that have been discussed to develop the framework for a construction project logistics system. The PDSA-cycle is therefore aligned to the governance strategy by using LPS principles.

Table 2 aligns the phases Plan, Do, Study and Act to the tactical and operational level of decision making. Therefore, activities are assigned to each phase of the PDSA-cycle. These activities are based on the five LPS principles of Koskela (1999), which have been discussed in §2.1.2. Furthermore, they are based on both the make-ready-planning and the weekly-production-process as is described by Feliz *et al.*, (2014) and shown in Figure 2. The activities that relate to the make-ready-planning are indicated with an asterisk (*) and are related to the first PDSA-cycle of Figure 2.

In addition, it is indicated what activities relate to what level of decision making in the governance strategy.

Table 2 is the foundation of the CPLS-framework as it shows that the Plan and Act phase operate on a tactical level and the Do and Study phase on an operational level. The PDSA-cycle links the two levels to each other which shapes the CPLS-framework, see Figure 3. The strategic level is not directly linked to the PDSA-cycle but provides the boundaries in which the PDSA-cycle operates by describing: project objectives, master programme /strategy, overall BIM strategy, investments, available software and available manhours, see Table 1.

Table 2. CPLS-activities

CPLS-activities in the Plan, Do, Study and Act phase based on **(Koskela, 1999; Feliz *et al.*, 2014)**		Relation to the governance levels, **Table 1** in §2.1.1
Plan	• Decide what tasks are confident to be prepared in time and can be pulled from the master plan to be incorporated in the lookahead programmes • Actively make sure all prerequisite work is performed for the tasks in the lookahead, this includes a logistics plan for each task * • Create a Backlog of “ready to execute” tasks *	Tactical
DO	• Actively making sure prerequisite work is completed * • Pull “ready to execute” tasks from the backlog to create a weekly programme, in line with the lookahead programmes, in which tasks can be managed daily • Set the logistics plan in action and execute the task	Operational
Study	• Daily review of prerequisite work log * • Daily control the conformance of the execution to the logistics plan	Operational
Act	• Learn why prerequisite work is not performed * • Learn from non-conformance based on the collected data and decide on remedial actions	Tactical

Table 2. CPLS-activities providing the link between the PDSA-cycle and the levels of decision making

Figure 3. CPLS-framework

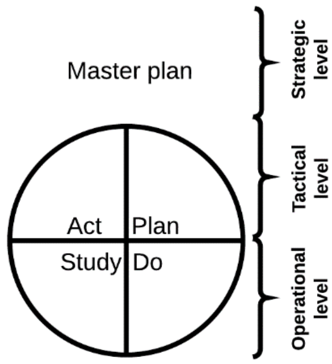

Figure 3. Construction Project Logistics System - framework

However, this framework cannot yet provide for a logistical process to support CLM. To allow a process, information should be provided at some point, communicated to another point where it is used, modified, or combined and then communicated again, until a result is achieved[2]. CLM should thus include a flow of information and therefore a logistical process (Sloot *et al.*, 2017). The components that are required to allow this process are introduced in the next section.

[2] A process is a series of actions that are needed to do something or achieve a result, Cambridge dictionary

2.2. Introducing logistical components and BIM

This section introduces Logistical Components (LC) to allow an information flow within the CPLS-framework. The concept of LC is introduced first, including their ability to share and communicate information within the CPLS-framework. The organisational structure of logistical components within the framework is called a CPLS-layout. Next, the application of logistics related BIM-applications as LC is discussed.

2.2.1. Introducing Logistical Components and the role of BIM in a CPLS-layout

The concept of LC that is applied in this study covers methods, resources or activities (Melles and Wamelink, 1993). Resources can be people, hardware, software, data sets, logistical equipment, procedure, et cetera. Melles and Wamelink found that "*The objective of an information system is realised by using* ***resources*** *to perform certain* ***activities*** *under the conditions and restrictions imposed by specific* ***methods*** (p.43)". Therefore, LC can be digital applications including for instance a Delivery Management System (DMS), a planning system such as MS-Project, or a BIM tool or model. But can also include organisational components such as Construction Consolidation Centres (CCC) or the use of a prefabricated or modular construction system. These and several other optional LC are pointed out in Appendix A and Appendix B.

The CPLS-framework should include LC to use, modify or combine, and communicate logistics related information and therefore allow a logistical process. Applying LC in a CPLS-framework and linking them to allow an information flow creates a CPLS-layout, see Figure 4. Such a layout should provide for executing the activities (see Table 2) in each phase of the CPLS.

Figure 4. Using the CPLS-framework

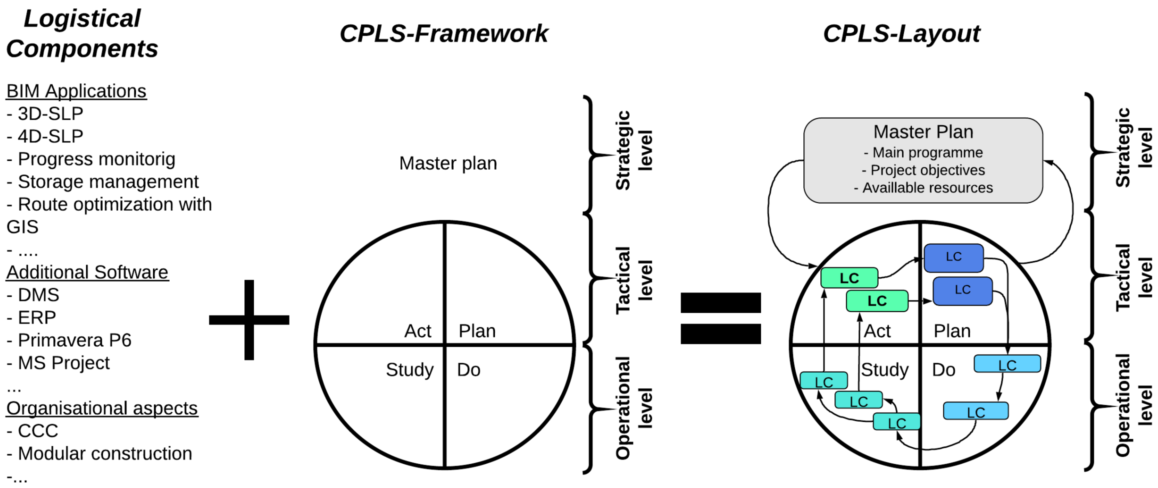

Figure 4. Design of a CPLS-layout by adopting LC in the CPLS-framework

2.2.2. Potential of BIM and BIM applications as Logistical Components

This section points out the potential of BIM and several BIM-application that can play a role within a CPLS-layout. BIM will be briefly discussed first. Then several logistics related BIM-applications are presented with the potential to fulfil several roles within a CPLS.

Important aspects of logistics are based on physical, geographical and semantic information of the materials to be processed, which can be obtained from BIM (Goulding and Arif, 2013; Sloot, 2018; Whitlock *et al.*, 2018). This includes for instance information such as quantities, material descriptions, weights, sizes and volumes, manufacturer or sub-contractor responsible, and the processing location (Eastman, 2011). Therefore, BIM and the construction programme are the starting point of the logistical information flows because they provide a quantifiable material demand over time. Both play a significant role as LC once applied in a CPLS-layout.

Yet, BIM provides additional applications for construction logistics besides the "basic" functions to extract quantities, visualise in 3D, and perform clash detection (Bosch-Sijtsema *et al.*, 2017). Several best practices of additional BIM-applications have been found in literature which are presented Figure 5. The literature that provides for an analysis or a review on a specific application is indicated with an asterisk (*), each of the other studies proposes a framework, method, or process for serving the corresponding logistical role within a CPLS. These applications can be used as LC in a CPLS-layout to provide for the project objectives. Appendix A provides an overview of the literature presented in this figure.

Figure 5. BIM-applications as potential LC

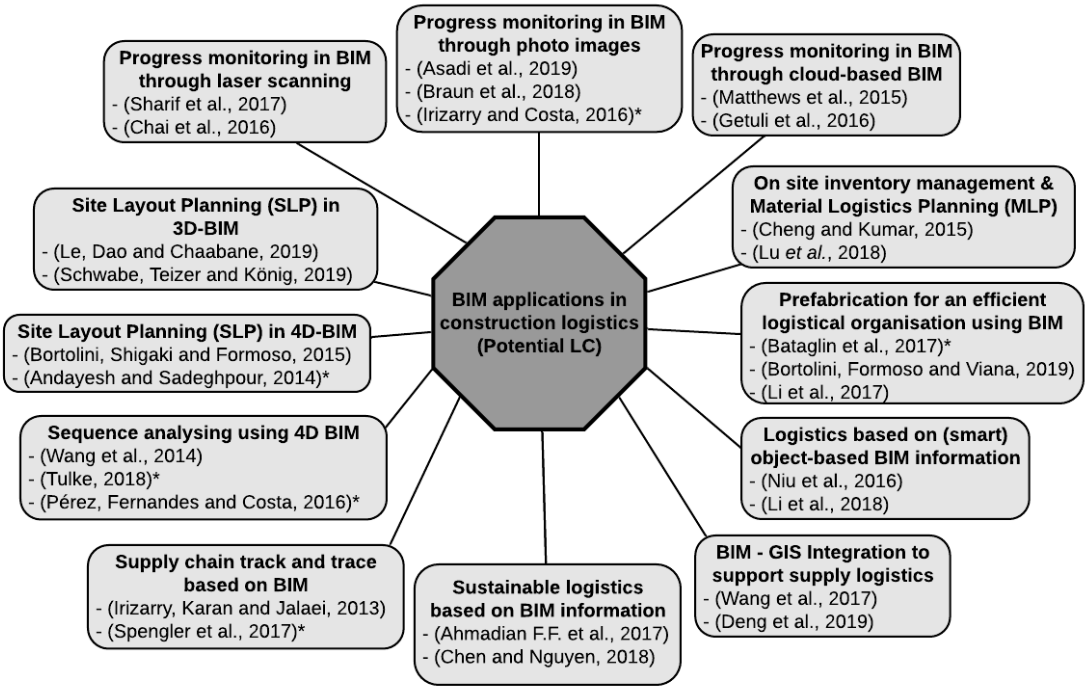

Figure 5. Logistics related BIM applications which can be used as Logistical Components

The CPLS-framework provides for a modular concept and flexibility and can be applied on different projects. A CPLS-layout can be adjusted to both the objectives of the project, and the project resources, which are for instance the software, knowledge, and labour that are available on the project. Both the objectives as well as the project resources are decided on a strategic level. As a consequence, CPLS-layouts of different projects can significantly differ between one another.

For instance, it might be a project objective to design a logistics system which minimises the environmental impact. Then it can be decided to use the BIM integrated plug-in, proposed by Chen and Nguyen (2018) as a logistical component to help in deciding on selecting sustainable sources of materials. While another project might have the objective to optimise the storage locations as there may be a lack of space on the construction site. In this case, the framework of Cheng and Kumar (2015) can be applied as a LC, as they focus on optimising material logistics planning. Nevertheless, it requires more than just the adoption of BIM and other digital technologies to establish a successful process for CLM on projects as is discussed in the next section.

2.3. Defining conditions for a successful implementation of a BIM-based CPLS

Successful implementation of Information Technologies (IT) in organisations is not solely dependent on the technology that is used or available (Hooper and Widén, 2015; Liu, van Nederveen and Hertogh, 2017). Therefore, this section aims to derive several conditions to allow effective implementation of BIM in CLM within the context of a contractor's organisation on a construction project. Four categories are identified, which include People, Process, Technology and Contracts and liabilities (PPTC). These four categories are subsequently related to the context of this study after which several conditions are defined leading to the PPTC-framework.

2.3.1. A framework based on people, process, technology, and contracts and liability

The three aspects People, Process, and Technology (PPT) have been frequently indicated in literature to ensure effective collaboration and successful implementation and application of digital technologies and IT in construction (Sommerville and Craig, 2006; Shelbourn *et al.*, 2007; Gu and London, 2010; Arayici *et al.*, 2011; Goulding and Arif, 2013; Enegbuma, Aliagha and Ali, 2015; Liu, van Nederveen and Hertogh, 2017). Additionally, a fourth aspect "contracts and liabilities" is recognised as being important for successful BIM implementation on construction projects (Thomson and Miner, 2006; Underwood and Isikdag, 2009; Abubakar *et al.*, 2014; Enegbuma, Aliagha and Ali, 2015).

Figure 6 visualises the four categories People, Process, Technology, and Contracts and liabilities (PPTC) representing the PPTC-framework conditions. The conditions in this figure are derived from literature. Each condition is elaborated below to indicate the relevance to the context of this study. These conditions are used throughout this study for the analysis of the data from field research to assist in defining enabling conditions for an effective BIM-based CPLS implementation.

Figure 6. PPTC-framework conditions

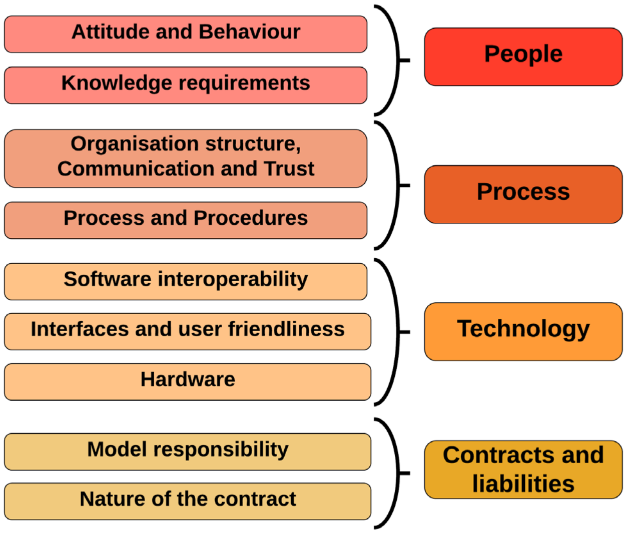

Figure 6. PPTC-framework categories and conditions for an effective implementation of BIM in CLM

People conditions in a BIM driven CPLS

The impact of people on communication technology and logistics is significant for an effective BIM-based CPLS (Sweeney, 2013). Human factors are described as a main condition for the implementation of digital technologies, including BIM (Abubakar *et al.*, 2014; Liu *et al.*, 2015; Liu, van Nederveen and Hertogh, 2017). The importance of people can be explained since the implementation of IT cause changes in communications and work cultures (Enegbuma, Aliagha and Ali, 2015). Also, the implementation of LPS is said to require a change in work cultures (Ballard, 2000). Two conditions of people are defined as being important for the effectiveness of a BIM-based CLM on projects.

The first condition is the *attitude and behaviour* of employees, which indicates a resistance towards new technology and the related process changes as is found by several scholars (Abubakar *et al.*, 2014; Ying, Tookey and Roberti, 2014; Enegbuma, Aliagha and Ali, 2015; Hooper and Widén, 2015; Liu, van Nederveen and Hertogh, 2017). It is considered in this study because the role of IT can be significant in a CPLS-layout. Also, a resistance to the introduction of LPS argued (Ballard, 2000). A lack of interest is especially recognised if employers have experienced negative, or no direct results in the use of digital technologies. This attitude is enhanced since construction workers are often production oriented (especially in the operational decision level), causing the use of digital technologies to be a second priority if there are not direct results (Jacobsson and Linderoth, 2010; Davies and Harty, 2013). This production-oriented mindset is also recognised by (Ballard, 2000, p.3-2) who argued that "*supervisors consider it their job to keep pressure on subordinates to produce despite obstacles. Granted that it is necessary to overcome obstacles, that does not excuse creating them or leaving them in place*". Although it is also found that some employees may acknowledge the benefits of digital technologies to improve practices, they will rather ask someone to use it for them, either because they don't have the skills or do not want to learn how to use new technologies (Liu, van Nederveen and Hertogh, 2017).

The second condition is the *knowledge requirement* of BIM by employees in the organisation. BIM can play a significant role in a CPLS and literature indicates the essence of having BIM skills for an effective BIM adoption (Underwood and Isikdag, 2009; Abubakar et al., 2014; Liu et al., 2015). Bosch-Sijtsema et al., (2017) found that a lack of BIM knowledge and skills is especially noticed on an operational level, which is caused by a lack of time to learn and use BIM. Enegbuma, Aliagha and Ali (2015) indicated a lack of awareness of the opportunities of BIM, which is said to cause a significant demand for employees with proper BIM knowledge and BIM skills. Therefore, Liu et al., (2015) and Liu, van Nederveen and Hertogh (2017) suggest training for existing staff to support the integration of BIM into practical operations. Also, it is indicated that senior management, often elderly and more experienced people, have a poor understanding of the opportunities of BIM for CLM (Liu, van Nederveen and Hertogh, 2017). Therefore, the unawareness and often high implementation costs can become barriers for sceptic decision-makers to adopt new BIM applications in their (logistics) systems (Abubakar et al., 2014; Liu et al., 2015; Bosch-Sijtsema et al., 2017).

Process conditions in a BIM driven CPLS

Also, issues related to processes are said to have a significant impact on the implementation of BIM (Shelbourn *et al.*, 2007; Enegbuma, Aliagha and Ali, 2015) and are essential for implementing LPS (Ballard, 2000; Arbulu and Ballard, 2004; Feliz *et al.*, 2014).

The first condition is *communication and trust* in the process as is found by Liu, van Nederveen and Hertogh (2017). These aspects are closely related to lean (the foundation of LPS), which aims to create a value stream. This, by knowing who the next person is dealing with your information. By recognising what this person needs and acknowledging the effect if the required information is not available, or the wrong information is provided (Womack and Jones, 2003; Mossman, 2007). Besides, Communication and trust are important aspects in LPS, and a lack of these aspects can therefore result in an ineffective CPLS. Understanding and communicating the right information that is required as input for certain systems and the way of providing information in general within a CPLS is essential. Besides, the issue of trust is found to be crucial for an effective process, even if the information needs are clearly defined. Literature argues that team members should integrate knowledge, expertise and skills to provide for in the information need, and a lack of trust hinders this integration (Liu, van Nederveen and Hertogh, 2017).

The need for *process and procedures* is a second condition ought to be important for this study as they drive LPS principles and cause commitment which are essential in the CPLS (Ballard, 2000; Feliz *et al.*, 2014). Procedures are required to ensure that employees are aware of their own responsibilities to provide for the five principles of LPS (Koskela, 1999). Besides, poor procedures can increase project risks caused by data inconsistency (Liu *et al.*, 2015), which is essential for an effective BIM-based CPLS implementation as a logistical process is based on sharing data and information between LC.

Technology conditions in a BIM driven CPLS

Digital technologies can support the communication of information of which BIM is the most important information driver as discussed previously. However, other digital systems, such as a DMS, can also be essential LC but are often not BIM-based (Whitlock *et al.*, 2018).

Therefore, the first condition relates to *software interoperability,* as BIM data often drives non-BIM-based systems which require an interaction between different software packages. Yet, not all software is able to communicate with each other causing incompatibility issues, which is frequently indicated in literature (Underwood and Isikdag, 2009; Eastman *et al.*, 2011; Lange and Schilling, 2015; Li *et al.*, 2017). Enegbuma, Aliagha and Ali (2015, p.71) argued that "*incompatibility in IT applications creates island of automation, challenging the normal business processes and computer integrated construction, there also exist limited communication between individual software packages"*. Issues in the interoperability are considered here since LC in a CPLS-layout are intended to share information between one another and LC can be based on different software packages which may cause similar issues.

The second condition relates to the *interfaces and the user friendliness* of digital applications because Ghaffarianhoseini *et al.*, (2017, p.4) highlighted "*the significance of BIM workability within the AEC industry as a key driver towards successful BIM adoption*". Which indicates that easy-to-use tools and simple interfaces are essential. Also, Shelbourn *et al.*, (2007) and Davies and Harty (2013) indicated the importance of easy-to-use technology and software systems and Rolfsen and Merschbrock (2016) concluded that a lack of easy to use interfaces increases the need for advanced IT skills. This is a barrier for the practical implementation of digital technologies in construction, which may also include the implementation of IT in a CPLS.

The third condition is related to inefficiencies in processes caused by *hardware*, which relates to the ease of using BIM efficiently (Arayici *et al.*, 2011; McGraw Hill Construction, 2012; Ghaffarianhoseini *et al.*, 2017). A lack of hardware capabilities can cause delays in the process as waiting times increase. Therefore, bigger storage capacity and an increased service power are assumed to be essential (Underwood and Isikdag, 2009). A lack of sufficient hardware can impact a CPLS-layout that is based on BIM or BIM data, which is why it is considered here.

Contracts and Liabilities conditions in a BIM driven CPLS

Contracts and liabilities are also of significant importance for BIM implementation (Thomson and Miner, 2006; Hooper and Widén, 2015).

The lack of *model responsibility* often relates to contractual issues and causes inaccuracies in BIM models that are used in projects (Hooper and Widén, 2015; Liu *et al.*, 2015). Therefore, is indicated as a contract related condition for BIM implementation in a CPLS. Legal and contractual constraints are mentioned as the second most important barrier for BIM adoption in the construction industry (Abubakar *et al.*, 2014). Hooper and Widén (2015) point out that the responsibility for the accuracy of information available in digital systems is often unknown as they found that "*many questions remain over the responsibility for the correctness of digital information*"(p.127). This can be essential if a BIM model is used as a logistical component to support logistical plan making.

A second contract related condition is the *nature of the contract* that is used, which is guided by contractual obligations from the client site and causes barriers for the implementation of BIM on projects (Underwood and Isikdag, 2009; Liu *et al.*, 2015). Underwood and Isikdag (2009, p.530) indicate that "*the lack of BIM hardware, software and experience with the client is a barrier to the adoption of BIM in a project*" because contracts are often 2D-based for this reason. Thomson and Miner (2006) provided an example of a project that used a 2D-based contract and a 3D-based working method to indicate the contractual impact on 3D workflows in a project. They stated that "*the downside is that if the model is expressly subordinate to traditional construction documents, the model cannot be relied upon during the pricing or construction process and traditional 2D documents must be duplicated, significantly decreasing the value of the model* (p.2)". Therefore, the value of the model decreases as it is not a liable document. The fact that the model cannot be relied on can also affect the use of BIM models or BIM data in a CPLS.

Chapter 3 - Empirical research design

This study aims to answer the following research question: *How to obtain an efficient construction logistics management process supported by BIM or BIM data in inner-city construction projects?* Qualitative research is conducted using an in-depth case study on a large inner-city project to collect field notes for four months on a full-time base. Archival research is performed within the same period and several interviews have been conducted. Emphasis has been put on the information flow between the LC in the CPLS-layout. Furthermore, the factors that influence the process, which are guided by the PPTC-framework conditions.

This chapter provides the research strategy applied throughout this study. The latter is done by first discussing the research design, in which the choice of using an in-depth case study is grounded. Moreover, the sampling design is described including the data collection method, after which the data analysis is elaborated, followed by the scope of the research.

3.1. Grounding the research design

The main objective of this research is to find empirical evidence on how BIM can be applied within a CPLS-layout to obtain an effective construction logistics management process on inner-city projects. An in-depth case study approach is applied, as a case study research seeks to deeper understand a contemporary and complex phenomenon in a real-life context (Yin, 1981). The case-study helped to find the underlying causes of problems in the operational process by finding explanations for the actions of specific employees. It helped to understand the social and human factors that play a role in the process, which might be something that employees themselves are not aware of. Therefore, other research designs, such as the use of a survey, would not provide the required in-depth understanding of such social aspects and the logistical processes.

Yin (2018) also stated that case study research is especially suitable: (1) if the research questions start with "how" or "why", which is the case for both the main question as well as most of the sub-questions in this research. (2) If there is limited ability to control the event that is the subject of the study, which is the case as many stakeholders, all with their own interest, were part of the logistics system that was studied. Besides, the site was constantly changing, making it close to impossible to influence the process. (3) It is a contemporary event, which is the case as well. Also, the scope of this research focuses on a relatively new area of processes, which is a characteristic of case study research (Meyer, 2001). Meyer (2001) stated that "*the key difference between the case study and other qualitative designs such as grounded theory and ethnography is that the case study is open to the use of theory or conceptual categories that guide the research and analysis of data* (p. 331)". This is in line with the research strategy in which the CPLS-framework and the PPTC-framework conditions are used to guide the research analysis, as is explained in the next sections.

3.2. Sampling design

The sampling design for the collection of field data is of great importance for the validity of research. Sampling is "*the process of selecting the right individuals, objects, or events as representatives for the entire population*" (Sekaran and Bougie, 2016, p.235).

The logistics system within the organisation of a contractor is analysed in this study. Four departments within the contractor's organisation were indicated in the case-project as being actively involved within the CPLS-layout that was studied. These were the logistics department, projects control department, engineering department, and the BIM department. The three levels of decision making as indicated in the CPLS-framework were aligned to the job description of various employees within these departments. Interviews have been conducted with all managers within these departments that are making strategic decisions. They were assumed to be knowledgeable and familiar with the issues and layout of the CPLS, and capable of providing the most significant information and visions. Furthermore, all the hierarchical positions of employees within the BIM departments have been interviewed as BIM was the main enabler for effective CLM on the project. An in-depth understanding of the use of BIM was required to indicate the role of BIM within the

CPLS-layout. Moreover, two interviews have been conducted with senior management as they were able to provide deeper insight into the contractual obligations that affected the use of BIM.

Interviews with employees on an operational level have not been performed as the technical background of the CPLS is not something of their interest. These employees are primarily interested in using the technologies, and not the system behind it. Therefore, primarily field notes where used to capture the use of the system on an operational level. Some of these respondents were recurring in analysing the field notes as they have been attending various meeting or informal conversations about the topic. These key persons and their job description have been identified and are presented in Appendix E, including the respondents from the interviews. The overall field data covers all three layers of decision making, whether it is through interviews or through field notes.

3.3. Data collection method

The data is collected from four main sources which are literature, archival research, field notes, and interviews. This allows for "triangulation" of the data, which is a way of verifying and strengthen the research findings by "in principle" using at least three data sources. This is a method that is frequently used in qualitative research (Eisenhardt, 1989; Yin, 2015).

3.3.1. Archival research

Archival research and documentation studies is a frequently used data source in case study research (Yin, 2015). This source has been used in this study to find out what logistical information in BIM models and construction programmes was based on. It was intended to find out what logistical information was included in BIM, who the persons were that created logistics related Revit sheets and 2D drawings from the models, why these drawings and models were assumed to be necessary, and who provided the input for these drawings.

3.3.2. Field notes from observations

The field notes, summarizing meetings and informal conversations (Eisenhardt, 1989), were collected over four months at the case-project. The researcher has been part of the BIM team during this period to support in the coordination of a logistical BIM model. Attending various meetings and daily informal conversations enabled to obtain an in-depth understanding of the processes and the information flow that drives the logistical operations. Field notes have been taken from these meetings and conversations, which provided a starting point to define the logistical information flow in the system. The notes were aimed to capture the following information:

- What logistical information is required, and who provides this information?
- What information/software systems are used to support logistical operations?
- How is information communicated between software systems?
- How is BIM or BIM data relevant for logistical planning/support?
- What are the needs in terms of software/communication?
- Where are the bottlenecks in the information flows?
- Is the potential of the current process fully used; how, or why not?
- What is the attitude towards the use of digital technologies used in the process, and where is this attitude based on?

3.3.3. Semi-structure interviews

In addition, eleven semi-structured interviews have been conducted to obtain structured answers but to also leave room for in-depth discussions (Argyris and Schön, 1989; Srivastava and Thomson, 2009). Interviews have been conducted with various members of the project team, as indicated in Table 8. The interviews took place in the last 6 weeks of the field research and interviews were recorded (if approved by the respondents) for analyses. Interviews were primarily aimed to validate findings found in the field notes, literature, and archival research data collection methods.

3.4. Data Analysis

This section elaborates on the analysis of the data in this study. First, it is described how the raw data from the field research is reviewed to be useful for the analysis. Then, it is discussed how the field data is applied to the CPLS-framework and analysed by using the PPTC-framework to define enabling conditions for effective implementation of a BIM-based CPLS.

3.4.1. Review of the raw field data

Several interviews have been conducted, and it is common to transcribe these interviews for analysis (Argyris and Schön, 1989). However, Tessier (2012) found that a combination of the analysis methods, field notes (summarising), transcribes, and tape recordings should be used preferably to substitution of one of these methods. This theory has been used on this research were not all interviews have been fully transcribed, but only the interviews with key figures are. Other interviews have been summarised or data is directly used from tape recordings. The research allowed this method as the scope of the interviews was narrow, which enabled to capture the required data in quotes and descriptions without the need of full transcriptions. Besides, the field notes, are mostly digitalised and include dates and the respondent's job title to allow analysis from perspectives of different departments and hierarchical levels.

3.4.2. The analysis of field research data

The data from the field research is applied to the CPLS-framework and analysed by using the PPTC-framework conditions which are discussed in this sub-section. Figure 7 presents the analysis process of the field data which was done in six steps as described subsequently:

1. Identifying all the logistical components that were applied to the case project.
2. Positioning every logistical component that was identified in the CPLS-framework after which the relations between the different LC was indicated by linking the LC with arrows. This resulted in the *CPLS-layout of the case-project*, which was proposed in the semi-structured interviews to validate.
3. Identify the logistical information flow that was planned between the different components. Every relation that was indicated in the CPLS-layout was studied in the field research to define the planned information flow throughout the logistics system, primarily by asking why LC were in place. The information transfer was subsequently added to the CPLS-layout which resulted in an overview of the *planned logistical process* on the case-project.
4. Similar to step three, the *operational logistical process* in the CPLS-layout is defined. The arrows were coloured red if the information transfer differed compared to what was planned. This process indicates the information transfer that took place on the case-project and the main problems that are identified in the process.
5. A gap analysis was performed which is "*concerned with the difference between […] the reality and the expected, but not with the time or discrete time-steps between these disparities*" (Langford *et al.*, 2008, p.14). The PPTC-framework conditions were used to define barriers from the field data that caused the gap between the planned and the operational logistical process. The barriers that were found could be categorised to the PPTC-framework conditions and subsequently assigned to the governance levels of decision making and the Plan-Do-Study-Act phases from the CPLS-framework. A matrix is used in which the four categories: people, process, technology, and contracts and liabilities including their conditions, are set out against the three levels of decision making: strategic, tactical and operational including the PDSA phases, as shown in Table 3. This allowed to indicate where the main barriers occurred.
6. Not all barriers had an equal impact on the process. Consequently, primary- and secondary-barriers were defined within the comprehensive list of barriers that was found. This is done by explaining the mutual relation between the barrier to explain the main problems in the operational process that were defined in step four.

Figure 7. Analysis of field data

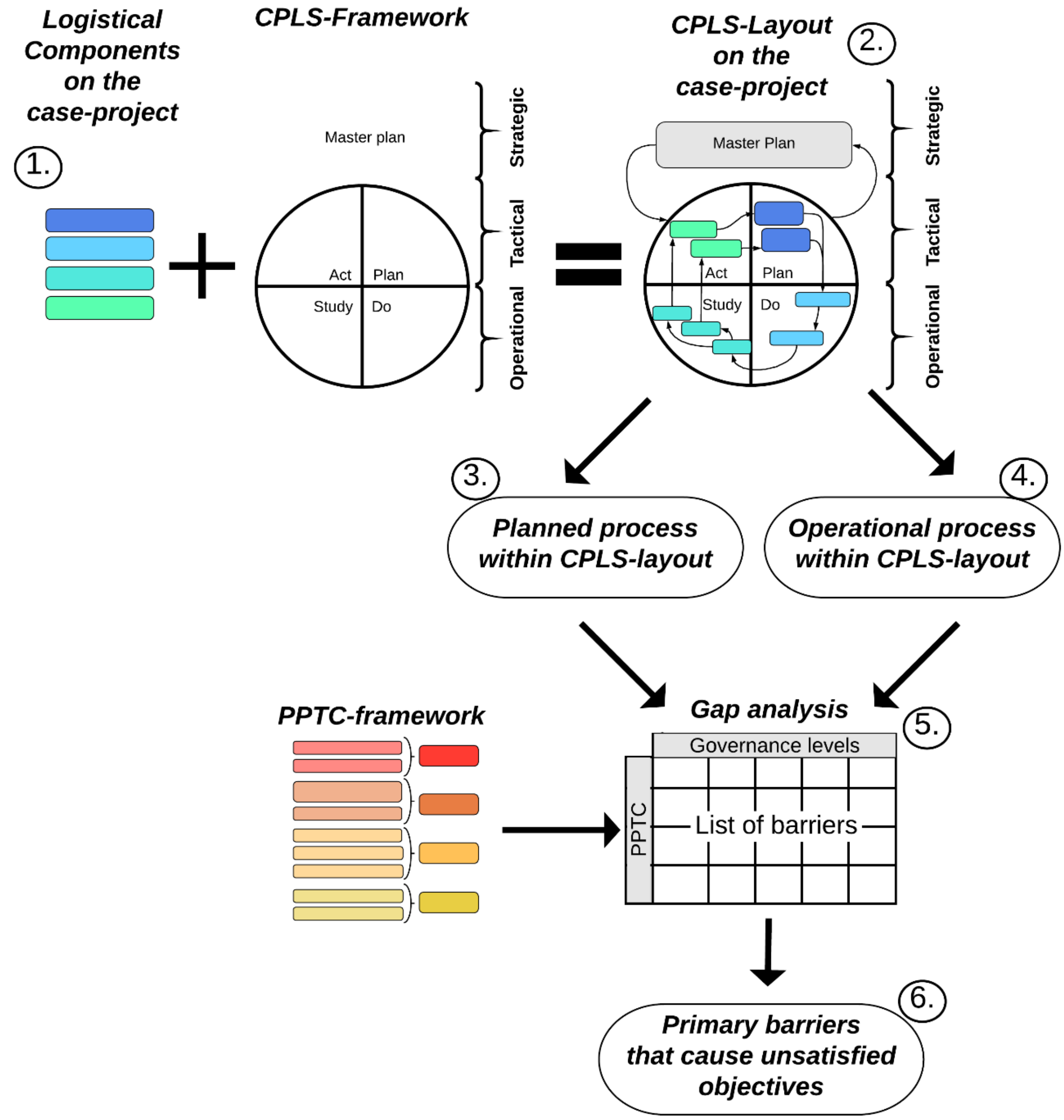

Figure 7. Six steps for the analysis of field data through the CPLS-framework and the PPTC-framework conditions

Table 3. Gap analysis matrix

Concepts	**Conditions**	**#**	**Barriers**	**Strategic**	**Tactical**		**Operational**	
					P	A	D	S
1. People	1.1. Attitude and behaviour							
	1.2. Knowledge requirements							
2. Process / Procedures	2.1. Knock-on effects							
	2.2. Process and Procedures							
3. Technology	3.1. Software Incompatibility							
	3.2. Poor interfaces							
	3.3. Hardware							
4. Contracts and liability	4.1. Model responsibilities							
	4.2. Nature of the contract							

Table 3. Data analysis PPTC versus levels of decision making & PDSA

The conditions to which the primary-barriers relate are considered the enabling conditions for effective implementation of a BIM-based CPLS. These enabling conditions are subsequently positioned against literature in the discussion chapter to explain how they relate to the findings of other studies.

3.5. Scope of the research

This research is primarily focussed on the process taking place on the tactical and operational level of the CPLS-framework and the relation between these two levels. The strategic level is solely considered to a limited extent as it provides the boundaries in which the tactical and operational level operate. However, the process and interaction between the strategic level and tactical level is not considered because part of this research aims at the role of BIM in CLM which is primarily relevant on a tactical and operational level.

Chapter 4 - Case description

~~Confidential~~

Chapter 5 - Results of the field study

This chapter includes four sections of which §5.1 outlines the CPLS-layout on the case-project and provides a brief explanation about some of the LC. Section §5.2 discusses the logistical process that was planned by fully utilising the capacities and capabilities of the CPLS-layout. The operational process on the case-project is discussed in §5.3. It represents the actual process and outlines the main problems in each phase (PDSA) of the CPLS. Section §5.4 describes the results of a gap analysis that is performed between the planned and the operational process. Besides, the primary-barriers are defined, based on the results of the gap analysis, that lead to the enabling conditions for a successful BIM-based CPLS-layout.

5.1. CPLS-layout of the case-project

Figure 11 provides the CPLS-layout of the case-project in which the LC are placed including their relation to one another. Some of the LC require a brief explanation before the planned and operational process are described in this chapter, which is provided in this section. The components that are explained here are labelled from A to I and are discussed according to these references. An extensive explanation of all the LC is provided in Appendix J.

Figure 11, CPLS-layout of the case-project

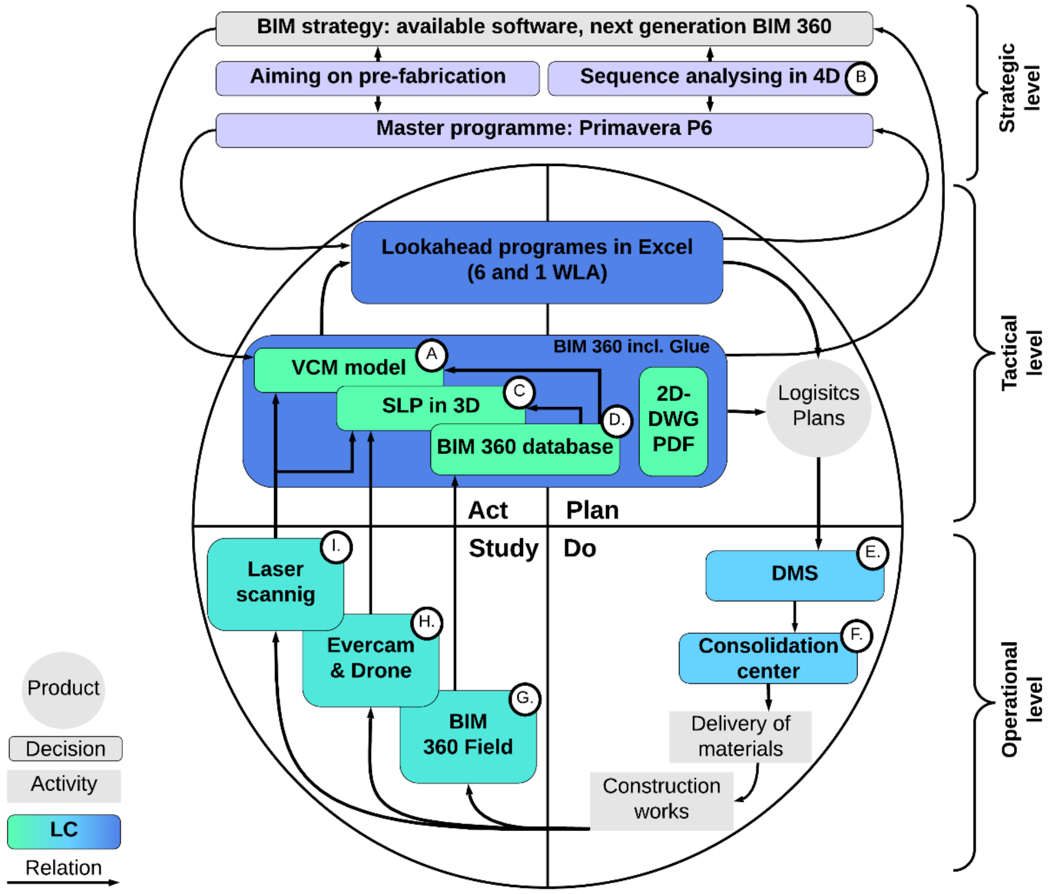

Figure 8. Logistical Components (LC) of the case-project positioned in a CPLS-layout

Several LC are presented on a strategic level which is not the primary scope of this research. Nevertheless, these LC are pointed out as they set the limitations and opportunities of the logistical process that takes place on the tactical and operational level. The BIM strategy is for instance decided on a strategic level including decisions on the software that is used, which are categorised as project resources. How these software packages are used within the organisation is decided on a tactical level. The following of this section discusses the labelled LC in Figure 11.

A – A Virtual Construction Model (VCM) - (Tactical)

This logistical component is a 3D-model in which all the pouring zones are indicated. Slabs are cut up in the pouring zones that are referred to by the programme. All columns and walls are linked to these pouring zones by a coding system. The model shows in green what elements are built already, see Figure 12, and can also be used to extract quantities, by filtering the pouring zones codes.

Figure 12. Virtual Construction Model (VCM)

~~ Confidential ~~

Figure 9. Virtual Construction Model (VCM) of level L00 indicating pouring zones and what has been built

B - Sequence analysing in 4D – (Strategic)

This logistical component is a 4D-model in which the main programme is linked to the pouring zones that are created in the VCM model. Batches (set of elements within a single task) in the programme are defined as resource groups in Synchro which are linked to start and finish dates. The 4D model presents a "video" of how the structure is going to be built. This component is linked to a strategic level because the main programme is linked to the VCM, the 4D model represents the overall project strategy.

C – Site Layout Planning (SLP) in 3D – (Tactical)

This logistical component is a 3D-model of the site layout in which all the components and equipment that is required for site-logistics is modelled. This includes the exact position of tower cranes, mobile cranes, hoists, concrete pumps, scaffolding, loading bays, canti-decks, access gates, storage locations, walking routes, et cetera, see Figure 13.

Figure 13. 3D-Site Layout Planning (SLP)

~~ Confidential ~~

Figure 10. 3D-Site Layout Planning (SLP) representing an accurate overview of the construction site

D - BIM 360 database (Field) - to check logistical equipment – (Tactical)

BIM 360-Field is a cloud-based platform that allows linking checklists to so-called "equipment", which can be construction elements but also zones or actual construction equipment.

This is done for all the scaffolding and cranes on site, which are identified as pieces of equipment to which daily or weekly checklists were linked. Employees can scan a QR code on scaffolding-tags or cranes and fill out quality checklist digitally to ensure the safety of these pieces of equipment. This ensures that everything that is modelled in the 3D-SLP is actually available and safe.

E - Delivery Management System (DMS) – (Operational)

A DMS is a logistical component that is made available as a project resource on a strategic level and is used on an operational level. It allows for instance supervisors, foreman and subcontractors to plan deliveries based on logistical plans. The DMS allows requesting a timeslot on a specific day in the agenda of logistical equipment: cranes, gates, loading bays, etcetera. The person or company who placed the request is provided with a delivery ticket once the request is accepted.

F - Consolidation Centre - (Operational)

A consolidation centre, or a HUB, is a point of transfer and/or storage location for construction materials, often outside of busy city centres to allow consolidated truck deliveries which reduces the number of vehicle movements in city centres. The use of the HUB is again decided on a strategic level as it is a project resource but used at an operational level.

G - BIM 360 Field – (Operational)

BIM 360 Field is also used to perform quality checklists of the constructed elements once the materials are processed. Field allows changing the status of elements, from “to be constructed” to “Completed/Installed”, if they have been constructed. This status update is pushed to a BIM 360 database which allows synchronising with the VCM model. The VCM model can be updated in this way and serve as an input to update lookahead programmes and logistical plans.

H - Evercam & drone (images) - (Operational)

Drone photos can subsequently be made of the construction site and the layout of the consolidation centre. Besides, Evercam allows to install live cameras around the site and attached to tower cranes. These images and videos can be used to visually keep track of the process and in discussions to make plans, as images or photos provide a direct overview of the actual situation.

I - Laser scanning (to BIM) – (Operational)

Laser scanning can be used to capture accurate data of the construction site. A point-cloud model is captured which represents a 3D-view of the actual situation by millions of points.

5.2. The planned process within the CPLS-layout

The previous section discussed the CPLS-layout on the case-project including an explanation of some of the LC. This section describes the planned logistical process within this CPLS-layout by fully utilising the functionality of the LC. Figure 14 shows the CPLS-layout of the planned logistical systems in which the LC are presented and linked by arrows representing the information flow. The grey squares indicate the information that is transferred between the LC thought the lines, and thus the process. The PDSA-cycle is run through daily, allowing employees on a tactical level to adjust the plans for the next day. The information flow in the planned process is described by using the numbers as a reference.

The main programme in primavera P6 is aligned with the VCM in Synchro (4D) to allow material demand smoothing for the upcoming months and visualise the process. Besides, the construction process is simplified by trying to pre-fabricate as much as possible. This strategy is decided on a strategic level.

Figure 14. Planned logistical process

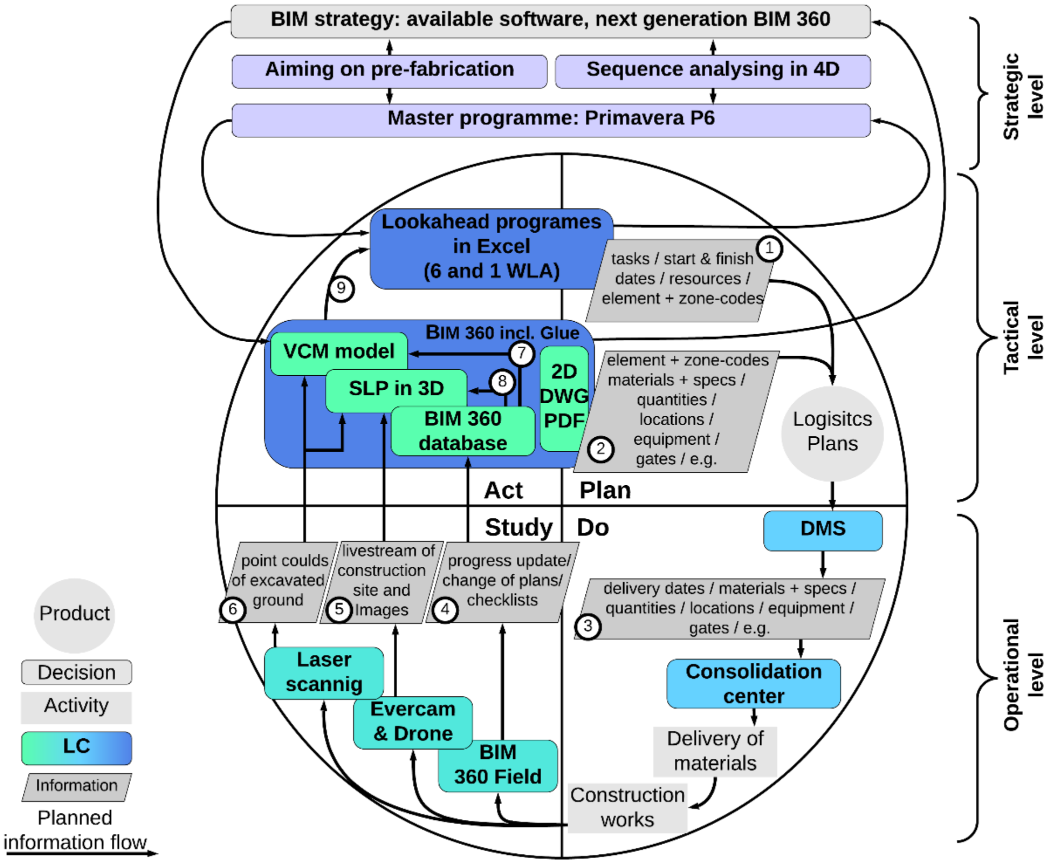

Figure 11. Visualisation of the planned logistical management process within the CPLS-layout

Plan phase

Logistical plans are developed in this phase. A six week and a weekly lookahead are developed in Excel to indicate what needs to be done for the next couple of days and weeks based on the main programme **(1)**. Furthermore, BIM is used to develop a VCM model and a 3D-SLP **(2)**. These three elements, the lookahead programmes, the VCM, and the 3D-SLP are used to develop logistical plans. The zone-codes in the lookahead programmes are used to perform a quantity take-off from the VCM by filtering on the zone codes **(1 & 2)**. This provides an overview of the location and the physical specifications such as size and weight of the prefabricated elements to be delivered and processed. The 3D-SLP is used to decide what access gate should be used, what logistical equipment is capable to move deliveries from the gate to their processing location, or where to store the load (if required). Drone images or the live stream of the construction site can be used supportively to detect practical issues and potential storage locations **(5)** for making the logistic plans.

Do phase

Then, the Do phase comes into place where the logistic plans provide the input for the DMS in which a time slot can be requested by foreman, supervisor or subcontractors (the last planners) to support JIT delivery as much as possible. Information that is added to the ticket is available in the logistics plan **(1 & 2)** and includes**:** person/subcontractor requesting, contact info, (pouring-) zone-code, element type/description, time slot of the requested equipment or gate, way of transport and way of unloading, CO_2 footprint of transport.
The logistical coordinator can both verify whether the requested delivery is in accordance with the programme by looking up the zone-code in the programme **(1)**, and to verify if the requested equipment is sufficient by using the 3D-SLP **(2)**. Once checked, the request is approved, and the requesting person or subcontractor is provided with a delivery ticket including a time slot for the requested equipment **(3)**. Elements are delivered through the HUB by using a delivery card system.

The drivers are provided with a delivery card which indicates the gate they should go to on the construction site. The HUB stays in contact with the construction site and truck drivers are only allowed to proceed to the site once the requested gate on site is available to avoid any queues at the gate. The delivery card is collected at the gate once the truck has arrived and is used again. The delivery is subsequently moved to its processing location on-site by use of the requested equipment.

Study phase

The Study phase comes into action once the delivered elements have been processed on-site. It is verified if the task that relates to an element are executed in accordance with what was planned in the lookahead programmes. Therefore BIM 360 field is used in which the status of every element that has been installed is changed to "constructed & installed". Besides, any deviations from the programme are notified, such as if only half a poring zone is poured, or only three out of the four rising elements are installed **(4)**. Besides, the reasons for any non-conformances are captured by maintaining a constraints log following LPS. Similar data is collected which indicates why logistics related deviations took place, by for instance measuring crane times, unloading times, or waiting times, which can also be set up in BIM 360 Field **(4)**. Laser scanning can be used to scan the surface of the site during excavation operations, two surfaces (scanned at a different point in time) could be subtracted from each other to determine the volume of dirt that is excavated. This volume can be used to check the billing of the subcontractor and to predict the number of truck movements for the upcoming weeks. Furthermore, it can be used to determine the exact position and height of tower cranes to enable an accurate 3D-SLP **(6)**.

Act phase

It is in the Act phase where all the information that is captured in Field is synchronised in the BIM 360 database after which the VCM is synchronised in Revit to update the statuses **(7)**. Any physical changes in pouring zones can be adjusted or new zones can be created in the VCM if required. The updated VCM model can subsequently be used by the project controls team to update the look-ahead programmes in excel. Also, the knowledge that was gained from the data on why deviations took place can be considered as it is stored in the BIM 360 database **(9)**. Such knowledge can provide insight if the programme was too optimistic, crane time was longer than expected, etcetera.

Additionally, the 3D-SLP is maintained to be used for positioning new logistical equipment (assets) on-site, including installing and dismantling dates related to the construction programme **(8)**. BIM 360 Field can be used to perform checklists on the logistical assets on-site to ensure usability and safety **(4)**. The cycle starts again after the three elements; the lookahead, the VCM and the 3D-SLP are updated and new plans can be made.

5.3. The operational process within the CPLS-layout

The previous section described the planned logistical process of the case-project. This section first describes the operational process in §5.3.1 by use of Figure 15. As shown, the CPLS-layout is the same as was used for describing the planned process, the same LC are used. The only difference is indicated in the red-dotted lines connecting the LC, which represents differences in the information flow between the components compared to the planned process. These red-dotted lines are discussed in this section to describe the process that actually took place on the case-project. The main problems that are found in the operational process are discussed in §5.3.2.

5.3.1. The operational logistical process

The strategic part of the operational process is similar to the planned process. All other structural elements are coded in a VCM to develop a 4D model. However, very little is done with the 4D model. Even a slab mountain in which the number of planned pours per week is plotted is not extracted from this model but is made in Excel, see Appendix H. Yet, emphasis is put on pre-fabrication to simplify the processes and reduce the number of activities on site. Both structural elements are prefabricated as well as MEP installations which are designed in modules.

Figure 15. Operational logistical process

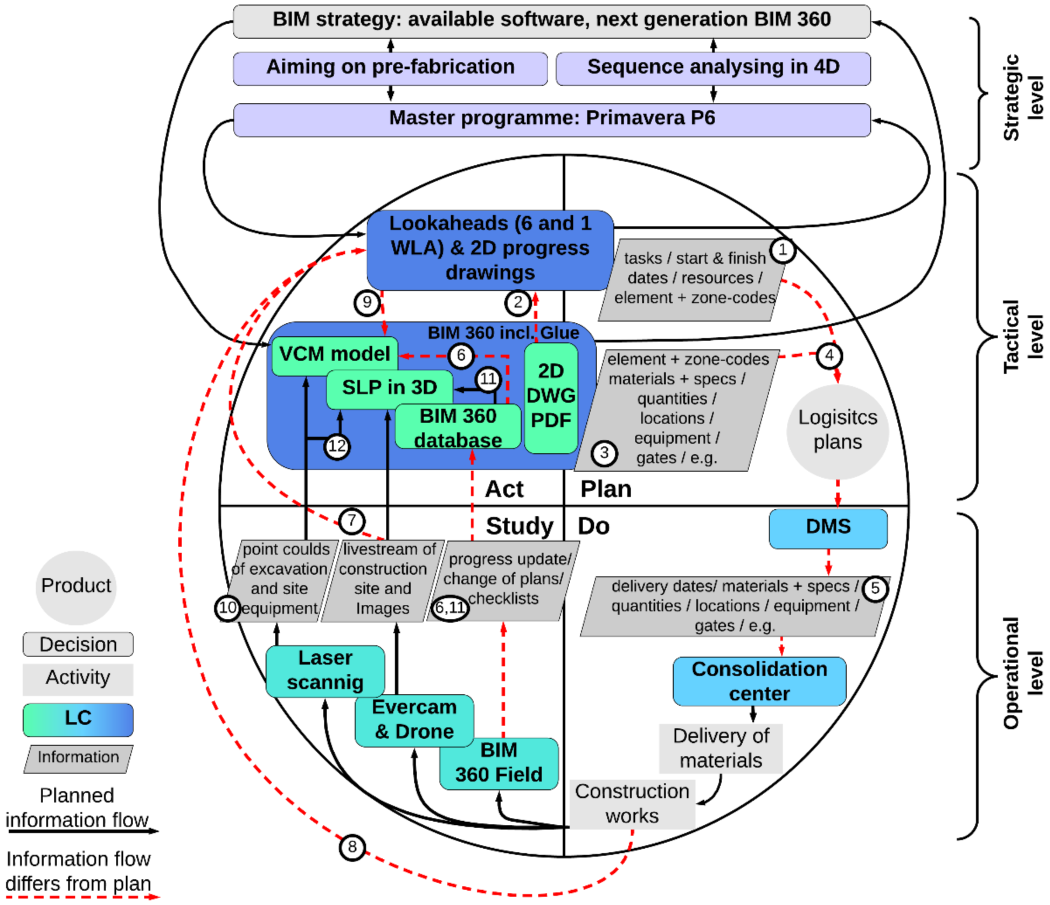

Figure 12. Visualisation of the operational CPLS-layout

Plan phase

The Plan phase starts with developing six weeks and weekly lookahead programs in Excel by partly following the LPS methodology **(1)**. Partly, since there is no make-ready-planning and no pull system used. Furthermore, the BIM department developed a 3D-SLP and a VCM in which pouring zones are cut from slabs, are coded and plotted to "2D progress drawings". However, even though the same three aspects are in place as in the planned process: a lookahead programme, a VCM and a 3D-SLP, these elements are barely used to make logistic plans.

2D progress drawings are used instead to decide on what to execute and to update the lookahead programmes **(2)**. Even though the zone codes in the VCM and the zone-codes referred to in the programme and the lookaheads are largely aligned. Besides, BIM models are not used for quantity take-off as they are assumed to be inaccurate due to various reasons as will be discussed in §5.4. Therefore, site engineers perform quantity take-offs from 2D design drawings and estimations which are manually aligned to the weekly lookaheads in Excel **(3)**.

The 3D-SLP is primarily used by the BIM team on request of other departments within the project organisation for assisting in large and challenging lifting operations, and not for every logistics planning as should be the case according to respondents **(3)**. Logistics plans are hardly made **(4)**, which is why it happens that elements cannot be lifted by the requested crane once arrived on site. Respondents argued that a logistics plan including accurate information about the weight and the processing location of the delivery could avoid these issues.

Nevertheless, an overall 3D-SLP is maintained to check for example if tower cranes can be extended, new cranes can be put in place and to decide on locations and physical performances for new hoists. Moreover, all the checklists of the cranes and the scaffolding are performed through BIM 360 Field to ensure the usability and safety of the assets in the 3D-SLP. Yet it took over a year before this was implemented on the case-project while this was already done at various other projects **(11)**.

The SLP model is updated every couple of weeks and provides a fairly accurate representation of the construction site. Exact locations of tower cranes are verified through laser scanning for instance, as they interfere with the structure and are indicated to be essential in the construction programme **(12)**. However, assembly and dismantling dates of site equipment are not used and are not considered or linked in the construction programme. The effort in defining those dates is lost as deviations in the project programme are not related to the site equipment installing dates, meaning that the dates in the model are outdated. Similar issues are found as "old" proposed locations of hoists and concrete pumps are still in the model, but no one takes responsibility to maintain this model.

Do phase

In the Do phase, about ninety per cent of the elements and concrete deliveries are planned through the DMS **(4)**. However, the DMS does not oblige to fill up all the available fields and logistics plans are often not available. Delivery requests are often incomplete in which quantities, descriptions of elements such as type, volume and weight, and the processing zones or codes are not appointed. Therefore, the logistical coordinator is unable to check whether deliveries are planned JIT according to the program, or if the requested crane or hoist suits the required lifting capacity for the planned delivery. It can only be assumed that the people who are requesting deliveries have checked these issues themselves by using the 3D-SLP. Besides, not all subcontractors and foreman are using the system themselves. Many place requests in a WhatsApp group or ring up the logistical coordinator, who fills the DMS at the end of the day based on these requests, causing a lack of commitment to the plans at an operational level.

Nevertheless, once the requests are accepted and truck drivers get their tickets **(5)**, they pass the HUB to collect a delivery card and additional materials if necessary before they head to the requested gate once available (as was planned). It was stated that "*the system works really well; it avoids queues at the gates as truck drivers know they will be sent away without a delivery card*".

Study phase

BIM 360 Field is used to keep track of the process after materials are delivered and processed. However, statuses of objects that have been installed are frequently not updated in Field, either not on the same day or not at all **(6)**. Besides, any changes in pouring zones and any data about for instance unloading and crane times are not collected or communicated through BIM 360 Field **(6 & 11)**. Data about logistics is not captured at all, for example why unloading times were exceeded **(11)**. This means that the Study phase in the PDSA-cycle is not used to its potential as information about the conformance of lookahead programmes is not effectively captured. Nevertheless, causes of deviations in the programme are (partly) captured manually in following LPS by indicating one of the 16 reasons that have been defined for delays, which are used to create a constraints log, see Appendix I **(8)**.

Act phase

Subsequently, in the Act phase, the VCM cannot be updated in Revit and logistical performances cannot be analysed since the required information is not pushed back to the BIM 360 database **(6)**. Furthermore, it ought not to be the responsibility of the BIM department to get this information from the engineering department, so no one is taking responsibility for updating the VCM **(6)**. Instead, the project controls department is required to go outside and check what is being done and what has changed, look at the live stream of the site or ask site engineers **(7 & 8)**.

Changes in zones are marked and new zones are created and coded on the hard copy 2D progress drawings by using different colours instead of using the VCM model to update the lookahead programmes **(2)**. The VCM is updated every couple of weeks based on these hard-copy progress drawings primarily for facility management purposes and updating the 4D model. This leads to a negative spiral in which the VCM model becomes more and more inaccurate over time until it is updated every few weeks **(9).** The model has therefore lost most its function in the logistical system as deliveries are planned, pouring zones are updated and schedules are adjusted based on 2D drawings **(2 & 3)**. Nevertheless, the VCM was used during excavation to subtract the surfaces captured through laser scanning after which truck movements were calculated from the volume of excavated dirt **(10)**.

5.3.2. Core problems in the operational process

The sub-section above described the operational logistical process on the case-project. This operational process differs compared to the planned process on several aspects as shown in Figure 15, in which an insufficient information flow is indicated with the red-dotted lines. This sub-section discusses the core problems that are indicated within the operational process.

Core problems in the "Plan" phase

The information flow in the Plan phase was not sufficient, which is caused by the fact that the BIM models, the VCM and the 3D-SLP are barely used to develop logistical plans, most of the plans that are made are based on traditional hard copy 2D-drawings. Besides, logistic plans are solely made for "special" deliveries, for instance, heavy steel elements, but not for every delivery.

Core problems in the "Do" phase

Also, the information flow in the Do phase differed compared to what was planned, partly caused by that fact that logistical plans are not consistently made in the Plan phase. It is found that supervisors, foreman and sub-contractors, which are defined as the last planners, do not take the responsibility to use the DMS. Besides, not all relevant logistical information is addressed in the DMS tickets. This causes logistics related problems during the execution of tasks as essential information (processing location, weights, etcetera) is not available on site.

Core problems in the "Study" phase

It is found that BIM 360 Field is barely used to capture progress information to update and maintain the VCM. Yet, a list that provides causes of delays is defined in following LPS but this list is barely used, and if used, solely by the project controls team, not by the last planners. In addition, it is found that logistics related data, about unloading times, for example, is not captured at all.

Core problems in the "Act" phase

There are also issues in the Act phase which are primarily caused by the fact that data is barely captured in the Study phase. Therefore, the VCM is not maintained, which is why the VCM has lost its function within the logistical process. This because issues in the logistical operations cannot be analysed as there is no data available to do so.

5.4. Defining primary-barriers in the logistics process

This section defines the barriers that cause core problems in the operational process. Sub-section §5.4.1 indicates all the barriers that define the gap between the planned and the operational logistics process, which are presented in a matrix. This matrix is subsequently used in §5.4.2, to clarified how these barriers explain the core problems by analysing their mutual relationship. It makes a distinction between primary-barriers and secondary- barriers to identify those barriers that have the most significant impact on the process.

5.4.1. Gap analysis between the planned and operational CPLS-layout

The barriers that are found during the field research are related to their corresponding condition in the PPTC-framework conditions to zoom in on the details and the root-causes of the gap. They are subsequently related to the level of decision making and the CPLS-phases (PDSA) in which they occur. This analysis is thoroughly discussed in Appendix K of which the results are presented in Table 4.

A total number of twenty-three barriers have been identified. Most of the barriers have been identified on a tactical level (fifteen), followed by the operational level (thirteen) and at last the strategic level (three). The barriers within the tactical and operational levels can be specified according to the PDSA-cycle in which the most barriers are found in the Plan phase (thirteen), followed by the Study phase (ten) and thereafter the Do phase (seven) and the Act phase (three).

Very little barriers have been indicated on a strategic level of decision making. This can be explained by the scope of this research that is primarily aimed at the Deming-cycle in the CPLS-framework that links the tactical to the operational level as explained in §3.5. Yet, these barriers are mentioned here as they have been indicated repeatedly by respondents but are not discussed in the remaining of this research. Nevertheless, they might be useful in future studies in which the upper part of the CPLS-framework can be analysed.

Moreover, many barriers have been defined on a tactical level but only three are related to the Act phase. This, because the Act phase is dependent on the Study phase. If data is not captured in the Study phase, there is nothing to act upon in the Act phase. Yet during field research on the case-project, it is found that little data is captured in the study phase and as a result, not many results have therefore been found on the Act phase which explains this low number of barriers.

Table 4. list of issues

Category	**Conditions**	**#**	**Barriers**	**Strategic**	**Tactical**		**Operational**	
					P	A	D	S
1. People	1.1. Attitude and behaviour	1.1.1	Stubborn attitude - *Experienced employees not willing to learn or work with new technologies*	X	X		X	X
		1.1.2	Production-oriented mindset - *anything else is second priority*		X		X	X
	1.2. Knowledge requirements	1.2.1	Lack of senior support – *makes it difficult to justify costs to improve processes*	X				
		1.2.2	Unaware of the benefits - *or potential of digital applications to simplify processes*		X		X	X
		1.2.3	Limited BIM skillset		X			
2. Process	2.1. Communication & Trust	2.1.1	Lack of labour-power		X			
		2.1.2	Unaware of their responsibilities - *lack of trust in co-workers, double works due to extra checks*				X	X
		2.1.3	The LOD in models – *LOD should fit the needs*		X			
		2.1.4	Inefficient use and setup of the SLP		X			
	2.2. Process and Procedures	2.2.1	No system way of thinking		X		X	X
		2.2.2	Lack of procedures		X		X	X
		2.2.3	Lack of data collection - *to improve logistics*					X
		2.2.4	Protocols and Standards	X				
3. Technology	3.1. Software Interoperability	3.1.1	Unable to synchronise model changes in the VCM with revised versions			X		
		3.1.2	Unable to update the program by input from BIM 360 Field			X		
		3.1.3	The DMS is not linked to either BIM 360 or the programme				X	
		3.1.4	Resource groups in Synchro cannot be synchronised with BIM 360 Field					X
	3.2. Interfaces and user-friendliness	3.2.1	Awkward interfaces and labour-intensive handlings					X
		3.2.2	Overwhelming amount of information		X			
	3.3. Hardware	3.3.1	Model size is too big - *over 3.3GB with over 170 models*		X			
		3.3.2	BIM 360 Field is only supported by IOS devices					X
4. Contracts and liability	4.1. Model responsibility	4.1.1	Lack of model responsibility		X	X		
	4.2. Nature of the contract	4.2.2	Contract is 2D-based but processes are 3D based		X			

Table 4. List of barriers in the current logistical process on the case.

5.4.2. Defining the primary-barriers in the logistical process

Next, it is important to zoom out from this comprehensive list to identify a set of primary-barriers which have the most significant impact on the process. This is done by defining the mutual relation between the barriers in the same phase (PDSA) and their relation to the core problems.

The problems in the Act phase are not particularly caused by any underlying barriers, as discussed. Therefore, the mutual relation of the three barriers in the Act phase are not discussed in the following of this analysis because the data of field research is considered insufficient. This leaves solely the barriers of the Plan, Do and Study phase to be analysed further.

Each of these three phases has several underlying barriers as indicated with an "X" in Table 4. These are discussed by the use of Figure 17, Figure 18, and Figure 19. The figures present primary-barriers and secondary-barriers and their mutual relationship that explains the core problems. The reasoning to categorise barriers as primary or secondary is provided in the text and is based on the fact that some barriers lead to or fortify other barriers. Some secondary-barriers do not have any relation to a primary-barrier. These are discussed at the end of each paragraph. The colours of the barriers represent the corresponding category of the PPTC-framework, see Figure 16.

Figure 16. PPTC Legend

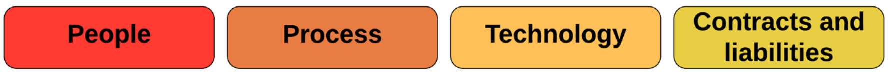

Figure 13. Legend of the PPTC-framework categories

Barriers in the Plan phase

The barriers discussed in this section refer to the Plan phase on a tactical level of decision making in the CPLS-framework. The main problems in this phase are the fact that the BIM models, VCM and 3D-SLP, are barely used, and that logistic plans are solely made for special deliveries. These problems will therefore be recurring in the following of this paragraph. Figure 17 helps to structure the barriers as primary or secondary to explain the difference between the planned and operational process in this phase. The primary-barriers are indicated as headings and their relation to the secondary-barriers is described subsequently for each one. The technical barrier "model size is to BIG" does not relate to any primary barrier and is discussed at the end of this paragraph.

Figure 17. Barriers in the Plan phase

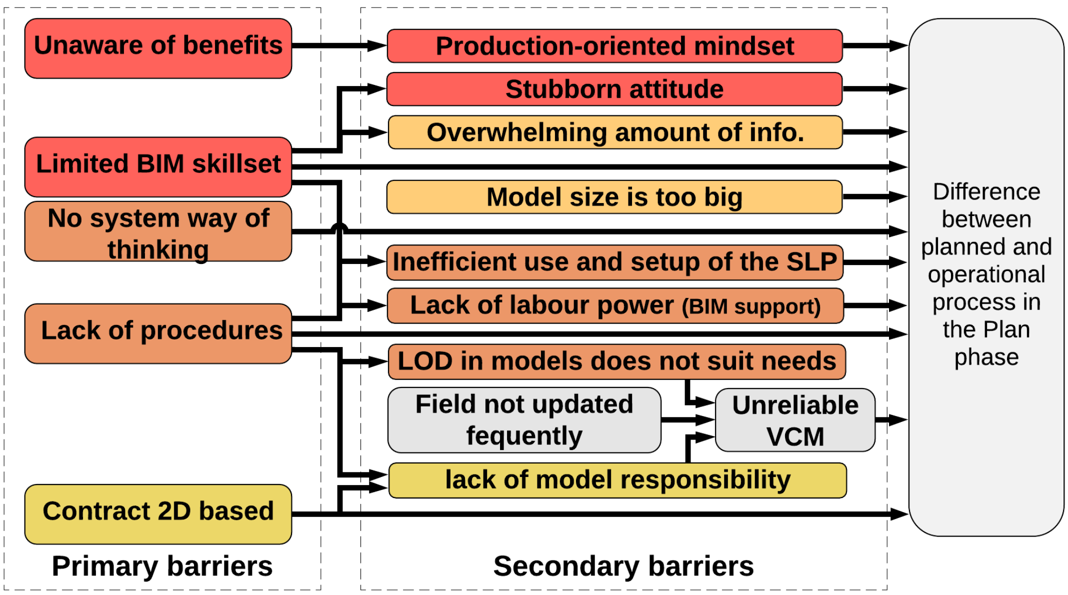

Figure 14. Barriers causing a poor use of BIM for logistics plan making – Plan phase

Unaware of the benefits

The first primary-barrier is that some employees at a strategic level are unaware of the benefits of using BIM to support logistics as can be indicated by the late introduction of scaffolding and crane checklists in BIM 360 Field. This application of BIM 360 Field was used on other projects already but was only implemented halfway during construction as the benefits were not recognised yet by the safety department. Besides, they have never really considered BIM to improve logistics, and aspects of logistics are also not considered in a BIM protocol that was communicated with sub-contractors. Furthermore, managers on a tactical level do not have time to stimulate people on an operational level to use digital technologies as they prioritise that their teams make production. At the same time, other managers argue that the poor use of the available tools, is causing inefficiencies in the production process.

Limited BIM skillset

The second primary-barrier is the poor BIM knowledge and a poor BIM skillset of employees. The BIM department is seen as a niche within the project organisation because very little employees can actually work with BIM, which relates to four secondary-barriers. Even though some respondents acknowledge the benefits of BIM, they would not take the initiative to learn how to use de technology themselves but would rather rely on others as a result of a stubborn attitude towards change. Besides, respondents argued not to have enough time to learn or use BIM. As a result, employees often have poor BIM skills, are unable to efficiently adjust the 3D-SLP or are overwhelmed by the amount of data in BIM models. Others are not able to use BIM at all, meaning that they are dependent on the BIM department to assist. Yet, it was argued that "*the BIM department is not here to create drawings; the BIM department is here to manage the models and the drawing created by different people*". Therefore, the BIM team is not big enough (in terms of labour capacity) to support everyone, as it is ought not their job to do so. This causes employees to use alternative ways instead of BIM, often 2D drawings, to get their information from for making logistical plans.

No system way of thinking

The third primary-barrier is the lack of a systematic way of thinking, which is significant for the logistical process and is found to be the reason that LPS principles are barely followed. Even though lookahead programmes are used and a list of constraints is developed in the Plan phase, several other important principles of LPS are not considered. For instance, to actively make sure that prerequisite work (which includes a logistics plan) is completed for each task in the lookahead to create a backlog of "ready to execute" tasks. Logistics plans are solely made for challenging and extraordinary deliveries, resulting in poor communication of logistics information for standard deliveries. Logistics plans for standard deliveries are simply not developed. This caused several logistical issues, which could have been avoided by having a logistics plan. Even just checking the crane capacity could have avoided several issues according to respondents.

Lack of procedures

The fourth primary-barrier is the lack of procedures causing people to be unaware of their responsibilities, where to get their information from and what information to provide to who. This leads to four secondary-barriers. Including the fact that the 3D-SLP was not aligned with the construction programme as installing and dismantling dates of logistical equipment are not available. Therefore, the 3D-SLP includes equipment that is not in place yet because no procedure indicates the requirements of such a model. Besides, the labour shortage in the BIM team is again addressed by a lack of procedures. It is found that employees do not know where to find information in the models and ask the BIM team to assist. A third barrier relates to the fact that the data in BIM models that was provided had an insufficient LOD for what was required by engineers on the case-project. This was indicated since rebar (reinforcement steel) was not modelled in concrete elements, which caused inaccurate quantity take-offs of concrete from the model. A clear example of not knowing what the next person requires. The lack of procedures also relates to a fourth barrier. This is a level of uncertainty that it is found in the responsibility to maintain the models. For example, the 3D-SLP, since the logistics department provides the input for this model but the BIM team is modelling (due to a lack of BIM skills in the logistics department).

Nature of the contract

The fifth primary-barrier is the fact that the contract is 2D-based. Therefore, engineers are liable for 2D drawings and will not use the models, as models can differ from the 2D drawings. This is categorised as a primary-barrier since it impacts the way of working significantly. A respondent from the BIM department stated "*Yes, so all this [having 3D work processes but construction being done from 2D drawing] is fighting against the contract. So, the contract says, drawings and documents are 2D. The contract is thus price from the drawings and specifications. So, if the drawing says, put a table in this room, we should put a table in this room, but is the model says it, never mind, it's the drawings that counts*". Therefore, especially engineers on a tactical level use 2D drawings to get their information from. Even if all employees can work with BIM and all technical barriers are solved, employees will still not use BIM as the BIM models have no legal value. An engineer argued: "*It is a BIM project ok? But in reality, everybody is working with 2D drawings*". This results in a secondary-barrier which indicates that no one is really responsible for maintaining BIM models as they are not contractually bounded. Besides, taking responsibility for the accuracy of a model would be a waste of time as the models are barely used.

Secondary barriers in the Study phase

An additional secondary-barrier is identified that is related to hardware. The model size is said to be too big, over 3.3 GB, which causes lags in using software on desktops, resulting in a disinterest in using the models. Besides, the BIM team needs to cut up the models to make it manageable for the iPads used on-site, resulting in inefficiencies in the process in terms of time delays. This barrier, however, is classified as a secondary-barrier as the available hardware still allows to do the job, even though efficiency can be improved.

Barriers in the Do phase

The structure of this section is similar to the previous section, but the barriers discussed in this section refer to the Do phase on an operational level of decision making of the CPLS-framework. The core problems that were indicated in this phase are the fact that the last planners do not consequently take responsibility to use the DMS, and not all relevant logistical information is addressed in the DMS tickets. Figure 18 helps to structure the barriers as primary or secondary to explains the difference between the planned and operational process in this phase. The technical barrier "The DMS is not linked to either BIM 360 or the programme" does not relate to any primary barrier and is discussed at the end of this paragraph.

Figure 18. Barriers in the Do phase

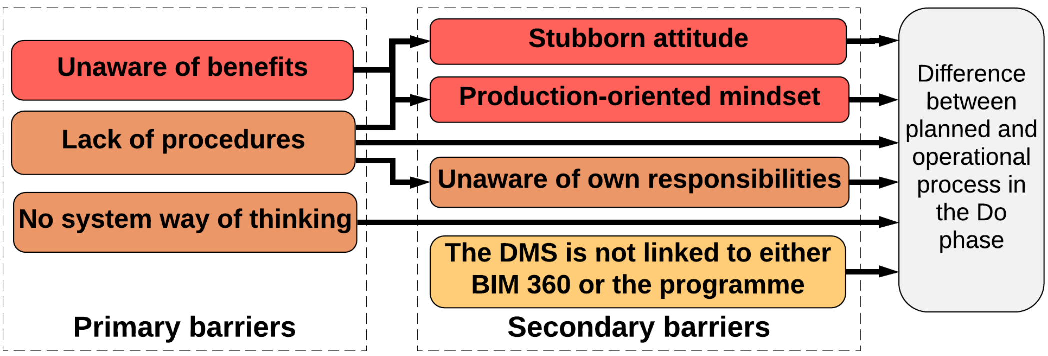

Figure 15. Barriers causing a poor use LC for plan execution – Do phase

Foreman and supervisors (the last planners) should utilise DMS in this phase to execute the work and manage material handling on site. However, there is no backlog for the last planners to pull "ready to execute" tasks from for the standard deliveries. Standard deliveries are planned ad-hoc by using the DMS system but are rather not sufficient as a result of several barriers discussed here.

Unaware of benefits

The first primary-barrier relates to the unawareness of the benefits of digital technologies, which is why some employees are not willing to use the available LC. Tasks that directly support production are prioritised over planning logistics proactively and avoid issues during the production process. It is found that employees even prioritise tasks outside of their own responsibilities, doing the work of others to keep production going. This leads to a reactive process as it is assumed, on an operational level, that logistic will happen anyway even without utilising the available LC. This is indicated as a stubborn attitude towards change. Using the DMS is seen as an additional task instead of a tool to simplify the job, while managers on a tactical level indicated the benefits of the DMS to reduce the workload if used properly.

Lack of procedures

The second primary-barrier is again the lack of procedures, but at an operational level causing issues in the Do phase. The DMS for example does not oblige people to fill up all fields in a ticket request as there is no specific protocol for making logistical plans or executing logistic plans. This relates to three secondary-barriers which include the willingness and attitude to use the DMS and the production-driven mindset as discussed previously. But also, a limited understanding of the employee's responsibilities to plan logistics and commit to the plans. It is for this reason that tickets are often requested through phone calls and a WhatsApp group instead of planning deliveries directly in the DMS. Responsibilities of employees have not been clearly defined and neither is a procedure defined to plan a delivery. Therefore, logistical information is poorly checked and communicated as it is not defined what information should be communicated to who, and who needs what information to ensure effective delivery of materials.

No system way of thinking

The third primary-barrier is the lack of a systematic way of thinking which refers to a process in which each task is planned individually. Respondents referred to the use of LPS and described that BIM should be the ideal tool to allow such a process in logistics. However, the current practice is that "*issues discussed about deliveries in the whiteboard meetings have no relation whatsoever to the programme*" and are managed ad-hoc. A respondent stated, "*What we need, is everybody coming in in the whiteboard meeting with all the tasks that need to be done today and tomorrow, linked to the elements, but now people are carrying a lot in their heads*". Nevertheless, these whiteboard meetings are on a daily base in which logistics is planned and tasks are discussed of the previous day, the current day, and the upcoming day. This does allow to discuss what is done yesterday and plan logistics and tasks for the next day in following LPS, which is done to some extent. Tasks are discussed, and conflicting tasks are indicated to find solutions in trying to avoid conflicts during execution. A list of deliveries is maintained on a whiteboard, which is translated to the DMS by the logistics manager. However, some deliveries have been on this board for days or even a week, repeatedly planned for the next day, without a clear discussion about the reasons why the materials are not delivered yet. The main cause is found to be a lack of clear overview of prerequisite work that needs to be executed since there are no lookahead programmes, no drawings and no models used in these meetings. All decisions are based on assumptions and experience of the last planners, which is sufficient to some extent but have caused serious delays when interfaces and site layouts become more complex.

Secondary barriers in the Do phase

There is an additional secondary-barrier, which is a technological barrier referring to the disconnected use of the DMS as it has no relation to BIM 360 or the programme. This means that zone codes, processing locations, etcetera cannot be pushed from BIM 360 as an input for delivery tickets. Employees must add such information manually so elements can be traced. Yet, element or zone codes are not consistently addressed in delivery tickets. Therefore, a respondent stated that "*BIM is a tool, DMS is a tool, but if the DMS is not talking to BIM, there is no value*". However, as indicated, the process could still function effectively if BIM information is manually appointed in the DMS, which requires procedures. Enabling an interface between BIM 360 and the DMS is therefore not a necessity, which is why it is categorised as a secondary-boundary.

Barriers in the Act phase

The structure of this section is again similar to the previous two sections, but the barriers discussed in this section refer to the Study phase on an operational level of decision making in the CPLS-framework. The core problems that were indicated in this phase are the fact that BIM 360 Field is barely used to capture progress information for updating the VCM, and that logistics related data is not captured. Figure 19 helps to structure the barriers that explain the difference between the planned and operational process in this phase. Several technical barriers are not related to any primary-barrier and are discussed at the end of this paragraph.

Figure 19. Barriers in the Study phase

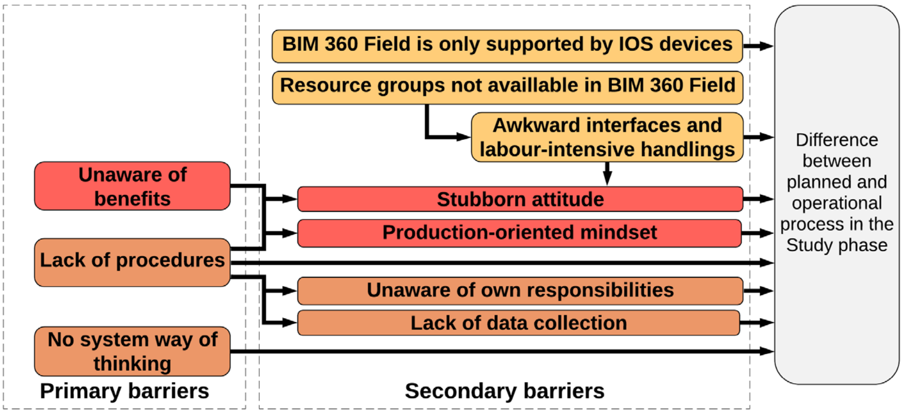

Figure 16. Barriers causing a poor use of LC for conformance control – Study phase

BIM 360 Field is considered the primary logistical component in this phase to get site information back to the office. However, the effectiveness of the tool is dependant of the people using it. Although several barriers are the same as in the previous section, yet they cause different issues in the Study phase of the CPLS-framework as will be discussed.

Unaware of benefits

The first primary-barrier is again the unawareness and attitude of employees at an operational level. Employees on-site are found to be not willing to or not prioritising to capture site information as they are unaware of the importance to capture this information. Even though managers at a tactical level argued the importance of capturing field data to improve practices by following LPS, the last planners seem to undervalue this importance and prioritise anything that directly adds to making production.

Lack of procedures

The second primary-barrier (including four secondary barriers) is the lack of procedures for capturing site information. It is not clearly defined for the last planners what must be updated and why it is important to capture this information. They are unaware of their responsibilities, find the tools a waste of time, and prioritised other things than required, like in the Do phase. Engineers on-site primarily argue that they have no time to capture everything that has been installed. However, it was argued by managers on a tactical level that they were often busy with doing or redoing and checking the work of others. Because they often did not trust their colleagues in having the right skills or knowledge. Besides, data about logistical operations is not captured at all, even though respondents (at a tactical level) indicated the importance of measuring crane and unloading times. Nevertheless, management has not provided a tool to capture such data and neither is anyone assigned to do this exercise.

No system way of thinking

The third primary-barrier is again the lack of a systematic way of thinking but in this phase to check the conformance of every task in following LPS, which is not happening. This makes it impossible to check what has been build and what not according to the VCM, forcing employees of the project controls department to find this information themselves by going out on site. By doing so, they fulfil the jobs of the last planners which are said to be responsible to capture this information.

Nevertheless, a set of constraints for non-conformance is maintained occasionally as discussed previously (Appendix I). However, this set of constraints is specified at capturing the conformance of tasks to the lookahead programme and is not specified on logistics related information. Even though several constraints do include aspects of logistics, there is not enough detail in the data to be useful for improving site logistical operations, such as data about crane times and unloading times.

Secondary barriers in the Study phase

A few technology-related secondary-barriers are found as well. These are categorised as secondary since they mainly cause cumbersome handlings in the process but do not cause the process to be unfeasible. The first one is related to hardware since BIM 360 Field is only running on Apple devices which can discourage employees to use it, as they may need to share iPads or purchase one as a subcontractor. Another barrier is the fact that batches (which are the resource groups in Synchro) that are referred to in the programme are not available in Field. This means that employees need to update the status of every individual element instead of batches, making it a labour-intense exercise. Furthermore, BIM 360 Field is not able to synchronise updates directly to construction lookahead programmes. It requires a manual translation of updates, even if all data is captured in Field and the VCM is accurate. This leads to the fact that barriers in the interoperability cause labour intensive and awkward processes, discouraging employees to update everything through Field. Nevertheless, these issues are categorised as secondary since the VCM has already lost its role in the Plan phase, so there is no real demand for accurate data to update the VCM. Besides, cumbersome interfaces do not cause the process to be impossible to execute.

Chapter 6 - Discussion

This study demonstrates how BIM can be used on construction projects to improve practices in construction logistics. Therefore, it contributes to the existing knowledge base as only very little literature is found on (logistical) BIM applications on an operational level (Matthews et al., 2015; Getuli et al., 2016). In particular, this study is performed in the context of inner-city projects in which there is little room to deviate if plans change (Kooragamage, 2015; Lundesjö, 2015b).

Paragraph 6.1 will discuss the relevance of the CPLS-framework to obtain an effective CLM process on inner-city projects. Paragraph §6.2 discusses how BIM can be applied within a CPLS-layout by outlining three potential roles of BIM within a CPLS-layout, and §6.3 will discuss the enabling conditions to allow a BIM-based CPLS to be effective on inner-city construction projects.

6.1. The applicability of the CPLS-framework and the role of BIM in CLM

This section discusses the usability of the CPLS-framework on inner-city construction projects by addressing its functionality and the relevance of the three dimensions in the framework. This section answers research questions SQ1. *What should a Construction Project Logistics System (CPLS) look like?* and SQ2. *How to establish an information flow and therefore a process within a CPLS?*

Inner-city construction projects are characterised by the fact that there are many stakeholders involved and there is little room to deviate from (logistical) plans (Kooragamage, 2015). This because of a lack of storage space, equipment, delivery routes, regulations and increasing project complexity. Therefore, it is found that the inner-city context requires a CPLS with emphasis on control to reduce deviations in the process.

Several scholars and theories address the need for logistical control. So did Balm *et al.*, (2018) who provided a level of control by introducing three levels of decision making in a logistical governance strategy for project organisations. Besides, Steadieseifi (2011) used comparable hierarchic levels. Both provide for a strategy that allows control in being able to adjust to deviations by narrowing down the scope of decisions. A similar hierarchy is recognized on the case-project. The interrelation between the levels is found to be negatively correlated to the project size. This makes it difficult to standardise processes and job responsibilities for multiple projects. Yet, the CPLS-framework can provide insight and an overview in the process, which can help to tailor processes to specific projects.

Another fundamental theory is to avoid deviations by constantly improving processes by using Deming' PDSA-cycle (Feliz *et al.*, 2014). However, the study and the act phase in this cycle are found to be challenging in practice. Process monitoring and process improvements were poorly executed, primarily because of soft parameters as discussed in §6.3. Nevertheless, the importance and the intention to monitor and constantly improve practices was recognised.

Furthermore, Mosseman (2007, 2012) highlighted the potential of LPS in construction logistics as he argues that logistics entails more than just a material flow but also includes a make-ready planning "*to better manage variability*". Therefore, Mosseman (2007, 2012) provides logistics control by being able to prepare activities and tasks, and to create a pull-based system. This ability to prepare logistical activities is recognised in the case as being essential. However, only very limited logistical activities were actually prepared, solely special deliveries, which is found to be caused by a lack of process thinking.

The three dimensions of control that are described above: being able to adjust, to improve, and to prepare are widely studied and applied in practice. Yet, it is the integration of these three elements what makes the CPLS-framework unique. Consequently, it is primarily the emphasis of control that indicates the suitability of this framework to the context of inner-city projects. Although the execution of these three elements can be improved, the value in applying them was recognised.

Especially LPS is found to be essential in the CPLS, one of the respondents argued that "*the problem is not the boxes [LC], the problem is the lines*". "*so the idea you have here is completely right, the difficulty is in communicating that it in a system that allows to be implemented on a large* *construction site, the methodology is last planner system, that will work, I have seen it work on jobs bigger than this.[...] The difficulty is getting commitment from the older people, to see that this is a better way of doing it* “. This challenge is further discussed in §6.3.

Figure 20. Designing a CPLS-layout

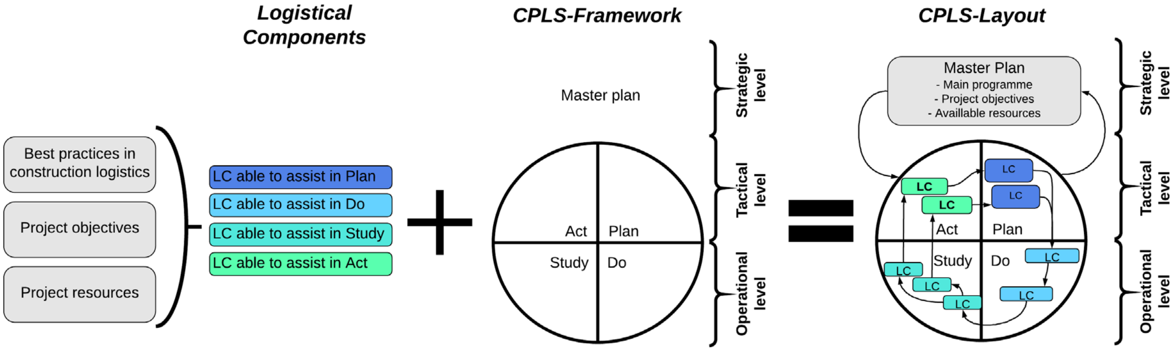

Figure 17. The process to design a tailor-based CPLS-layout for construction projects

Furthermore, the CPLS-framework provides for a modular approach to help in shaping logistical processes on construction projects, see Figure 20. Logistical processes can be tailored to the project objectives (sustainability, improving productivity, reducing failure costs, etcetera) and project resources (available labour, knowledge, skills, IT setup, available software packages, etcetera), which are defined on a strategic level of decision making.

Therefore, the study builds on the research of Rudberg and Maxwell (2019) who indicated that projects with varying characteristics require “*a reconfigurable modular approach* (p.529)” to align the logistics strategy to the context of the project (construction method, building type, size, location, etcetera). The modular system proposed in this study helps to establish a logistical process that suits the required logistical strategy and indicates the potential role of BIM within this system.

The CPLS-framework differs in this way from other logistical frameworks, such as Asnaashari (2011), who also developed a holistic and flexible conceptual logistics model. Yet, he did not explicitly appoint the applicability of BIM applications and best practices (in ICT) to support construction logistics. Also, Said and El-Rayes (2014) developed a logistics system which includes five modules to optimize logistics. However, their model is static as it prescribes the use of certain knowledge and software and is therefore not adjustable to the context of the project (project objectives and resources). Another example is the Smart Construction Objects (SCO)-enabled logistics and supply chain management system that is proposed by Niu et al. (2016) to support in logistical decision making. Yet, their system does not consider an explicit element of control.

6.2. The potential role of BIM in a CPLS

The potential of BIM to obtain an effective CLM process on inner-city construction projects is also addressed in this study. Three logistical BIM applications within the CPLS-layout are found in the empirical results. These are: supporting a systematic approach for project-based CLM, supporting in logistics plan making (plan phase), and support in capturing site-information and conformance monitoring (study phase). This section will discuss these three roles of BIM within a CPLS and answers SQ3. *What is the potential role of BIM within a CPLS?*

6.2.1. Supporting a system approach for project-based CLM – throughout the CPLS

A respondent stated that “*the beauty of BIM and the beauty of Synchro is that every element can be identified, and what you have to do is take your programme, and bring it down to such a level that you identify every single element*”. This is primarily beneficial if prefabricated elements are used, as each element can be identified as an object with a unique ID number. Bortolini, Shigaki and Formoso (2015) shows how these ID numbers can be used for logistics control and plan-making in ETO processes. Also, Li et al., (2018) indicated its usefulness and pointed out the potential of effectively applying LPS for element assembly on site. This allows to develop a pull system on an element, similar to the principles strived in the case-project. This is found particularly valuable in inner-city projects as emphasis is often put on JIT because of limited storage capacity on site. Therefore, the use of BIM is essential as such an element approach is close to impossible by using 2D construction methods, especially once projects become more complex (Eastman *et al.*, 2011).

6.2.2. Assisting in logistics plan making - Plan phase

In addition, the 3D-SLP model is found to benefit the understanding, the opportunities, and limitations of the active construction site and enables to develop logistic plans. Le, Dao and Chaabane (2019) and Schwabe, Teizer and König (2019) addressed similar findings in their attempts to improve SLP. Nevertheless, limitations of this model are addressed as the 3D-SLP is a phased model. It does not represent daily site layout changes related to the programme but is only updated every few weeks. Therefore, several respondents have argued the potential of 4D-SLP as a logistical component in the CPLS-layout to plan site-space more efficient. Also, Pérez, Fernandes and Costa (2016) and Andayesh and Sadeghpour (2014), who discussed the difference and potential of static, phased, and dynamic SLP indicated that most potential is found in dynamic (4D) models.

Furthermore, a 4D-SLP can be used to improve safety (Hu and Zhang, 2011), which impacts construction logistics and vice versa, especially in projects where there is limited space (Mossman, 2007; Browne, 2015). A respondent stated "*safety is actually of big importance for our processes, they [the safety department] can come out every time and say stop, this is not happening, with exclusion zones for example. Safety are the on/off switch for everything, but then you should include safety as well in your process*". Nevertheless, the safety department was not explicitly involved in logistics plan making, which often includes technical details. A detailed 4D-SLP can support since safety employees are often not structurally literate. A "video" about what is going to happen in the upcoming days allows them to understand the process as they can take precautionary measures to avoid issues and improve logistical efficiency (Bortolini, Shigaki and Formoso, 2015).

6.2.3. Capturing site information through BIM – Study phase

Another role of BIM is the ability to allow conformance checking in the Study phase of a CPLS. Nevertheless, the monitoring process through BIM 360 Field was found to be poor which is caused by soft aspects as discussed in §6.3. Yet, in line with the previous paragraph, also visual tools are available to capture site information by matching photographic material to BIM models (Irizarry and Costa, 2016; Braun *et al.*, 2018; Asadi *et al.*, 2019). Such "visual" tools can subsequently input a 4D model and reduce the complexity of logistics plan making as they allow everyone to understand what is done and being done.

6.2.4. Roles of BIM in the Do phase and Act phase

Roles of BIM in the Do phase and Act phase have not been identified on the case-project. Nevertheless, respondents argued that the implementation of the new generation of BIM 360 (see Appendix C) provides for opportunities in the Act phase. The Artificial Intelligence (AI) layer in BIM 360 could be used to automatically aid in remedial actions if logistical plans deviate or assign logistical tasks or issues to the responsible persons. Yet, this application of BIM 360 in the context of construction logistics is not found in literature. However, a similar line of thinking is recognised in literature as Yaseen *et al.*, (2020) developed a model based on AI to predict logistical variability. Also, Asadi, Alsubaey and Makatsoris (2015) developed a machine learning approach to predict variability in logistical plans based on collected data.

In addition, respondents argued that the use of Augmented Reality (AR) was found to be beneficial during execution (Do phase) in previous projects, to improve site layouts. Ciuffini *et al.*, (2016) also pointed out the applicability of AR in the context of layout planning and logistics to support in managing inventory. The use of AR in logistics is found to be more common as pointed out by Raheb (2019) who, however, also provided numerous challenges in the use of AR for logistics. Although experience in the use of these technologies for construction logistics is still immature, they may provide a role as LC in future projects.

6.3. Enabling conditions

Both the potential of logistical BIM applications, as well as the three elements of control in the CPLS-model to were recognised on the case-project. Nevertheless, the expected best-practice on the application of BIM for CLM is not recognised as the empirical results reveal a faltering organization of logistical management on the case-project. This is ought remarkable given presence of the three CPLS elements to ensure logistical control, given the project size (over €1.7 billion), the location and the political atmosphere around the project. Suggesting that a best-practice was expected. Therefore, this research also contributes by providing insight into current practices and providing an explanation for the faltering performance of CLM. This section discusses three enabling conditions that are found to ensure effective implementation of a BIM-based CPLS on construction projects and therefore answers SQ4. *What are enabling conditions for effective implementation of BIM in a CPLS?*

The PPTC-framework conditions allowed to identify twenty-three barriers in the operational logistical process. The analysis of these barriers revealed five primary-barriers for the faltering performance. These five barriers are categorised under three enabling conditions for an efficient BIM-based CPLS, as shown in Table 5. All these barriers take place on a tactical level which is found to be the level in which much can be gained.

Table 5. Primary-barriers

Category	**Enabling conditions**	**#**	**Barriers**	**Strategic**	**Tactical**		**Operational**		**Occurrences**	**Link to secondary**	**Direct link to problems**
					P	A	D	S			
1. People	1.2. Knowledge requirements	1.2.2	Unaware of the potential benefits of digital technologies		X		X	X	3/3	2	No
		1.2.3	Limited BIM skillset		X				1/3	3	Yes
2. Process	2.2. Process and Procedures	2.2.1	Lack of a systematic way of thinking		X		X	X	3/3	0	Yes
		2.2.2	Lack of procedures		X		X	X	3/3	5	Yes
4. Contracts and liability	4.2. Nature of the contract	4.2.2	Contract is 2D-based but processes are 3D based		X				1/3	1	Yes

Table 5. Primary-barriers for the implementation of a BIM-based CPLS

The fact that primary-barriers are found within the categories people and process is not unsurprisingly in relation to literature about collaboration and BIM adoption (Shelbourn *et al.*, 2007; Enegbuma, Aliagha and Ali, 2015). Also, Wilkinson (2005, p.123) states that "*an industry rule of thumb suggests that successful implementation of collaboration systems depends 80 per cent on tackling the people and process issues and only 20 per cent on resolving the technology aspects*". This study found a similar correlation in the context of a BIM-based CPLS. This can be explained as collaboration is essential in the context of inner-city construction projects as space is scarce and working areas and equipment needs to be shared between various stakeholders (Kooragamage, 2015).

Although, it was also found that the GC deals with serious staff turnovers. This might strengthen the fact that most of the barriers are found on a tactical level (fifteen out of twenty-three), which includes most of the GC' "own staff". It is primarily on this tactical level where employees require BIM training and where logistics plans should be made, which requires collaboration. Short staff turnover can make it hard to train employees in obtaining a BIM skillset, to create a culture, or to get employees familiar with procedures. Especially considering a high workload and time pressure that was witnessed on the project. This may have influenced the results of the findings.

On the other hand, the fact that technology barriers are not listed as primary-barriers can be explained since the planned logistical process, as described in §5.2, can be executed from a technological perspective. It is how the LC are used that causes the gap. Although several secondary-barriers are indicated that relate to incompatibility issues between technologies, which have also been addressed by several scholars (Eastman *et al.*, 2011; Enegbuma, Aliagha and Ali, 2015). Yet, the barriers in this study are mainly causing awkward or labour intense processes, similar to issues in the ease of use of interfaces which are found by Shelbourn *et al.*, (2007) and Davies and Harty (2013). Nevertheless, these barriers are awkward or labour intense compared to the envisioned BIM process which is often found to be a utopia (Arbulu and Ballard, 2004; Miettinen and Paavola, 2014). Therefore, cumbersome processes in using the LC can still be more effective compared to not using them at all. Consequently, respondents at a tactical level still believe in the use of digital technologies, as was stated "*If you have a very good process that everybody understands, than the process becomes like a factory, that's what you need but technology makes it easier to do bigger projects and makes it easier to communicate the information*". Coping with these technology barriers is therefore not a first priority but is definitely something that can be improved.

6.3.1. Knowledge Requirements

Figure 21 Knowledge requirements

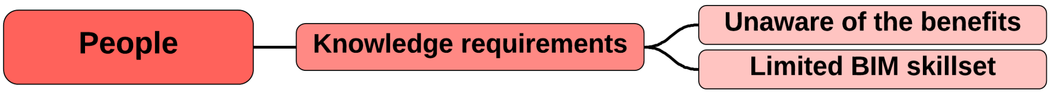

Figure 18. The relation between the category based on the PPTC-framework, the condition, and the primary barriers

This condition comprises two types of knowledge. First, knowledge in terms of a skill set that is required to use BIM since "*the full potential of BIM […] cannot be realised without corresponding changes in the work tasks and skill sets of the project participants*" (Liu, van Nederveen and Hertogh, 2017, p. 692). Second, the knowledge that is required to acknowledge the opportunities of BIM to improve processes (directly or indirectly), which is an incentive to use the technology. This aligns with the findings of Sloot (2018), who found that incentives to use BIM for logistics are essential but having sufficient BIM knowledge and BIM-skilled employees within the organisation is a precondition for strong incentives.

In sum, no matter how well procedures are defined or how accurate models are, BIM will not be used to make logistics plans if employees throughout the different departments do not have a proper BIM skillset or acknowledge the potential of BIM in CLM.

6.3.2. Process and Procedures

Figure 22 Process and procedures

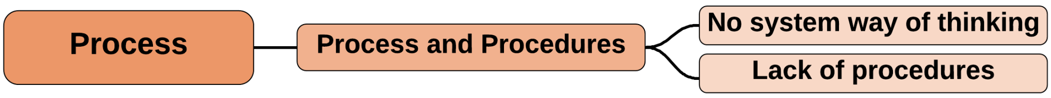

Figure 19. The relation between the category based on the PPTC-framework, the condition, and the primary barriers

The two barriers within the condition "Process and Procedures" are both indicated recurrently in the empirical findings and are frequently appointed in literature as well (Wilkinson, 2005; Shelbourn *et al.*, 2007; Enegbuma, Aliagha and Ali, 2015; Liu, van Nederveen and Hertogh, 2017). The importance of procedures is found to guide a systematic way of working in following LPS, which is essential, not only for logistics management but also for projects control (Ballard, 2000; Arbulu and Ballard, 2004).

However, the LPS principles of Koskela (1999) are not satisfied with current practices, causing processes to be rather reactive. Especially the fact that the make-ready-planning as described by Feliz *et al.* (2014) (see Figure 2) was not recognised in the operational process caused recurring issues. The unprepared logistical plans caused deviations in the execution. Yet, there was limited space to deal with deviations due to the inner-city project context, causing project delays. This acknowledged the essence of a proactive process to ensure conformance to the plan upfront by preparing all necessities for execution, including logistics plans, and avoid negative variances (Melles and Wamelink, 1993; Koskela, 1999).

6.3.3. Contract and Liability

Figure 23 Contracts and Liabilities

Figure 20. The relation between the category based on the PPTC-framework, the condition, and the primary barriers

Even though the condition "contract and liabilities" only has its impact on a tactical level, is only relevant in the Plan phase of the CPLS-framework, and only relates to one secondary-barrier, it plays a significant role in the use of BIM for CLM on projects. Two major issues are recognised related to this condition.

First, the design was far from complete, even about two and a half year after the contract was signed (during the time of the field research). This is partly caused by the fact that a traditionally grounded contract was used which enhances fragmentation (Mohd Nawi, Baluch and Bahauddin, 2014). Therefore, "*the clock does not start for the design team to do something with [design] issues we raise as they still own the model, once handed over, they have a limited time frame to react on issues. However, traditional leverage can yet not be used, it does happen with the drawing, but not with the models*". Causing differences between models and 2D drawings.

Furthermore, Flyvbjerg (2012, 2014) and Flyvbjerg *et al.*, (2018) argued from a behaviour point of view that it is common that politicians and decision-makers provide "misleading" information about the readiness of the design on such social sensitive mega-projects. This, to make sure that the project is pushed through which is ought to benefit their pro-active attitude towards their voters. This argument was used by a respondent who related this behaviour to the fact that politicians wanted to make a statement during their short (four-year) period of leadership. However, if true, this behaviour has caused significant issues in the execution process which are rooted in the procurement phase.

Nevertheless, Love and Ahiaga-dagbui (2018, p.362) do not agree with the "behaviourist" line of thinking of Flyvbjerg and argue that "*there is no commonly agreed international standard that has been established to determine the level of [design] reliability required to create an estimate at the point of decision-to-build*". Meaning that the decision-to-build can be taken at any time and does not require a certain readiness of the design. Therefore, literature argues that integrated contracts should be used to improve construction logistics on projects as design and execution become integrated (Sloot, 2018).

Second, it is found essential that contracts are based on 3D if operational processes are based on 3D (BIM). Currently, contracts are based on 2D, causing differences between 2D-drawings and 3D-models. This may cause employees to be liable for errors in the execution while using 3D models. Resulting in a decreasing value of construction models as employees will not consider the BIM models and build solely from 2D-drawings (Thomson and Miner, 2006). This was recurrently argued by respondents on all levels of decision making. Therefore, the impact of the client (who determines the contract form) on processes during the execution phase, is found to entail significant risks for the general contractor, which also affects the logistical processes.

Chapter 7 - Conclusion

7.1. Major conclusions

Effective construction logistics can significantly benefit both construction organisations and city-mobility but is often undervalued in the industry. Scholars and industry pioneers have indicated the need to improve construction logistics and the potential of BIM to allow effective Construction Logistics Management (CLM). Besides, effective CLM is found to be especially important in inner-city construction projects. Therefore, the objective of this study was to investigate the potential of BIM in a modular logistics system in inner-city construction projects and to provide guidance in obtaining an effective logistics process. The main question to be answered was:

How to obtain an efficient construction logistics management process supported by BIM or BIM data in inner-city construction projects?

In answering this question, a theoretical framework is set. This includes the development of a Construction Project Logistics System (CPLS-framework). An in-depth case study is used in which the CPLS-framework is used to outline the planned and the operational BIM supported logistical process. A gap analysis is subsequently performed to indicate barriers in the operational process by using the People, Process, Technology and Contracts and liabilities (PPTC-framework) conditions which are derived from academic literature. Data is obtained from field research primarily using observations for four months, eleven semi-structured interviews, and archival research.

The first main contribution of this study is the CPLS-framework. Three dimensions of this framework are found to be essential in an inner-city context as they provide an element of control for logistical management on projects. These include a *governance strategy*, required to adjust to variations in the process and based on three levels of decision making: strategic, tactical, and operational. An element of *production process improvement* by using the PDSA-cycle of Deming, which allows to improve practices. Furthermore, an element of *production control* provided by Last Planner Systems (LPS), which enables to prepare the execution of tasks to avoid process variability.

Moreover, it is found that the CPLS-framework can provide for clear guidance to analyse and design logistical processes in a flexible and modular manner, tailored to the project organisation. The framework indicates the activities in four essential phases (PDSA) and provides the flexibility to design a CPLS-layout with several Logistical Components (LC). This implicates that the LC supporting the process are not prescribed but can be chosen in accordance with the project objectives and strategy (including the CPLS-activities), and the project resources. Meaning that LC can be any BIM application, software, tool, or organisational aspect that provides for these requirements and is made available on a strategic level.

The use of BIM and various applications of BIM can provide for LC within a CPLS-layout to design effective logistics processes. The unique ability of BIM to identify each element individually and link each element to tasks, plans and documents allows tracing materials throughout a logistic process. This enables to plan tasks systematically on a very detailed level, in line with LPS. This is found to be essential to guide effective logistics management on projects.

In addition, the empirical results showed that BIM applications can support in achieving two CPLS-activities, which are developing logistic plans and monitoring the construction progress. The use of an accurate 3D-SLP is found to be effective for making logistic plans as it indicates the opportunities and limitations of the construction site and the site equipment. Especially the use of 4D-SLP was found to be very useful, as also non structurally literate (safety) personnel can understand the work that is planned by visualising the activities. This allows tackling activity clashes, logistics issues, and safety issues virtually before execution.

Moreover, three conditions have been found that should be carefully considered when designing or obtaining a BIM driven logistical process in inner-city construction projects. These are:

- The knowledge requirements of employees in the organisation should be sufficient. This includes the understanding of the opportunities of BIM and other relevant digital technologies, and the BIM skillset of individuals on a tactical level of decision making.
- Process and procedures are found to be essential to establish an effective logistical process. They should be clearly defined to support a system way of thinking and enhance the aspects of LPS in a CPLS-framework. Employees should be aware of their own responsibilities and conscious of where to get their information from, what to do with it, and where it is going.
- Contracts and liabilities should be carefully considered in the procurement phase of projects, as liability issues significantly impact BIM-related processes during execution. Besides, contracts should ideally be model-based if processes are model-based because BIM models lose their value if employees are liable for 2D drawings. Additionally, the readiness of design should be carefully considered. An unfinished design can have significant effects on construction processes as traditional leverage cannot be used once the design is not finished.

In sum, the answer to the main research question is provided by the development of the CPLS-framework. The three dimensions: governance strategy, production process improvement, and production control are essential to provide for logistics control in an inner-city context. Furthermore, by describing the applicability of the CPLS-framework to develop CPLS-layouts using LC, by discussing the role of BIM in a CPLS, and by providing three conditions to obtain an effective BIM-based CPLS.

7.2. The scientific and practical contribution

7.2.1. Scientific contribution

Although the importance of construction logistics is underestimated in the industry, Scholars have devoted substantial effort to improve logistics in the construction industry by providing various logistical tools, concepts, and methods. This research contributes to the existing scientific knowledge base of construction logistics by defining three dimensions of a construction project logistics system.

The combination of these elements provides for optimal control of logistical processes. Therefore, the CPLS-framework differs from existing logistical frameworks, concepts, or methods who seek improvements of CLM on projects but lack the element of control. Yet, it is the control of logistical processes that are found to be essential in the context of inner-city projects.

Furthermore, this study contributes by providing a thorough understanding of barriers and subsequently enabling conditions to ensure effective use of BIM within a CPLS. Many scholars have indicated barriers in collaboration and the use of BIM in construction but only a few in the context of construction logistics on an operational level.

7.2.2. Practical contribution

Moreover, the study provides a practical contribution by proposing the applicability of the CPLS-framework as a modular system for CLM. The framework enables to consider several areas of logistical improvements to satisfy the objectives of a project in terms of logistics. This allows to incorporate those best practices that are relevant for reaching the project objectives and can be executed with the available resources on the project. Therefore, it provides a new tailored approach for CLM on construction projects.

Also, this study provides for conditions to allow effective implementation of BIM applications in a logistic process based on the primary barriers that are found in a BIM-based CPLS. The enabling conditions can guide to improve current practices in a BIM-driven CPLS.

7.3. Future research

In addition to the contributions of this study, several areas require future research. Especially since this study introduced a new framework to the existing knowledge base of construction logistics. Indicating that it provides various opportunities to ground that what has been proposed. Therefore, future research could focus on applying the CPLS-framework and the PPTC-framework conditions in the context of other case-projects. Especially in projects where site-data is actively collected and emphasis is put on the Act phase, which is something that the case-project in this study could not provide for.

Another opportunity for future research is to explore the functionality of the CPLS-framework from a wider perspective. That is, similar to the PDSA-cycle that links the tactical to the operational level of decision making. There is also a PDSA-cycle that links the strategic to the tactical level, caused by a pull system based on LPS, see Figure 24. LPS argues that work is only allowed to be pulled from the main programme (strategic level) and planned in the lookahead programmes (tactical level) if planners are confident that prerequisite work will be finished before the planned starting date (Ballard, 2000). These tasks are subsequently used in the Do phase to make plans. Furthermore, any deviations in the lookahead programs are studied in the Study phase and translated back to the master schedule for remedial action in the Act phase. This research is primarily focused on the lower half (tactical and operational) of the CPLS-framework. Therefore, future research could consider the upper-half this framework, or the full framework.

Figure 24. Full CPLS-framework

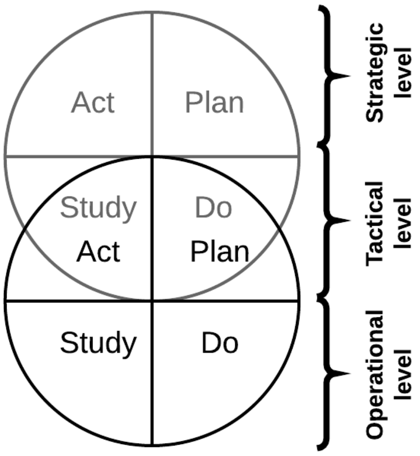

Figure 21. Full CPLS-framework including the PDSA-cycle linking the strategic to a tactical level

Also, the need for job-specific training was indicated repeatedly in interviews. Employees should have a wider understanding of the different departments including BIM. Especially once employees enter higher job-positions in the organisational hierarchy. A matrix was developed during one of the interviews to indicate the required knowledge about different departments for a particular job description as is described in Appendix L. Yet, the development of this matrix was outside of the scope of this research and is therefore not discussed. However, the line of thinking about the required BIM maturity of individuals within a project organisation was beneficial. Primarily for designing tailored BIM training to improve practices and actively adopt BIM for logistics. One of the respondents stated about the matrix "*that's a really powerful tool, [ ] That might be a small bit of your thesis, but it is actually key to understanding to make the training effective*". Yet, the matrix is not theoretically grounded which is something that could be relevant for future research.

Chapter 8 - Recommendations

An optimum CPLS-layout for the case was proposed in interviews during the time of the field research in which three changes are made in the operational CPLS-layout, which are:

- a planning software program Aphex Planner is proposed to replace the use of Excel for planning the lookaheads programs;
- Synchro 4D is proposed on a tactical level instead of only on a strategic level in which the lookahead programs provide the input; and
- Aphex Planner is proposed instead of BIM 360 Field to collect data about the construction progress.

The choices for these LC in the CPLS-layout are based on proposed suggestions by respondents during the field study as elaborated in Appendix M. Yet, prior attention should be given to the enabling conditions “knowledge requirements” and “process and procedures” to improve practices in the current operational process, and to allow the current process and eventually this optimum process to be effective.

Chapter 9 - References

Abubakar, M. *et al.* (2014) 'Contractors Perception of the Factors Affecting Building Information Modelling (BIM) Adoption in the Nigerian Construction Industry', *Computing in Civil and Building Engineering*, pp. 167–178. doi: 10.1061/9780784413616.053.

Ahmadian F.F., A. *et al.* (2017) 'BIM-enabled sustainability assessment of material supply decisions', *Engineering, Construction and Architectural Management*. Emerald Publishing Limited, 24(4), pp. 668–695. doi: 10.1108/ECAM-12-2015-0193.

Altintas, A. (2013) *Bouw Logistiek 2.0: Op weg naar een efficiënt bouwproces; Een onderzoek naar de toepasbaarheid van innovatieve bouwlogistieke concepten in binnenstedelijke projecten en de voor- en nadelen van deze concepten vanuit een efficient perspectief*. Technical University of Delft.

Andayesh, M. and Sadeghpour, F. (2014) 'The time dimension in site layout planning', *Automation in Construction*. Elsevier B.V., 44, pp. 129–139. doi: 10.1016/j.autcon.2014.03.021.

Arayici, Y. *et al.* (2011) 'Technology adoption in the BIM implementation for lean architectural practice', *Automation in Construction*, 20(2), pp. 189–195. doi: 10.1016/j.autcon.2010.09.016.

Arbulu, R. and Ballard, G. (2004) 'Lean Supply Systems in Construction', *12th Annual Conference of the International Group for Lean Construction*, (January 2004), p. 13. Available at: http://iglc.net/Papers/Details/291/pdf%5Cnhttp://iglc.net/Papers/Details/291.

Argyris, C. and Schön, D. A. (1989) *Research Methods in Education*. Sixth. Oxon and New York: Routledge.

Asadi, A., Alsubaey, M. and Makatsoris, C. (2015) 'A machine learning approach for predicting delays in construction logistics', *International Journal of Advanced Logistics*. Informa UK Limited, 4(2), pp. 115–130. doi: 10.1080/2287108x.2015.1059920.

Asadi, K. *et al.* (2019) 'Real-time image localization and registration with BIM using perspective alignment for indoor monitoring of construction', *Journal of Computing in Civil Engineering*, 33(5). doi: 10.1061/(ASCE)CP.1943-5487.0000847.

Asnaashari, E. (2011) 'A Holistic Conceptual Model for Managing Construction Logistics in Building Projects : the Case of Iran', (November).

Ballard, G. and Howell, G. (1998) 'Shielding production: Essential step in production control', *Journal of Construction Engineering and Management*, 124(1), pp. 11–17. doi: 10.1061/(ASCE)0733-9364(1998)124:1(11).

Ballard, H. G. (2000) *The Last Planner System of Production Control*, *University of Birmingham Research Archive*. University of Birmingham. doi: 10.1007/BF00837862.

Balm, S. *et al.* (2018) *Slimme bouwlogistiek: onderzoek naar de fundamenten van slimme en schone bouwlogistiek in steden*.

Barison, M. B. and Santos, E. T. (2010) 'An overview of BIM specialists', *Computing in Civil and Building Engineering, Proceedings of the ICCCBE2010*, (141).

Bataglin, F. S. *et al.* (2017) 'Application of Bim for Supporting Decisionmaking Related to Logistics in Prefabricated Building Systems', *25th Annual Conference of the International Group for Lean Construction*, (July), pp. 71–78. doi: 10.24928/2017/0278.

den Boer, E. *et al.* (2017) 'Outlook City Logistics 2017', pp. 1–91. Available at: https://topsectorlogistiek.nl/2017/06/09/download-nu-outlook-city-logistics/.

Boissinot, A. and Paché, G. (2011) 'Opportunism control in exchange relationships: Lessons from the French logistics industry', *Problems and Perspectives in Management*, 9(1), pp. 71–77.

Borrmann, A. *et al.* (2018) 'Building Information Modeling: Why? What? How?', in Borrmann, A. et al. (eds) *Building Information Modeling: Technology Foundations and Industry Practice*. Springer International Publishing AG, part of Springer Nature, pp. 1–34. doi: 10.4324/9781315797076.

Bortolini, R., Formoso, C. T. and Viana, D. D. (2019) 'Site logistics planning and control for engineer-to-order prefabricated building systems using BIM 4D modeling', *Automation in Construction*. Elsevier, 98(November 2018), pp. 248–264. doi: 10.1016/j.autcon.2018.11.031.

Bortolini, R., Shigaki, J. S.-I. and Formoso, C. T. (2015) 'Site Logistics Planning and Control Using 4D Modeling: A Study in a Lean Car Factory Building Site', in *23rd Annual Conference of the International Group for Lean Construction*. 28-31 July, Perth, Australia, pp. 361–370.

Bosch-Sijtsema, P. *et al.* (2017) 'Barriers and facilitators for BIM use among Swedish medium-sized contractors - "We wait until someone tells us to use it"', *Visualization in Engineering*. Visualization in Engineering, 5(1). doi: 10.1186/s40327-017-0040-7.

Braun, A. *et al.* (2018) 'BIM-Based Progress Monitoring', in Borrmann, A. et al. (eds) *Building Information Modeling: Technology Foundations and Industry Practice*. Springer International Publishing AG, part of Springer Nature 2018, pp. 463–476. doi: 10.4324/9781315797076.

Browne, M. (2015) 'The challenge of construction logistics', in Lundesjö, G. (ed.) *Supply Chain Management and Logistics in Construction - Delivering Tomorrow's Built Environment*. Kogan Page Limited Apart, pp. 9–24.

BZK (2014) *Regeling van de Minister voor Wonen en Rijksdienst van 16 juni 2014, nr. 2014-0000293800,* The Netherlands.

Chai, J. *et al.* (2016) 'Automatic as-built modeling for concurrent progress tracking of plant construction based on laser scanning', *Concurrent Engineering Research and Applications*, 24(4), pp. 369–380. doi: 10.1177/1063293X16670449.

Chen, P.-H. and Nguyen, T. C. (2018) 'A BIM-WMS integrated decision support tool for supply chain management in construction'. doi: 10.1016/j.autcon.2018.11.019.

Cheng, J. C. P. and Kumar, S. (2015) 'A BIM-Based Framework for Material Logistics Planning', *23rd Annual Conference of the International Group for Lean Construction (IGLC) at Perth, Australia*, pp. 33–42. Available at: http://www.iglc.net/papers/details/1158.

Ciuffini, A. F. *et al.* (2016) 'Application of Virtual / Augmented Reality in steelmaking plants layout planning and logistics S imulation', pp. 5–10.

CLOCS (2018) *Construction Logistics Plan Guidance*. Available at: https://www.clocs.org.uk/resources/clp_guidance_clocs_final.pdf.

Croydon Council (2015) *A practical guide to drafting a construction logistics plan*. Available at: https://www.croydon.gov.uk/sites/default/files/articles/downloads/A practical guide to drafting a construction plan.pdf.

Dakhli, Z. and Lafhaj, Z. (2018) 'Considering Materials Management in Construction: An Exploratory Study', *Logistics*, 2(1), p. 7. doi: 10.3390/logistics2010007.

Davies, R. and Harty, C. (2013) 'Implementing "site BIM": A case study of ICT innovation on a large hospital project', *Automation in Construction*. Elsevier B.V., 30, pp. 15–24. doi: 10.1016/j.autcon.2012.11.024.

Deming, W. E. (1950) 'Deming's 1950 Lecture to Japanese Management'. Available at: http://hclectures.blogspot.com/1970/08/demings-1950-lecture-to-japanese.html (Accessed: 14 March 2020).

Deng, Y. *et al.* (2019) 'Integrating 4D BIM and GIS for Construction Supply Chain Management', *Journal of Construction Engineering and Management*, 145(4), p. 04019016. doi: 10.1061/(ASCE)CO.1943-7862.0001633.

Dijkmans, T. *et al.* (2014) 'Samenwerking in Amsterdamse logistiek'.

Dixit, S. *et al.* (2017) 'A study of enabling factors affecting construction productivity: Indian scnerio', *International Journal of Civil Engineering and Technology*, 8(6), pp. 741–758.

Dubois, A., Hulthén, K. and Sundquist, V. (2019) 'Organising logistics and transport activities in construction', *International Journal of Logistics Management*. Emerald Group Publishing Ltd., 30(2), pp. 620–640. doi: 10.1108/IJLM-12-2017-0325.

Eastman, C. *et al.* (2011) *BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors*. John Wiley & Sons.

Eisenhardt, K. M. (1989) 'Building Theories from Case Study Research', *The Academy of Management*, 14(4), pp. 532–550.

Ekeskär, A. and Rudberg, M. (2016) 'Third-party logistics in construction: the case of a large hospital project', *Construction Management and Economics*, 34(3), pp. 174–191. doi: 10.1080/01446193.2016.1186809.

Enegbuma, W. I., Aliagha, G. U. and Ali, K. (2015) 'Effects of perceptions on BIM adoption in malaysian construction industry', *www.jurnalteknologi.utm.my*, 77(15), pp. 69–75.

Fadiya, O. O. (2012) *Development of an integrated decisions analysis framework for selecting ICT-based logistics systems in the construction industry*.

Feliz, T. *et al.* (2014) 'Leveraging software for learning-in-action using commitment-based planning', *22nd Annual Conference of the International Group for Lean Construction: Understanding and Improving Project Based Production, IGLC 2014*, pp. 1307–1318.

Flyvbjerg, B. (2012) 'Why mass media matter and how to work with them: Phronesis and megaprojects', in Flyvbjerg, B., Landman, T, Schram, S., E. (ed.) *Real Social Science: Applied Phronesis*. Cambridge: Cambridge University Press, pp. 95–121. doi: 10.1017/CBO9780511719912.008.

Flyvbjerg, B. (2014) 'What you should know about megaprojects and why: An overview', *Project Management Journal*, 45(2), pp. 6–19. doi: 10.1002/pmj.21409.

Flyvbjerg, B. *et al.* (2018) 'Five things you should know about cost overrun ☆', *Transportation Research Part A*. Elsevier, 118(September), pp. 174–190. doi: 10.1016/j.tra.2018.07.013.

Getuli, V. *et al.* (2016) 'Field BIM and Supply Chain Management in Construction : an On-going Monitoring System', *Creative Construction Conference 2016 - Proceedings*, pp. 620–625. Available at: http://2016.creative-construction-conference.com/ccc-2016-proceedings/.

Ghaffarianhoseini, Ali *et al.* (2017) 'Building Information Modelling (BIM) uptake: Clear benefits, understanding its implementation, risks and challenges', *Renewable and Sustainable Energy Reviews*. Pergamon, 75, pp. 1046–1053. doi: 10.1016/J.RSER.2016.11.083.

Goulding, J. and Arif, M. (2013) *Research Roadmap Report: Offsite Production and Manufacturing*, *CIB General Secretariat*. Available at: https://site.cibworld.nl/dl/publications/pub_372.pdf.

Gu, N. and London, K. (2010) ‘Understanding and facilitating BIM adoption in the AEC industry’, *Automation in Construction*. Elsevier B.V., 19(8), pp. 988–999. doi: 10.1016/j.autcon.2010.09.002.

Hooper, M. and Widén, K. (2015) ‘BIM Inertia: Contracts and Behaviours’, in Issa, R. R. A. and Olbina, S. (eds) *Building information modeling: applications and practices*. American Society of Civil Engineers, pp. 107–134.

Hu, Z. and Zhang, J. (2011) ‘BIM- and 4D-based integrated solution of analysis and management for conflicts and structural safety problems during construction: 2. Development and site trials’, *Automation in Construction*, 20(2), pp. 155–166. doi: 10.1016/j.autcon.2010.09.013.

Irizarry, J. and Costa, D. B. (2016) ‘Exploratory Study of Potential Applications of Unmanned Aerial Systems for Construction Management Tasks’, *Journal of Management in Engineering*, 32(3), pp. 1–10. doi: 10.1061/(ASCE)ME.1943-5479.0000422.

Irizarry, J., Karan, E. P. and Jalaei, F. (2013) ‘Integrating BIM and GIS to improve the visual monitoring of construction supply chain management’, *Automation in Construction*. Elsevier B.V., 31, pp. 241–254. doi: 10.1016/j.autcon.2012.12.005.

Jacobsson, M. and Linderoth, H. C. J. (2010) ‘The influence of contextual elements, actors’ frames of reference, and technology on the adoption and use of ICT in construction projects: A swedish case study’, *Construction Management and Economics*, 28(1), pp. 13–23. doi: 10.1080/01446190903406154.

Janné, M. (2018) *Construction Logistics Solutions in Urban Areas*. Linköping University.

Janné, M. and Fredriksson, A. (2019) ‘Construction logistics governing guidelines in urban development projects’, *Construction Innovation*, 19(1), pp. 89–109. doi: 10.1108/CI-03-2018-0024.

Jayasena, H. S. and Chitra, W. (2013) ‘Assessing the BIM maturity in a BIM Infant Industry’, *‘Assessing the BIM maturity in a BIM infant industry.’ In Proceedings of the Second World Construction Symposium 2013: Socio-Economic Sustainability in Construction*, pp. 14–15.

Karabulut, B., Van der Voort, T. and Van Doorn, A. (2013) ‘Afval , transport en logistiek in de bouw moeten duurzamer’, (april), pp. 82–83.

Kassem, M. *et al.* (2016) ‘A Tool for Assessing the Compliance of Project Activities and Deliverables Against the Requirements of BIM Level 2 Policy Documents’, *13th International Conference on Construction Applications of Virtual Reality*, (April).

Klakegg, O. J. (2009) ‘Challenging the interfaces between governance and management in construction projects’, in Reykjavík University, I. (ed.) *5th Nordic Conference on Construction Economics and Organisation*, pp. 181–201.

Kooragamage, R. (2015) ‘Managing construction logistics for confined sites in urban areas’, in Lundesjö, G. (ed.) *Supply Chain Management and Logistics in Construction - Delivering Tomorrow’s Built Environment*. Kogan Page Limited, pp. 205–224.

Koskela, L. (1999) ‘Management of production in construction: a theoretical view’, *Proceedings IGLC-7*, pp. 241–252.

Kovacs, G. and Kot, S. (2016) ‘New Logistics and Production Trends As the Effect of Global Economy Changes’, *Polish Journal of Management Studies*, 14(2), pp. 115–126. doi: 10.17512/pjms.2016.14.2.11.

Krumme, K. (2019) ‘Supply chains and systems of sustainability: An attempt to close the gap’, in *Innovative Logistics Services and Sustainable Lifestyles: Interdependencies, Transformation Strategies and Decision Making*. Springer International Publishing, pp. 21–60. doi: 10.1007/978-3-319-98467-4_2.

Lange, S. and Schilling, D. (2015) 'Reasons for an optimized construction logistics', in Seppänen, O., González, V. A., and Arroyo, P. (eds) *IGLC 23 Global Problems-Global Solutions Proceedings*. Perth, Australia, pp. 733–742.

Langford, G. *et al.* (2008) 'Gap Analysis: Rethinking the Conceptual Foundations'.

Le, P. L., Dao, T. M. and Chaabane, A. (2019) 'BIM-based framework for temporary facility layout planning in construction site: A hybrid approach', *Construction Innovation*, 19(3), pp. 424–464. doi: 10.1108/CI-06-2018-0052.

Li, C. Z. *et al.* (2017) 'Integrating RFID and BIM technologies for mitigating risks and improving schedule performance of prefabricated house construction', *Journal of Cleaner Production*. Elsevier Ltd, 165, pp. 1048–1062. doi: 10.1016/j.jclepro.2017.07.156.

Li, C. Z. *et al.* (2018) 'An Internet of Things-enabled BIM platform for on-site assembly services in prefabricated construction', *Automation in Construction*, 89(July 2017), pp. 146–161. doi: 10.1016/j.autcon.2018.01.001.

Liu, S. *et al.* (2015) 'Critical Barriers to BIM Implementation in the AEC Industry', *International Journal of Marketing Studies*, 7(6), p. 162. doi: 10.5539/ijms.v7n6p162.

Liu, Y., van Nederveen, S. and Hertogh, M. (2017) 'Understanding effects of BIM on collaborative design and construction: An empirical study in China', *International Journal of Project Management*. Elsevier Ltd, APM and IPMA, 35(4), pp. 686–698. doi: 10.1016/j.ijproman.2016.06.007.

Love, P. E. D. and Ahiaga-dagbui, D. D. (2018) 'Debunking fake news in a post-truth era : The plausible untruths of cost underestimation in transport infrastructure projects', *Transportation Research Part A*. Elsevier, 113(June 2017), pp. 357–368. doi: 10.1016/j.tra.2018.04.019.

Lu, H. *et al.* (2018) 'Study on construction material allocation policies: A simulation optimization method', *Automation in Construction*. Elsevier, 90(September 2017), pp. 201–212. doi: 10.1016/j.autcon.2018.02.012.

Lundesjö, G. (2015a) 'Consolidation centres in construction logistics', in Lundesjö, G. (ed.) *Supply Chain Management and Logistics in Construction - Delivering Tomorrow's Built Environment*. Kogan Page Limited, pp. 225–242.

Lundesjö, G. (2015b) *Supply Chain Management and Logistics in Construction - Delivering Tomorrow's Built Environment*. Edited by G. Lundesjö. Kogan Page Limited.

Matthews, J. *et al.* (2015) 'Real time progress management: Re-engineering processes for cloud-based BIM in construction', *Automation in Construction*, 58, pp. 38–47. doi: 10.1016/j.autcon.2015.07.004.

McGraw Hill Construction (2012) *The Business Value of BIM in North America: Multi-Year Trend Analysis and User Ratings (2007–2012), SmartMarket Report*.

Melles, B. and Wamelink, J. W. F. (1993) *Production control in construction: Different approaches to control, use of information and automated data processing*. Delft University.

Merriënboer, S. Van and Ludema, M. (2016) 'TKI project " 4C in Bouwlogistiek "', 2016(november), p. 38.

Methanivesana, N. (2012) 'Improving Construction Logistics A case study of Residential Building Project', (190).

Meyer, C. B. (2001) 'A Case in Case Study Methodology', *Field Methods*, 13(4), pp. 329–352. doi: 10.1177/1525822X0101300402.

MHC (2014) *The Business Value of BIM for Construction in Major Global Markets*, *SmartMarket Report*. Available at: http://static.autodesk.net/dc/content/dam/autodesk/www/solutions/building-information-modeling/construction/business-value-of-bim-for-construction-in-global-markets.pdf.

Miettinen, R. and Paavola, S. (2014) 'Beyond the BIM utopia: Approaches to the development and implementation of building information modeling', *Automation in Construction*. Elsevier B.V., 43, pp. 84–91. doi: 10.1016/j.autcon.2014.03.009.

Moen, R. and Norman, C. (2006) 'Evolution of the PDCA Cycle', *Society*, pp. 1–11.

Mohd Nawi, M. N., Baluch, N. and Bahauddin, A. Y. (2014) 'Impact of Fragmentation Issue in Construction Industry: An Overview', *MATEC Web of Conferences*, 15, p. 01009. doi: 10.1051/matecconf/20141501009.

Morgan, J. M. and Liker, J. K. (2006) *The Toyota product development system*, *Machine Design*. Productivity press. doi: 10.4324/9781482293746.

Mossman, A. (2007) 'Lean logistics: Helping to create value by bringing people, information, plant, equipment and materials together at the workface', *Lean Construction: A New Paradigm for Managing Capital Projects - 15th IGLC Conference*, (July), pp. 198–211.

Mossman, A. (2012) 'Last Planner', (March), pp. 1–18.

Niu, Y. *et al.* (2016) 'An SCO-Enabled Logistics and Supply Chain–Management System in Construction', *Journal of Construction Engineering and Management*, 143(3), p. 04016103. doi: 10.1061/(asce)co.1943-7862.0001232.

Pérez, C. T., Fernandes, L. L. A. and Costa, D. B. (2016) 'A literature review on 4D BIM for logistics operations and workspace management', *IGLC 2016 - 24th Annual Conference of the International Group for Lean Construction*, 55, pp. 53–62.

Ploos van Amstel, W. (2016) *Citylogistiek: Op weg naar een duurzame stadslogistiek voor aantrekkelijke steden*, *Tijdschrift voor toegepaste logistiek*. HvA, Hogeschool Van Amsterdam.

Ploos Van Amstel, W. (2002) *Het organiseren van logistieke beheersing*. Vrije Universiteit Amsterdam.

Quak, H. *et al.* (2011) 'Bouwlogistieke oplossingen voor binnenstedelijk bouwen'.

Rejeb, A. (2019) 'The Challenges of Augmented Reality in Logistics : A Systematic Literature Review', 134(August), pp. 281–311.

Riopel, D., Langevin, A. and Campbell, J. F. (2005) 'The Network of Logistics Decisions', in Langevin, A. and Riopel, D. (eds) *Logistics Systems: Design and Optimization*. New York: Springer Scienc+Business Media, Inc. (GERAD 25th anniversary series), pp. 1–38. doi: https://doi-org.ezproxy2.utwente.nl/10.1007/b106452.

Robbins, S. (2015) 'Effective management of a construction project supply chain', *Supply Chain Management and Logistics in Construction - Delivering Tomorrow's Built Environment*, pp. 62–76.

Rolfsen, C. N. and Merschbrock, C. (2016) 'Acceptance of Construction Scheduling Visualizations: Bar-charts, Flowline-charts, or Perhaps BIM?', *Procedia Engineering*. The Author(s), 164(1877), pp. 558–566. doi: 10.1016/j.proeng.2016.11.658.

Rudberg, M. and Maxwell, D. (2019) 'Exploring Logistics Strategy in Construction', in *© IFIP International Federation for Information Processing 2019*. Springer International Publishing, pp. 529–536. doi: 10.1007/978-3-030-30000-5.

Saheb, Y. *et al.* (2015) *Energy Renovation: The Trump Card for the New Start for Europe*. doi: 10.2790/39989.

Said, H. and El-Rayes, K. (2014) ‘Automated multi-objective construction logistics optimization system’, *Automation in Construction*. Elsevier B.V., 43, pp. 110–122. doi: 10.1016/j.autcon.2014.03.017.

Schmidt, G. and Wilhelm, W. E. (2000) ‘Strategic, tactical and operational decisions in multi-national logistics networks: A review and discussion of modelling issues’, *International Journal of Production Research*, 38(7), pp. 1501–1523. doi: 10.1080/002075400188690.

Schwabe, K., Teizer, J. and König, M. (2019) ‘Applying rule-based model-checking to construction site layout planning tasks’, *Automation in Construction*. Elsevier, 97(November 2017), pp. 205–219. doi: 10.1016/j.autcon.2018.10.012.

Sekaran, U. and Bougie, R. (2016) *Research Methods For Business: A Skill Building Approach*. 7th edn. John Wiley & Sons.

Sharif, M. M. *et al.* (2017) ‘Automated Model-Based Finding of 3D Objects in Cluttered Construction Point Cloud Models’, *Computer-Aided Civil and Infrastructure Engineering*, 32(11), pp. 893–908. doi: 10.1111/mice.12306.

Shelbourn, M. *et al.* (2007) ‘Planning and implementation of effective collaboration in construction projects’, *Construction Innovation*, 7(4), pp. 357–377. doi: 10.1108/14714170710780101.

Silva, F. B. Da and Cardoso, F. F. (1999) ‘Applicability of logistics management in lean construction: a case study Approach in Brazilian building companies’, *Proceedings IGLC*, 7, pp. 147–158.

Sloot, R. *et al.* (2017) ‘LOGISTICS IN CONSTRUCTION PROJECT : PHASES , ACTORS , TASKS AND INFORMATION NEEDS’, pp. 1–9.

Sloot, R. (2018) *Design and validation of BIM scenarios, incentives and protocol for construction logistics*.

Sommerville, J. and Craig, N. (2006) *Implementing IT in construction*, *Implementing IT in Construction*. London & New York: Routledge, Taylor & Francis Group. doi: 10.4324/9780203030394.

Spengler, A. J. *et al.* (2017) ‘Supply Chain Tracking im BIM Modell’, in *Innovative Produkte und Dienstleistungen in der Mobilität*. Wiesbaden: Springer Fachmedien Wiesbaden, pp. 571–582. doi: 10.1007/978-3-658-18613-5_36.

Srivastava, A. and Thomson, S. B. (2009) ‘A Qualitative Methodology for Applied Policy Research’, *Applied Policy Research. JOAAG*, 4(2), pp. 72–79. doi: 10.7748/nr2011.01.18.2.52.c8284.

SteadieSeifi, M. (2011) ‘Logistics Strategic Decisions’, in Farahani Zanjirani, R., Rezapour, S., and Kardar, L. (eds) *Logistics Operations and Management: Concepts and Models*. Elsevier, pp. 43–53. doi: https://doi.org/10.1016/C2010-0-67008-8.

Sullivan, G., Barthorpe, S. and Robbins, S. (2010) *Managing Construction Logistics*. John Wiley & Sons.

Sundquist, V., Gadde, L. E. and Hulthén, K. (2018) ‘Reorganizing construction logistics for improved performance’, *Construction Management and Economics*. Routledge, 36(1), pp. 49–65. doi: 10.1080/01446193.2017.1356931.

Sweeney, E. (2013) ‘The People Dimension in Logistics and Supply Chain Management – its Role and Importance’, in Passaro, R. and Thomas, A. (eds) *Supply Chain Management: Perspectives, Issues and Cases*. Milan: McGraw-Hill, pp. 73–82.

Tessier, S. (2012) ‘From field notes, to transcripts, to tape recordings: Evolution or combination?’, *International Journal of Qualitative Methods*, 11(4), pp. 446–460. doi: 10.1177/160940691201100410.

Thomson, D. B. and Miner, R. G. (2006) ‘BIM: Contractural Risks are Changing with Technology’, *Consulting-Specifying Engineer*, 40(2), pp. 54-56+.

Transport for London (2013) *Construction Logistics Plan Guidance; For Developers*. Available at: https://www.clocs.org.uk/wp-content/uploads/2014/05/construction-logistics-plan-guidance-for-developers.pdf.

Trindade, L. D. *et al.* (2016) 'Building Information Models as the Basis of Business Strategy: A Case Study of an Integrated BIM-Based System for Construction Management', *Bim*. Available at: http://itc.scix.net/cgi-bin/works/Show?_id=w78-2016-paper-003&sort=DEFAULT&search=Bim implementation strategy &hits=579.

Tulke, J. (2018) 'BIM-Based Design Coordination', in Borrmann, A. et al. (eds) *Building Information Modeling: Technology Foundations and Industry Practice*. Cham: Springer International Publishing, pp. 317–327. doi: 10.1007/978-3-319-92862-3_18.

Underwood, J. and Isikdag, U. (2009) *Handbook of Research on Building Information Modeling and Construction Informatics*. doi: 10.4018/978-1-60566-928-1.

United Nations (2018) *2018 Revision of World Urbanization Prospects | Multimedia Library - United Nations Department of Economic and Social Affairs*, *16 may 2018*. Available at: https://www.un.org/development/desa/publications/2018-revision-of-world-urbanization-prospects.html (Accessed: 29 April 2019).

Vries, A. M. R. and Ludema, M. W. (2012) 'Bouwlogistieke HUB, zin of onzin', in *Vervoerslogistieke werkdagen*, pp. 345–357.

Waddell, M. (2015) 'Resource efficiency benefits of effective construction logistics', in Lundesjö, G. (ed.) *Supply Chain Management and Logistics in Construction - Delivering Tomorrow's Built Environment*. Kogan Page Limited Apart, pp. 139–158.

Wang, T. K. *et al.* (2017) 'Integrated supplier selection framework in a resilient construction supply chain: An approach via analytic hierarchy process (AHP) and grey relational analysis (GRA)', *Sustainability (Switzerland)*, 9(2). doi: 10.3390/su9020289.

Wang, W. C. *et al.* (2014) 'Integrating building information models with construction process simulations for project scheduling support', *Automation in Construction*. Elsevier B.V., 37, pp. 68–80. doi: 10.1016/j.autcon.2013.10.009.

Whitlock, K. *et al.* (2018) 'BIM for Construction Site Logistics Management.', *Journal of Engineering, Project, and Production Management*, 8(1), pp. 47–55. doi: 10.32738/jeppm.201801.0006.

Wilkinson, P. (2005) *Construction Collaboration Technologies*. Taylor & Francis.

Womack, J. P. and Jones, D. T. (2003) *LEAN Thinking—banish waste and create wealth in your corporation*. Free Press, A Division of Simon & Schuster.

Womack, J. P., Jones, D. T. and Roos, D. (1990) 'The machine that changed the world', p. 323.

Yaseen, Z. M. *et al.* (2020) 'Prediction of risk delay in construction projects using a hybrid artificial intelligence model', *Sustainability (Switzerland)*, 12(4), pp. 1–14. doi: 10.3390/su12041514.

Yin, R. K. (1981) 'The Case Study as a Serious Research Strategy', *Science Communication*, 3(1), pp. 97–114. doi: 10.1177/107554708100300106.

Yin, R. K. (2015) *Qualitative Research from Start to Finish*. New York, London: THE GUILFORD PRESS.

Yin, R. K. (2018) *Case Study Research and Applications, Design and Methods*. Sixth, *Journal of Chemical Information and Modeling*. Sixth. SAGE Publications.

Ying, F., Tookey, J. and Roberti, J. (2014) 'Addressing effective construction logistics through the lens of vehicle movements', *Engineering, Construction and Architectural Management*, 21(3), pp. 261–275. doi: 10.1108/ECAM-06-2013-0058.

Zijm, H. and Klumpp, M. (2016) 'Logistics and Supply Chain Management: Developments and Trends', in Zijm, H. et al. (eds) *Logistics and Supply Chain Innovation: Bridging the Gap between Theory and Practice*. Springer International Publishing Switzerland. doi: 10.1007/978-3-319-22288-2 ISSN.

Chapter 10 – Appendices

10.1. Appendix A

BIM Applications and logistical components

This section points out several logistical applications of BIM that have been proposed in primarily the last five years in literature. Table 6 provides an overview of the different aspects of CLM that can be served by BIM-applications including relevant literature which can be used to design a CPLS-layout that serves the objectives of the project. The literature that provides an analysis or a review on a specific application is indicated with an Asterisk (*), each of the other studies propose a framework, method, or a process for serving the corresponding topic.

Table 6. Logistical BIM-application as potential LC

Topic	**Literature**
Site Layout Planning (SLP)in 3D	*(Le, Dao and Chaabane, 2019)* A systematic hybrid approach for SLP in which both qualitative is used based on rule-based modelling and quantitative data in a BIM platform *(Schwabe, Teizer and König, 2019)* Managing SLP through a model-based rule checking by the use of available rule management systems in combination with the Industry Foundation Classes (IFC)
SLP in 4D	*(Bortolini, Shigaki and Formoso, 2015)* An interactive process in outlined in which detailed 4D modelling is used combined with visual management to develop logistic plans. *(Andayesh and Sadeghpour, 2014)** A distinction is made between static, phased, and dynamic SLP in which the aspect of time is considered in the last two. It is argued that the dynamic approach results in the most efficient layouts.
On site inventory management and Material Layout Planning (MLP)	*(Cheng and Kumar, 2015)* Framework for automated MLP and management using the Revit Application Programming Interface in a BIM environment and programme information to define dynamic layout models. *(Lu et al., 2018)* Developing a framework to support decision making in inventory replenishment by modelling the integration of site and supply logistics.
Prefabrication for an efficient logistical organisation using BIM	*(Bataglin et al., 2017)** Using Design-Science Research (DSR) to indicate the application of 4D modelling in which semantic information and equipment is considered to assist in decision making in logistics of Engineer to Order (ETO) processes of prefabricated concrete structures. *(Bortolini, Formoso and Viana, 2019)* Using 4D BIM to develop a logistics planning and control model in making use of the synergy between BIM and Lean for site assembly of ETO prefabricated elements *(Li et al., 2017)* Using a Smart Construction Objects (SCO) and RFID-enabled BIM platform to deal with critical schedule factors in manufacturing, logistics and site assembly based on real time information in Prefabricated House Construction (PHC)
Logistics based on (smart) object-based BIM information	*(Niu et al., 2016)* A Smart Construction Object (SCO)-enabled LSCM system is developed with the intention to improve logistical processes and the logistical information flow for better decision making

	(Li et al., 2018) BIM is used together with IOT to develop a platform for prefabricated housing projects. The platform supports in real time decision making for various stakeholders to improve efficiency and effectiveness of daily operations regarding on site assembly of prefabricated elements
BIM – GIS integration to support supply logistics	*(Wang et al., 2017)* A framework based on BIM-GIS integration in a Resilient Construction Supply Chain (RCSC), tailored to an effective integration of SCM by enabling transparent information flows, supply chain status visualisation, and supporting supplier selection. *(Deng et al., 2019)* An integrated framework is developed using 4D BIM and GIS integration to coordinate the CSC from the construction site to other locations that relate to the project such as suppliers, including support for supplier selection, determine the number of material deliveries and the allocation of consolidation centres
Sustainable logistics based on BIM information	*(Ahmadian F.F. et al., 2017)* A framework is developed based on information from customised BIM models to describe the decision hierarchy of material supply processes and assists in decision making of the trade-offs between economic and environmental impact. *(Chen and Nguyen, 2018)* A BIM-integrated plug-in is developed based on BIM and Web Map Service (WMS) to support decision making in selecting sustainable construction material sources. A trade of is made between costs, delivery time and location related credits applied in green building standards
Supply chain track and trace based on BIM	*(Irizarry, Karan and Jalaei, 2013)* A BIM-GIS integrated system is developed allowing to monitor the supply chain status and warns to ensure material deliveries *(Spengler et al., 2017)** The current developments and track and trace methods are discussed including enabling conditions. The current digital environment in the industry is yet not sufficient enough to support track and trace.
Sequence analysing using 4D BIM	*(Wang et al., 2014)* 4D BIM is used to perform quantity take-offs in order to support simulations of construction operations on construction sites which leads to a project schedule. It enables to consider competing needs for resources and evaluates allocation strategies in an interface system. *(Tulke, 2018) ** The opportunities, benefits, and conditions of three concepts of clash detection, process animation in 4D and the checking of models are discussed which can be beneficial for logistics management. (Pérez, Fernandes and Costa, 2016) * A literature review that indicated a number of studies on 4D BIM to support logistical processes and minimise waste streams in construction processes.
Progress monitoring in BIM through laser scanning	*(Sharif et al., 2017)* Point cloud models are used, and an algorithm is written enabling to automatically detect objects in point clouds. The method enables automated process control in a quick and robust way. *(Chai et al., 2016)* They propose an automated data process which uses laser scans to identify objects in BIM models. Algorithms are used to define objects from laser scans. These objects can be recognised in BIM models to create as build models with semantic information.

Progress monitoring in BIM through photo images	*(Asadi et al., 2019)* A method is proposed for automated detection of video sequences and images frames in which the perspective of objects in images is aligned to 3D views in BIM to track the progress. *(Braun et al., 2018)* A progress tracking approach is proposed in which photogrammetric surveys are used to develop point clouds which are subsequently aligned to 4D BIM. *(Irizarry and Costa, 2016)** Reveals the potential of using Unmanned Aerial Systems (AUSs) based images and videos for progress monitoring and site logistics.
Progress monitoring through cloud-based BIM	*(Matthews et al., 2015)* The cloud-based BIM 360 Field software is used to capture real time site information to support progress monitoring by the use of action research in which paper-based processes are reengineered. *(Getuli et al., 2016)* An Interactive Building Model (IBModel) is developed to capture site information for monitoring purposes and visualisation of the conditions on construction sites.

10.2. Appendix B

Developments in literature to improve construction logistics

This appendix points out attempts to improve construction logistics that have been proposed over the last decades. Starting with Logistical Management Techniques (LMT) aiming to improve logistics from a management point of view by incorporating principles from other industries. These techniques have been applied in several logistical concepts, in which the organisation of logistical processes changed to improve logistics.

10.2.1. Logistical Management Techniques

Academia and the construction industry have tried to optimise construction logistics by proposing numerous Logistics Management Techniques (LMT). These techniques aimed to improve logistics from an management perspective by applying tools, often based on lean principles, focussed on removing unnecessary handlings, waiting times, and other "mudas" (waste in the process) (Womack, Jones and Roos, 1990).

Examples are Just in Time (JIT), which aims to deliver materials as close to the time of actual production as possible (Womack, Jones and Roos, 1990). This avoids extra handlings of materials, extra storage and the chance of damaging materials on construction sites (Altintas, 2013; Dakhli and Lafhaj, 2018).

Demand smoothing is another management technique which focusses on both a steady material demand to avoid peaks in deliveries, but also on stable equipment and resource demands (Methanivesana, 2012; Waddell, 2015; Whitlock *et al.*, 2018).

The use of a Delivery Management System (DMS) is also indicated in literature, which often requires a software to that allows to block timeslots in an agenda. This can be the agenda of every logistical element that is assumed relevant to be manage such as equipment, gates, loading bays or exclusion zones. Such a system often allows to add information to the time-slots, such as specifications of the materials, the recipients, location of processing and provide insight in the planned and actual deliveries on construction sites (Waddell, 2015; Whitlock *et al.*, 2018).

Transport for London (2013) developed a guidance for sustainable construction in London which included the use of Construction Logistics Plans (CLP) as a tool for managers. A CLP provides a framework to manage vehicle movements from and to construction sites which will improve reliability and safety aspects (Browne, 2015). Guidelines for writing CLM plans are Croydon Council (2015) and CLOCS (2018).

These LMTs are used as a key tools for logistical managers to coordinate both supply and site logistics (Whitlock *et al.*, 2018). They are frequently adopted in the industry, but they facilitate only small areas of all the aspects that are included with CLM. The industry and academia have therefore proposed several logistical concepts that focussed on changing the organisation and process in CLM. These were designed especially at the end of the first decade when the interest in construction logistics started to grow, and will be discussed in the next sub-section

10.2.2. Logistical concepts

The logistical concepts discussed in this appendix aim to improve the organisation of CLM and can often be facilitated by several LMTs. One of these logistical concepts is the use of Construction Consolidation Centres (CCC) just outside of busy city-centres to reduce vehicle movements in cities. Browne (2015, p.21), describes CCCs as " *a distribution facility through which material deliveries are channelled to construction sites. Specialist material handling, storage and consolidated delivery combine to improve the overall resource efficiency of a construction project*". Sullivan, Barthorpe and Robbins (2010) introduced the concept extensively, and Vries and Ludema (2012), Altintas (2013), and Lundesjö (2015a) critically discuss the usefulness and applicability of CCCs. Besides, Janné (2018) elaborated on the changing organisation and required governance approach for applying a CCC.

Furthermore, Karabulut, Van der Voort and Van Doorn (2013) described the concept of Smart Building Logistics (SBL), which is developed by the company of BAM together with UTS (a removal firm). SBL makes use of a CCC that consolidates full truck loads and delivers to site after working hours. Carrying crews bring these materials to their production location, saving time for workers, and bring back waste to the CCC. Altintas (2013) however, indicated that this method is manly applicable in the completion phase of a project.

Altintas (2013) also highlighted the concept of a centralised point of logistical coordination. Zijm and Klumpp (2016) explained the aspects of a control tower to coordinate logistics in a centralised manner for multiple projects, and Merriënboer and Ludema (2016) elaborated on Cross Chain Control Centres (4C) by analysing multiple case-studies.

Another recurring concept is through simplifying logistical processes by using prefabricated construction methods (Engineer to Order). This is a third aspect that is proposed by Koskela (1999) besides *Production Control* and *Production System Improvement*, which are both integrated in the CPLS-framework. She describes this aspect as *System Design* to reduce variability in the process. The use of pre-fabricated construction elements is frequently mentioned in other literature as well to organise logistics more effectively by reducing transport movements and waste on site (Methanivesana, 2012; Waddell, 2015; Whitlock *et al.*, 2018). This because construction activities are shifted to manufacturers which reduces the number of transports with low value densities which are costly (Browne, 2015).

10.3. Appendix C

Next generation BIM 360

The next generation of Autodesk BIM 360 is something that the general contractor is implementing internally. Using BIM 360 Documentation Management and Field Management with the intention to move fully onto next generation BIM 360 as the project develops. Figure 25 shows the layout of the new generation of BIM 360 consisting of three levels, Forge, Project data, and Analysis and Insight.

Figure 25. BIM 360

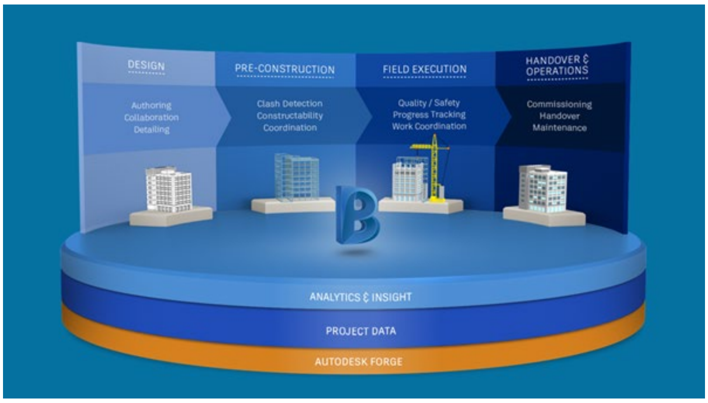

Figure 22. New generation of BIM 360

Currently, integrated/full BIM is being adopted in the AEC industry by combining multiple management tools in an open source environment. However, the software tools that are used have often to deal with incompatibility between one another as they are app-based and never fully designed because Autodesk bought these apps from other companies.

The new generation of BIM 360 is the industry new leading platform that allows any software package to plug in to an online database called Forge[3]. This is a cloud-based API developer platform that allows third party developers to integrate construction applications such as planning tools, design software, analysing software, to be integrated in a single source.

This can best be explained by taking the Apple app store as an example. Apple provides the database to which everyone can plug on to by writing applications that are able to interact with the database. Forge provides a similar platform allowing software providers with a wide range of applications and functionalities to plug in. All the project information coming in through Forge is therefore available in a single database in which all information is centralised.

Besides, the analytics layer allows to use this data by using algorithms and artificial intelligence (AI), allowing to run automated clash detections. But also, to automatically assign issues to the right persons, based on their work packages, which could be logistics. This allows to get people an overview of only those things necessary for their work package without being overwhelmed by information of which half is not relevant for this person. However, respondents argued that a full use of AI is still a couple of years ahead, but that the use of Forge and the centralised database is something that will benefit soon.

[3] https://www.autodesk.com/autodesk-university/class/Demystifying-BIM-360-and-Forge-APIs-2017#video

10.4. Appendix D

Literature table

The theoretical framework is described in Chapter 2 of the study and addresses several topics on which the frameworks are based. These are provided in the following table including the literature relate to these topics and the search terms used to find this literature. Academic search engines such as Google Scholar, Web of Science, Scopus, and the Library of the University of Twente LISA were used to find the relevant literature.

Table 7. Search terms for literature

Topic in theoretical framework	***Search terms***	***Literature***
Definition of CLM	“construction AND logistics” or “construction AND logistics AND process”, “construction AND logistics AND management” or “CLM” or “logistics AND CSCM”	(Silva and Cardoso, 1999; Browne, 2015; Lange and Schilling, 2015; Sloot *et al.*, 2017; Sloot, 2018; Sundquist, Gadde and Hulthén, 2018)
Governance strategies and decision-making levels on construction projects	“project AND governance” or “data AND governance AND construction AND logistics” or “management AND levels AND construction AND logistics” or “management AND levels AND logistics” or “project AND decision AND making” or “construction AND management” or “construction AND management AND hierarchies”	(Schmidt and Wilhelm, 2000; Ploos Van Amstel, 2002; Riopel, Langevin and Campbell, 2005; Klakegg, 2009; Boissinot and Paché, 2011; SteadieSeifi, 2011; Trindade *et al.*, 2016; Borrmann *et al.*, 2018)
Production control using LPS	“Last AND Planner AND Systems AND Construction” or “Last AND Planner AND Construction” or “Last AND Planner AND Construction AND Logistics” or “Production AND Control AND Construction”	(Melles and Wamelink, 1993; Ballard and Howell, 1998; Koskela, 1999; Ballard, 2000; Mossman, 2007, 2012)
PDSA cycle for production process improvement	“Last AND Planner AND Systems AND Construction” or “Deming AND PDSA” or “Last AND Planner AND PDSA”	(Deming, 1950; Ballard, 2000; Moen and Norman, 2006; Feliz *et al.*, 2014)
BIM implementation and corporation in construction through People, Process, Technology, and contracts	“Implementing AND Technology and Construction” or “BIM AND Adoption” or “BIM AND Adoption AND Construction” or “BIM AND collaboration” or “People AND Process AND technology AND BIM” or “Contractual AND Risks AND BIM” or “BIM AND Implementation AND Contract”	(Sommerville and Craig, 2006; Thomson and Miner, 2006; Shelbourn *et al.*, 2007; Underwood and Isikdag, 2009; Gu and London, 2010; Arayici *et al.*, 2011; Goulding and Arif, 2013; Abubakar *et al.*, 2014; Enegbuma, Aliagha and Ali, 2015; Hooper and Widén, 2015; Liu, van Nederveen and Hertogh, 2017).

Table 7. Search terms for literature regarding the theoretical framework

10.5. Appendix E

Table of respondents

Table 8. Respondents from field research

Resp. #	Department	Job Description	Data source
1.	Engineering	ENG\TECH-Project Manager (Construction manager)	Semi-structured interview & field notes
2.	Engineering	ENG/TECH-Project Manager	Semi-structured interview & field notes
3.	Engineering	ENG/TECH-Senior Site Engineer (Project manager)	Semi-structured interview & field notes
4.	Engineering	ENG/TECH-Graduate Engineer	Field notes
5.	Engineering	ENG/TECH-Graduate Engineer	Field notes
6.	BIM	Digital construction manager	Semi-structured interview & field notes
7.	BIM	Digital construction specialist	Semi-structured interview & field notes
8.	BIM	Digital construction specialist	Semi-structured interview & field notes
9.	BIM	Digital construction specialist	Semi-structured interview & field notes
10.	BIM	BIM Technician	Field notes
11.	Project Controls	ENG/TECH-Planner	Field notes
12.	Project Controls	Project Control's Manager	Semi-structured interview & field notes
13.	Project Controls	4D manager	Field notes
14.	Project Controls	Planner	Field notes
15.	Logistics	Project manager	Field notes
16.	Logistics	ENG/TECH-Site Engineer	Field notes
17.	Higher Management	Construction Director	Semi-structured interview & field notes
18.	Higher Management	DC Technical Deployment Specialist	Semi-structured interview & field notes
19.	Higher Management	Digital Construction Operations Manager	Field notes
20.	Subcontractor (Mechanical)	BIM Co-Ordinator	Semi-structured interview
21	Software provider	Founder of Aphex planner	Software demonstration including Q&A

Table 8. Respondents from field research, their roles, and their input for the research

10.6. Appendix F

Project site layout

Figure 26. Site layout

~~ Confidential ~~

Figure 23. Site layout of the project, date 01-2020

10.7. Appendix G

DMS interfaces

Figure 27. DMS submission format

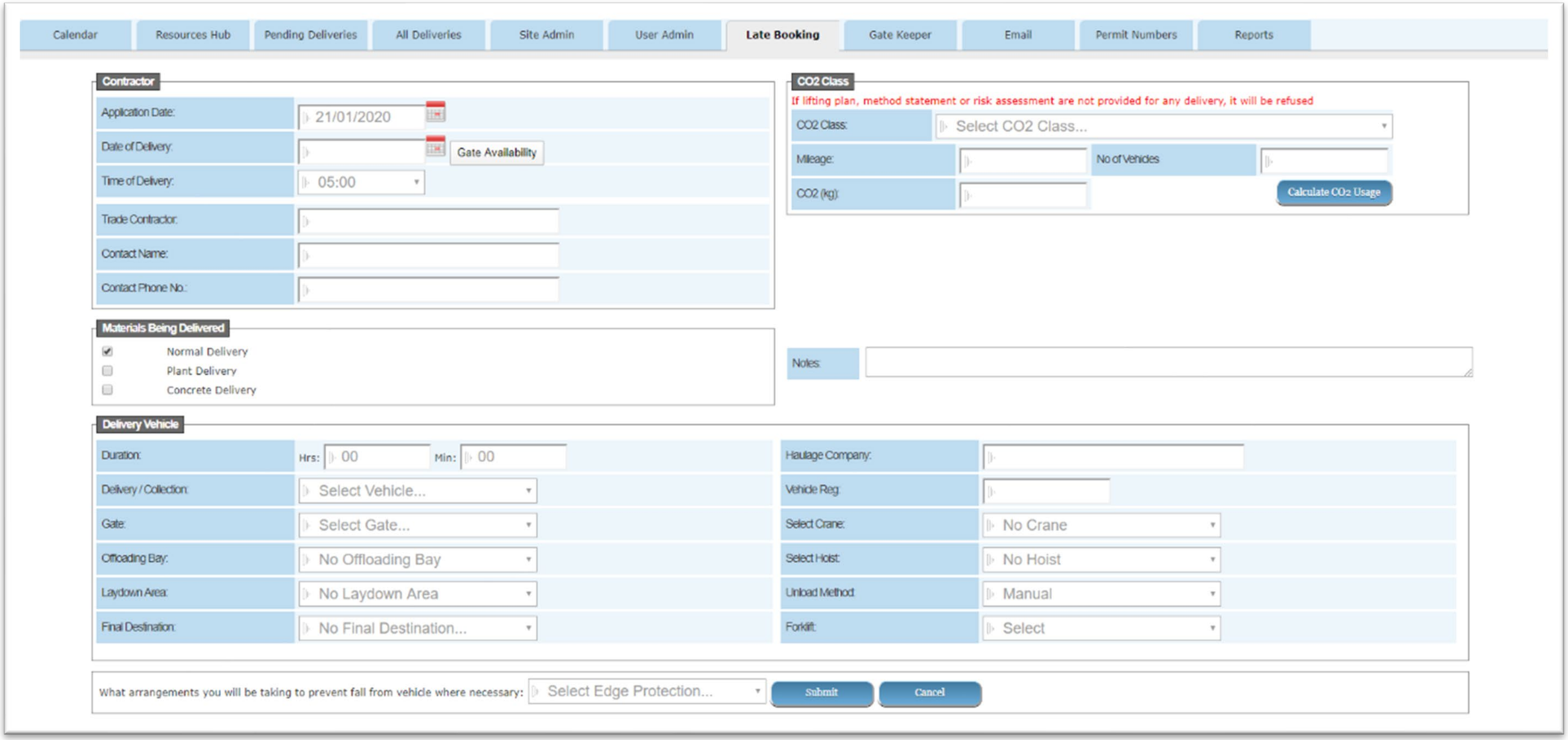

Figure 24. Submission format of the DMS system

Figure 28 DMS overview

~~ Confidential ~~

Figure 25. Overview of delivery requests in the DMS

10.8. Appendix H

Slab mountain in excel

A Slab Mountain, see Figure 29, can be developed to provide insight in the resources that are required, on a weekly base, to meet the programme. The quantities can be subtracted from the 3D BIM model and Synchro provides the opportunity to extract such a graph from the programme. Yet, this slap mountain is made in Excel.

Figure 29 Slab mountain

~~ Confidential ~~

Figure 26. Slab mountain in Excel indicating the slaps to be poured over time

10.9. Appendix I

Causes of non-conformation of tasks

Table 9. Table of non-conformances of tasks

No	Constraints	Example
1	Equipment / Plant Failure	Plant broken down
2	Prior commitment missed	Knock on delay from previous activity
3	Misunderstanding	Poor communication
4	Working on other areas	Other tasks were prioritised over this task
5	Ambitious planning	Plan was not achievable regardless of resource
6	Interface with other Sub-C	Area not free to work in or too congested
7	Resource not available	Resource shortages
8	Internal Sign off	Sign off still required from Contractor
9	Permits / External Sign off	Sign off still required from Case / Council / 3rd Party
10	Weather	Weather not allowing work to complete
11	Forgot	Human Error
12	Poor Performance	Low Productivity
13	Scope Change	Change of working scope
14	Material	Material not available
15	Design	Design not available
16	Access	Access not permitted

Table 9. Table of non-conformances for the case, based on LPS

Figure 30. LPS scorecard

Weekly Summary		April 2019 RC Concrete Scorecard							
Week	Summary		Week 1		Week 2		Week 3		Week 4
Meeting Date			18-apr		25-apr		2-mei		9-mei
	Planned	Completed	Planned	Completed	Planned	Completed	Planned	Completed	Planned	Completed
Activities										
PPC %										
Missed Commitments										
Constraints Matrix			1 5 9 13 2 6 10 14 3 7 11 15 4 8 12 16		1 5 9 13 2 6 10 14 3 7 11 15 4 8 12 16		1 5 9 13 2 6 10 14 3 7 11 15 4 8 12 16		1 5 9 13 2 6 10 14 3 7 11 15 4 8 12 16	
Critical Activities										

Figure 27. LPS scorecard on case

10.10. Appendix J

CPLS-layout of the case-project

This section describes the logistical components in the CPLS-layout on the case. Figure 31 indicates the LC including their relation to one another. The components are labelled from A to H and are discussed according to these references. Several essential principles and tools are printed in italics in the description of the LC discussed in this section, which indicates that a brief theoretical explanation and relevant literature on those topics is provided in Figure 31.

Figure 31. CPLS-layout

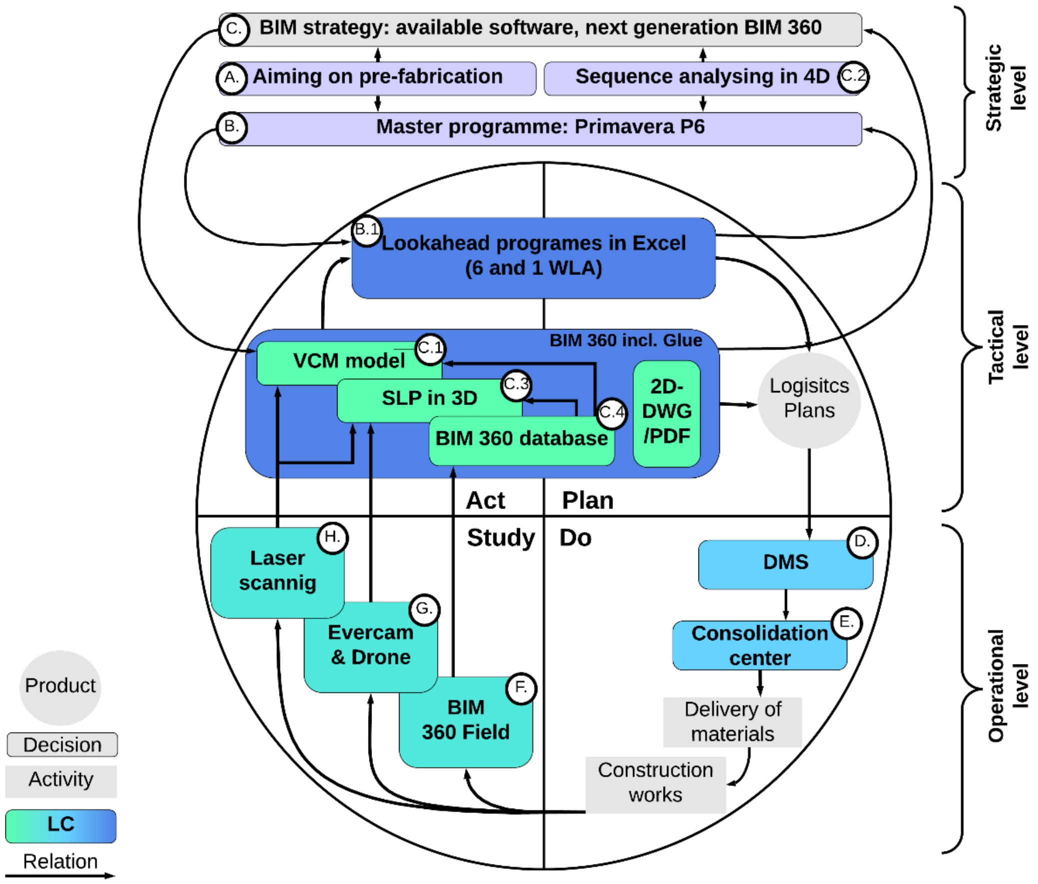

Figure 28. CPLS-layout on the case-project

A – Aiming on pre-fabrication - (Strategic)

It is decided to use prefabricated elements, ***ETO processes***, as much possible to allow quick assembly on-site and therefore speed up the construction process. The design has been changed to allow pre-fabrication for the structural elements in which in-situ[4] columns and walls have been replaced by twin-walls and prefabricated columns and walls. This was required to reduce the number of activities on-site, the number of transport movements and waste streams, since there was a lack of space on site as the boundaries of the structure are basically the boundaries of the site.

Also, the main M&E sub-contractor has defined Assembly to Order (ATO) and ETO prefabricated modules to allow a quick assembly on site. The maximum benefit is said to be established by designing modules that approach the maximum physical properties allowed for freight transport as this reduces the number of truck movements and increases the value density on trucks.

[4] Build on the project site by the use of formwork, rebar, and concrete.

BIM is used to support this process by using the physical information available in the models. Elements can easily be checked on size and dimensions. Besides, safety zones are designed and modelled in BIM to protect the prefabricated elements during transport and when stored on site.

B – Master programme - (Strategic)

As described, logistics is driven by the main construction program. This main program basically represents the project in terms of work packages and batch sizes and their related starting and finishing dates in a certain logic. These work packages and batch sizes are designed to divide tasks in more or less equal time and resource units, called ***demand smoothing***. This enables the process to be run through in the stable pace with a fairly constant number of resources required over time. Work packages and batches are based on zones, which are designed by dividing slabs in pouring areas and rising elements, such as walls and columns, placed on top of these pouring areas. The main program is designed in Primavera P6 software and has the contractual obligation to be designed at a LOD in which activities in general take no longer than 10 to 15 days. As a reference, this means, that is indicated in the programme that a pouring zones are being constructed, but it does not describe the activities that are required for the completion of these pours.

B.1 – Lookahead programmes in Excel - (Tactical)

However, a respondent from the project controls department argued that "people do not like to give bad news". Meaning that in general people will say they are on schedule throughout the duration of a task until the finish date, when it is found out that they have behind schedule along the way. This results in a direct change of the project end date as there is no insight of the actual status within this 10 to 15-day task. Tasks are therefore broken up in smaller activities (in a higher LOD) in order to obtain more control and protect the project deadline with a greater certainty.

The P6 software, however, is not user friendly for increasing the LOD for a project this size (usually every project over +/- 200-300 million depending on the number of tasks). Therefore, other software is often used to create more detailed programs. Excel is chosen on the case-project as it is cheap, fast and flexible. A six week lookahead is developed in excel to plan the structure, envelope and fitout in more detail, which is ultimately finetuned to a weekly lookahead schedule, guided by Last Planner Systems (LPS) methodology. The same zones are used in the more detailed programme in excel to allow the traceability of materials and tasks.

C - BIM strategy - (Strategic)

BIM is applied based on the contractual obligations and the BIM vision of the General Contractor (GC). It is decided by the GC to gradually move *to* the ***next generation of BIM 360,*** see Appendix C This next generation BIM 360 platform is something that the GC has implemented internally, using BIM 360 Documentation Management, BIM 360 Glue, and Field Management (which is discussed later) with the intention to move fully onto next generation BIM 360 as the project develops. Revit is used to deliver a Facility Management (FM) model and to prepare supportive drawings and models.

C.1 – A Virtual Construction Model (VCM) - (Tactical)

Within this context, BIM is used to support the construction programmes by dividing concrete slabs in pouring zones in a so-called Virtual Construction Model (VCM). Every slab is cut in pouring zones and labelled with a code, which can be traced back in both the Revit model, BIM 360 and in all the construction lookahead programmes. The code for structural elements is built up as followed:

ZONE "Section" – "Level" – "Number" – "Sub code".

Section describes:

- N (North zone)
- S (South zone)
- C (Central)

Level

- LB3 / LB2 / LB1 (Basement -3 / -2 / -1)
- LG (Lower Ground)
- L00 – L07 (level 00 till 07)

Number

- 1 – 122 (sometimes included with a small letter)

Sub code (mostly used if pouring zones have changed during the process)

- A, B, C, D, E, F… sometimes included with a number (A.1 for example)

This coding system is used for the structural frame; however, the same principle is done for coding all the rooms, and for coding façade zones for example. These are given a unique code enabling to link materials, elements or checklists to. The Revit file that includes the pouring zones and the codes is pushed to the open source Autodesk BIM 360 Glue which is accessible for every partner in the supply chain that is given permission to visualise.

C.2 - Sequence analysing in 4D – (Strategic)

The zones and codes defined in Revit are linked to the main program in Primavera P6 using Navisworks software to provide a clear visualisation of the progress per week. This 4D BIM model was initially developed to present a 4D schedule of the complete construction process as was demanded by the client in the procurement phase. During construction, Synchro software was used instead of Navisworks, as it was more user friendly.

This 4D model is not directly part of the logical information flow but it provides a visual understanding of the main building process on a strategic level. However, it can be used to forecast a material demand over time. This allows to apply ***demand smoothing*** for materials in trying to avoid peaks in material deliveries that may exceed the capacity of loading bays, tower cranes and other logistical equipment on site (the SLP).

C.3 – Site Layout Planning (SLP) in 3D – (Tactical)

Another logistics related BIM application that is used on the case aims on site-logistical aspects. Site logistics is an important aspect in CLM since materials that are being delivered at the gates need to be distributed to their processing location or a storage location on site, which requires Site Layout Planning (SLP).

Again, BIM can provide the semantic and geometric information to support SLP. A 3D-SLP model is developed which includes numerous aspects required to distribute materials on the site itself, see Figure 32.

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Figure 29. Logistics 3D-SLP model in BIM including No-Go-Zones (NGZ)

This model is part of the contractual agreement with the client on this case-project. However, such models are also frequently used on projects where it is not obliged since it is argued by several respondents that it provides essential information for logistics and safety. The model provides an accurate visualisation of the construction site and the position of tower cranes is even verified using laser scanning to define the exact position and hight. A clash detection can be used to see what elements interfere after which it can be checked how this relates to the programme to define optimum layouts with minimised interference.

Besides, the physical interference of logistical assets mutual can be analysed by the model to for example check if fixed tower cranes interfere with temporary mobile cranes or concrete pumps by modelling No-Go-Zones (NGZ), Figure 32. But also, to check if a jib of a tower crane can be extended without reaching above houses or hitting other fixed cranes on the site.

The assets in the model can be planned and designed for the whole construction process and can include installing and dismantling dates. Meaning that it can be thought through and planned, that a specific type of hoist will be positioned on a certain location to provide for the supply of materials to a certain processing area for a certain period.

In addition, the model can provide an overview about the main walking routes on site, the location and naming of gates, and the position of loading bays, canti-decks, scaffolding, hacky stairs, and skips. This allows to determine the size of temporary storage locations and access point to get materials in the structural frame, but also to plan escape routes and other safety issues.

Besides, this model can be used in the design process for subcontractors as it sets design requirements or limitations for specific elements. That is, the functional limitations of logistical equipment determine the physical restrictions of materials or elements, for instance, the lifting capacity determines the maximum weight of prefabricated elements.

C.4 - BIM 360 database (Field) - to check logistical equipment – (Tactical)

An important aspect closely related to the SLP model, is to make sure that all logistical site equipment and scaffolding (assets) is available, safe, and ready to use. No matter how well logistics plans are prepared, it cannot be executed without it being checked if the assets are safe to use, as the SLP can change from one minute to the next if an unsafe crane for instance cannot be used.

Several checklists must be performed to ensure the quality of these temporary assets which includes daily, weekly, monthly, and yearly checks. This can be a labour-intensive exercise which requires lots of paperwork. To illustrate, during the time of this field research, there was a list of around 180-scaffolds including 86 that were still active of which each required two weekly checklists, meaning 172 checklists to fil out on a weekly basis just on scaffolding. Furthermore, there were 9 fixed tower cranes and on average 5 temporary cranes on site which all required daily and weekly checks summing up to about 85 checklists a week. Not even mentioning the additional checklists that are required for instance during assembly and dismantling.

BIM 360 Field can be set up to digitalise this process and ensure that all required assets for logistical operations are safe and useable, which was already done at other projects of the GC. All the assets can be coded and listed as a piece of equipment in BIM 360 Field. Field allows to add digital instead of paper-based checklist to each piece of equipment. QR codes can be created, representing the equipment code which can be added to scaffolding tags and cranes. This allows to scan the QR code with a mobile device, fill up the checklist on site and directly push the information through on the BIM 360 database. Saving a lot of paperwork and at the same time centralising the information as everybody can see the maintenance history and if something needs to be done to ensure the quality and safety of the assets, increasing the reliability of the SLP.

D - Delivery Management System (DMS) – (Operational)

Materials that need to be delivered can be requested in an open source ***Delivery Management System*** (DMS). This system allows stakeholders to block timeslots in the calendar of gates, hoists, and tower cranes for instance, and can be managed by a logistical coordinator. A delivery request is created by the system which allows to include specifications about the delivery such as the date, subcontractor, contact information, time slot, the gate, loading bay, storage location, laydown area, final destination of materials, and the equipment that is needed. The DMS even allows to indicate the CO_2 emissions of deliveries. Besides, it allows traceability of materials as the processing zone and codes as used in the program can be added. See Appendix G, a ticket application form, and the interface where incoming tickets and an equipment planning is presented. A logistical coordinator can either accept or deny these requests after which a time slot is created in the requested calendar once approved.

E - Consolidation Centre - (Operational)

A delivery ticket is provided once a request is approved by the logistical coordinator. In following, every delivery truck is demanded to pass a ***consolidation centre*** **(HUB)**, with this ticket to pick up a delivery card and additional materials if required. The HUB is about 2.5 kilometres away from the project site and situated between the highway exit and the construction site. The ticket system forces trucks to pass the HUB, allowing to avoid traffic jams on site because trucks can wait at the HUB until the requested gate is available in case of delays. The delivery cards that are taken by the truck drivers are collected at the requested gates once the truck arrives on site. Access is denied without a delivery card to ensure every truck passes the HUB. The materials that are being unloaded are planned to be processed right away as emphasis is put on ***Just in Time (JIT)*** deliveries. Subcontractors are therefore forced to use the DMS system to allow a smooth delivery process and to exclude unplanned deliveries on the construction site.

F - BIM 360 Field – (Operational)

If a logistics plan is executed, it is important to check the conformance to the logistical plans and the programme once the materials are processed on site, which is set up in BIM 360 Field. BIM 360 Field is a mobile application that allows to control and monitor the actual construction on site including QA/QC. Field allows site engineers to perform quality checks on site by using an iPad or another Apple based mobile device and can support in progress monitoring. Site engineers can change the status of an element or object (called a piece of equipment) and can also mark up any deviations in the shape of planned pouring zones for example. This information can be pushed back to the VCM in Revit through BIM 360.

The VCM can be set up to visualise the actual progress by filtering on the status of elements and assigning the colour green to the element with the status “completed/installed”, showing in green that what has been build, see Figure 33. Besides, the VCM can be adjusted for deviations if for example only half of the pouring zone is poured. This allows all stakeholders to visually check whether slabs are poured as planned or if the progress deviates from the planned programme, allowing to update the programme and accordingly the logistics plans.

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Figure 30. Frame VCM model level L00

G - Evercam & drone (images) - (Operational)

Site images can also be used to keep track of the process and in discussions to make plans, as images or photos provide a direct overview of the actual situation. Drone photos can be made of the site and the layout of the consolidation centre. Besides, Evercam allows to install live cameras around the site and attached to tower cranes. These photos and live streams can be used to, for example, determine what materials are present at the HUB but also to see what is happening on site, where materials can be stored and when deliveries arrive.

H - Laser scanning (to BIM) – (Operational)

Laser Scanning to BIM was introduced primarily to capture what has been built for creating a Facility Management (FM) model. However, it can be applied for logistical purposes as well to keep track of the excavation process on the construction site for example. The surface of the dirt was scanned every month during excavation and subtracted from the surface from the month before to calculate the difference in volume, which represents the excavated dirt. The total quantity of dirt removed could be divided by the capacity of a truck to estimate the number of truck movements. This information could be used to check the bills from the excavation subcontractor and to forecast the required traffic movements for the next month. Laser scanning was also used to determine the exact locations of tower cranes as they interfere with structure. The exact location was therefore required as temporary structures might be required, or additional safety aspects.

10.11. Appendix K

Detailed gap Analysis

This appendix provides the gab analysis of this study on which Table 4 is based. All four categories are discussed in which the barriers are elaborated based on the empirical findings. Therefore, this analysis provides the foundation of the results of this study.

People

Category	**Condition**	**#**	**Barriers**	**Strategic**	**Tactical**		**Operational**	
					P	A	D	S
1. People	1.1. Attitude and behaviour	1.1.1	Stubborn attitude - *Experienced employees not willing to learn or work with new technologies*	X	X		X	X
		1.1.2	Production-oriented mindset - *anything else is second priority*		X		X	X
	1.2. Knowledge requirements	1.2.1	Lack of senior support – *makes it difficult to justify costs to improve processes*	X				
		1.2.2	Unaware of the benefits - *or potential of digital applications to simplify processes*		X		X	X
		1.2.3	Limited BIM skillset		X			

Table 10. Barriers in the people condition

Condition #1.1 Attitude and behaviour

The first barrier indicated was a ***stubborn attitude*** by employees towards the use of new technologies. Especially elderly, more experienced, and practical oriented employees are often not willing to obtain more knowledge about the opportunities of new technologies or learning to use them to make logistical plans in the Plan phase for instance. Some foreman on an operational level in the Do and Study phase find use of the DMS and BIM 360 Field to be a waste of time. They state that in construction, things will never go according to plan. Besides, higher management on a strategic level, can have a hard time to see the benefits of new technologies and would rather stick with software they are familiar with, the use of Excel for the lookahead programmes was given as an example. Even though other software was more suitable. Nevertheless, it was also found that some did acknowledge the benefits of digital technologies, but would rather ask someone to do it for them instead of getting familiar with the software themselves. The latter was especially indicated on a tactical level were BIM support was requested by the logistics department to make logistics plans with insight from the 3D-SLP. Engineers or managers came down to the BIM team on almost a daily basis to view something in the model, to request adjustments or to request a drawing.

Another barrier is the fact that employees are aimed at making production and do not consider using digital technologies as a first-priority task. The ***production-oriented mindset*** has priority over feeding site information back into the system by using BIM 360 Field in the Study phase or using the DMS in the DO phase. Often because "*there is no time to do so*". This is one of the main reasons why, on an operational level, status updates are often not done in Field and subcontractors place delivery requests in a WhatsApp-group or through a phone call. Besides, on a tactical level in the plan phase, "*managers can't sit on top of it [make sure site information is pushed back through Field] as they have so many other things to do*" leaving an ineffective process.

Condition #1.2 Knowledge requirements

In general, there is a lack of BIM knowledge and BIM skills on all three levels of decision making. Several respondents indicated a ***lack of senior support*** at a strategic level to adopt new technologies or make full use of technologies that are present. Many have argued that there is much more potential to run a more efficient process by making full use of the available software, but that it requires additional manhours. Also, additional technologies were suggested which require investment costs that are often significant but argued to be worth it. Respondents mentioned that they are not able to justify such costs to their higher management as there are no direct quantifiable financial benefits aligned to the investment or a significant productivity improvement that can been demonstrated.

Nevertheless, one respondent pointed out the use of quantitative risk analysis to justify costs based on the expected reduction of the chance and the impact of project risks, which does not require to quantify the benefits. An example was given from another project in which this method worked well for justifying investment costs of Artificial Intelligence (AI), however the same respondent indicated that the risk analysis of the case-project was not extensive enough to apply this method.

Besides, it is found that employees at a tactical in the Plan phase and operational level in the DO and Study phase are often ***unaware of the benefits*** or potential of digital applications to simplify their processes. An example is the late introduction of using BIM 360 Field to perform checklists for cranes and scaffolding. Even though this was already done on other projects and it was proposed by the BIM team to adopt, it was initially decided to stick with the old, paper based, system. However, decisions changed after months into the project after which Field was set-up for this process. This was done within a week since the appropriate settings in Field could be used from other projects. Yet, all the paper-based checklist that were performed already (around 1500) were required to be digitalised to have everything in the same system. Taking hours of double work which could have been avoided if safety managers were aware of the potential of Field. Nevertheless, the potential of BIM 360 Field was noticed as the crane coordinator asked, within a week of the implementation, if the same was possible for crane checklists, which was set up accordingly.

Furthermore, employees have a very ***limited BIM skillset*** outside of the BIM department on especially a tactical level in the Plan phase. This was indicated by almost all respondents. The BIM department is seen as a niche within the project organisation, as there is a major lack of BIM knowledge throughout the different departments. One of the engineers stated "*let's say the engineers that I'm working with at the moment, maybe only 35% could open up a model and have a look, the rest could maybe open it and have a look around, but have no idea how to check, how to measure, make a 2D out of it or run a clash control*". The lack of BIM knowledge makes departments and individuals within the organisation dependant on the BIM department. However, the BIM department is very limited in size, only four people. They cannot support all departments with minor issues, such as plotting a drawing, updating the 3D-SLP or check limitations of equipment in the SLP-model, which was asked almost on a daily basis. If employees do not have the skills and the BIM department cannot support, employees tend to search for alternative ways to find information or communicate without using BIM, often in 2D.

Walking routes are for instance indicated on PDF files instead of the 3D-SLP model since the person updating these drawings did not have the skills to use BIM for it. Many respondents indicated the lack of BIM skills as a major barrier. Therefore, roles have changed and BIM should not be a niche within the project organisation and employees in general should have a higher understanding and a basic skillset of BIM. One of the senior engineers stated: "*Junior engineers should be able to extract quantities from BIM and even perform clash detections between temporary works and the structure"*. Yet at the moment, some have never even opened the model. Specific BIM training based on job descriptions is therefore key, especially since "*BIM is now coming to a point where it is mandatory for every contract*".

Process

Category	**Condition**	**#**	**Barriers**	**Strategic**	**Tactical**		**Operational**	
					P	A	D	S
2. Process	2.1. Communication & Trust	2.1.1	Lack of labour power		X			
		2.1.2	Unaware of their responsibilities - *lack of trust in co-workers, double works due to extra checks*				X	X
		2.1.3	The LOD in models – *the LOD should fit the needs*		X			
		2.1.4	Inefficient use and setup of the SLP		X			
	2.2. Process and Procedures	2.2.1	A system way of thinking - *is not adopted*		X		X	X
		2.2.2	Lack of procedures		X		X	X
		2.2.3	Lack of data collection - *to improve logistics*					X
		2.2.4	Protocols and Standards	X				

Table 11. Barriers in the process condition

Condition #2.1 Communication & Trust

It is found that the VCM and 3D-SLP on a tactical level and Field on an operational level are poorly used in the operational process within the CPLS-layout. It is already discussed under "people" that engineers state that there is no time to update element statuses, because of their production-oriented mindset. This lack of time was indicated by many respondents as one of the reasons for inefficiencies in the logistical process that was studied which is caused by two factors.

First, a ***lack of labour power*** is forcing employees to perform tasks outside of their own job responsibilities, especially on a tactical level in the Plan phase. For example, a senior engineer is preparing claims while it was not his job, yet there is no one else to do it. While this same respondent claimed that he would like to plan logistics more effectively, but that he does not have the time.

However, as a second reason, respondents indicated that employees are often ***unaware of their responsibilities***, causing an increasing workload and therefore a lack of time. There is a lack of trust in the knowledge or skills of employees / colleagues. Therefore, employees are controlling of redoing the work of others to keep production going. This happens primarily on an operational level in both the Do and Study phase. Site engineers control the work or redoing the work of others, leaving them with less time for their actual job, which is planning deliveries in the DMS and updating the VCM through Field for example.

An important statement is made by one of the respondents that follows upon these responsibilities: *"you should know who the next person is to deal with the information provided by me, and what exactly does the next person need"*. This relates to several aspects including the fact that the VCM was not used for quantity take-offs on a tactical level. This, because the structural model was not finished and handed over yet to the GC, meaning that the design of the structure is still changing during construction. This caused issues in dividing slabs in the 3D models into smaller pouring zones (batch sizes) as referred to in the program. Therefore, the VCM is a frozen version of the structural model. It is not possible to synchronise the work done on the frozen model with a new version of the structural model, meaning that the VCM is already outdated before it is used.

Besides, it was found that the rebar was not modelled. Meaning that the volume of rebar could not be subtracted from the concrete volume of a slab, wall, or column in the Plan phase. A respondent stated "*Lets say, if you model all the rebar that is installed, than the chances of having the quantities of concrete right from the model are quite high. By not having rebar in the model, it is a complete disaster, you won't get it [the quantity of concrete] right, you really need all the rebar, box outs, etcetera*". This example indicates that ***the LOD in models*** is of significant importance for the usability of models on a tactical level, which is another example of knowing what the next person requires.

Furthermore, there are two examples of an ***inefficient use and setup of the SLP*** on a tactical level in the Plan phase. The 3D-SLP is a key tool for making logistics plans, however a drawback of this phased model is the missing link with the program. The assembly and dismantling dates of assets (if provided) are based on the insights from a year ago. However, strategy changes and deviations in the program cause changes in these planned dates or positions. The work done to define these dates is therefore lost as none of these dates are linked to the programme and none of these dates are still relevant.

The importance of having these assets accurately modelled and checked in the model is significant as can be indicated by a clash that was found. A crane was put in place and stated to be in the exact place by engineers. Later it was found that this crane clashed with a structural column. However, one respondent indicated that this clash was already noticed during a clash detection with the actual crane position that was captured through laser scanning. The fact that the crane base was wider than what was modelled was the problem, and the clash was issued to the design team to adjust the design. Nevertheless, the clash resulted in the fact that temporary structural walls had to be built from LB2 till L04 (7 stories). These walls can only be removed after the crane is dismantled and the designed columns are put in place on each level, which carries significant costs. Similar issues occur with putting static concrete pumps down shafts after which it was realised that pumps are placed in the wrong position and clashes with mechanical installations within a couple of months. Besides, the locations of these pumps and other assets than tower cranes are not verified by scans, making it very difficult to identify the effects of misplaced assets.

Condition #2.2 Process and Procedures

Several respondents advocated a ***system way of thinking*** by following LPS which is, as one argues, "*not dependant on the technology, but about the process, that needs to be designed for every single element. If we break it [the process] down into small elements, we can manage the program on element level, we need to only be looking at the next three days, because the system is to reactive to plan any longer*". The planned process allows this to happen but in reality, this is only being done for high value materials or challenging deliveries. Logistics plans are not made and executed for regular deliveries as it should be. Therefore, prerequisite work is unknown in the Do phase and the conformance is not checked in the Study phase, causing that the Act phase cannot be executed.

This is closely related to ***a lack of procedures*** within the project organisation. It is not prescribed where from, what is expected from them to do with this information and to whom they are supposed to give new information. Employees are doing what they ought to be necessary for delivering the project. However, the lack of predefined actions and rules embedded in job descriptions is found to cause missing information and poor communication. Employees are not instructed what information should be provided for the next step in the process.

A number of examples can be given to indicate the lack of procedures. For instance, several respondents indicated the traceability of elements and materials throughout the process as one of the most important aspects for logistics. They argued that BIM can play an important role for logistics as "*BIM and 4D really allow to trace production by element*". However, the ability to trace every element in BIM through the logistics process is not operational since quantities are taken from 2D drawings and estimations instead of model-based information. This because there are no procedures describing to get this information from the models in the Plan phase.

Therefore, the VCM is not used as an input for the DMS. Besides, it is not obliged or outlined in a procedure to fill out all the necessary information in a delivery request in the DMS. This is why, zones, codes, material descriptions, quantities, etcetera are not always appointed on the requested delivery tickets, resulting in poor communication of relevant logistics information. These tickets have often no relation to BIM 360 or a programme and could not be checked on a tactical level.

Furthermore, not all deliveries were planned in the DMS, also caused by a lack of procedures. Many subcontractors to bring in their own deliveries parallel to the DMS. This allows subcontractors to deliver materials whenever they want. Therefore, JIT principles cannot be ensured which can result in increased stock levels on site, damaged and lost materials. However, respondents mentioned that excessive misuse of the system was not indicated yet. Nevertheless, several stipulated the likelihood of misuse during the phase-out, since many additional subcontractors will be involved, all striving their own needs.

Last, foreman and supervisors in the Study phase were not aware of the fact that logistical information should be captured. Although managers at a tactical level indicated the need to measure crane and unloading times, no procedure was in place and no one was assigned to do this exercise.

Deliveries often take longer or shorter than planned in the DMS since crane time that is planned is not checked by means of standardised time estimates based on statistics or measures. Nevertheless, several respondents acknowledge a ***lack of data collection to calculate estimated delivery times*** and therefore the inability to monitor the conformance. Therefore, respondents initiated to measure crane times with a digital device that could be used for this exercise, which was unfortunately not available on the case. Another respondent stated that "*checking the time of unloading should be something the foreman could do*". Yet, this is not done because of a lack of skills and labour power in the foreman staff.

Moreover, a consistent naming is beneficial since codes that are assigned to zones and elements can be used to create 4D models in a more simplified manner because synchro allows automated alignment of tasks and objects. However, this requires a consistent naming that can be established with ***protocols and standards*** defined upfront, which is however not consequently applied in the case. Linking the task to objects without prepared consistent naming is therefore done manually to create the 4D model on the strategic level. This is a highly labour-intensive exercise as it requires to select each element individually to create resource groups.

Technology

Category	**Condition**	**#**	**Barriers**	**Strategic**	**Tactical**		**Operational**	
					P	A	D	S
3. Technology	3.1. Software Interoperability	3.1.1	Unable to sync model changes in the VCM with revised versions			X		
		3.1.2	Unable to update the program by input from BIM 360 Field			X		
		3.1.3	The DMS is not linked to either BIM 360 or the programme				X	
		3.1.4	Resource groups in Synchro cannot be synchronised with BIM 360 Field					X
	3.2. Interfaces and user friendliness	3.2.1	Awkward interfaces and labour-intensive handlings					X
		3.2.2	Overwhelming amount of information		X			
	3.3. Hardware	3.3.1	Model size is too big, over 3.3GB with over 170 models		X			
		3.3.2	BIM 360 Field is only supported by IOS device					X

Table 12. Barriers in the technology condition

Condition #3.1 Software interoperability,

Several LC are used in the process including different software packages and therefore different file formats to share information between these LC. Several barriers have been indicated where files were incompatible with other software, or where software limits the usability of documents or models in the process.

First, in the Act phase on a tactical level, employees are ***unable to synchronise model changes in the VCM with revised versions***. Changes in the VCM (cutting up slabs into pouring zones) can be done in both Revit, Navisworks and Synchro. However, it is not possible to synchronise the changes made in the structural design model to a new and updated version of the structural design model. The model used in Synchro is therefore outdated and irrelevant for extracting quantities.

Another barrier indicates that the software ***does not allow to update the program by input from BIM 360 Field***. BIM 360 Field is not able to update progress on site directly to the programmes in Excel or in P6 in the Act phase of the process. Although BIM 360 Field can be used to track the construction progress, it is not designed for it. For instance, physical changes cannot be updated in the construction model on the iPad, such as updating pouring zones if sizes have been changed last minute. This needs to be done within a design software like Revit, based on mark-ups that can be made in Field. This makes it an awkward process, even if Field is use as planned. Nevertheless, it must be pointed out that progress tracking on the case-project is found to be very challenging as the site layout changes in a very a fast pace. A respondent stated, *"it is really hard to capture all the changes as it could be a daily task for someone due to the size of the project*".

Besides, a barrier was found in the Do phase, which is disconnected use of the DMS. ***The DMS is not linked to either BIM 360 or the program*** and operates as a stand-alone software. The effort taken to code and link pouring zones to tasks in the programme is therefore partly nullified for logistical purposes if employees do not manually refer to these codes. When deliveries are not always linked to zone codes, it becomes very hard to track if the materials planned for delivery are aligned with the programme. Besides, it is hard to check if physical conditions and the processing location of the delivery are suitable for the requested logistical equipment because the materials can hardly be traced back in programmes or models.

Moreover, a barrier is indicated in the incompatibility between Synchro and BIM 360 Field, which affects the process in the Study phase. Pouring zones often contain several slabs in the model and the tasks "Install rising elements" several columns or walls. Elements related to these tasks are assigned to resources groups in Synchro after which the whole resource group is linked to the task. However, these ***resource groups in Synchro cannot be synchronised with BIM 360 (Field)***. Updating the status of a task in the program in Field therefore requires updating the status of all elements in that specific resource group individually as is discussed in the next paragraph.

Condition #3.2 Interfaces and user friendliness

Updating statuses in Field is a labour intensive and cumbrous process since all elements must be selected individually in the Study phase. Such ***awkward interfaces and labour-intensive handlings*** cause disinterest in the use of the software. For instance, let's say a batch consists of 5 elements, then every element needs to be selected individually to change the status, which requires 5 clicks for each element and thus 25 clicks in total, which makes it a labour-intensive task, especially with over a thousand structural elements per level.

Furthermore, the ***overwhelming amount of information*** and data that is available when opening a BIM model scares employees to find the information they need, especially in the Plan phase. This is caused by of a lack of BIM skills and is another reason they fall back on familiar 2D drawings. Lots of effort is already made by the BIM team to categorise issues and models and present only the relevant information related to job descriptions, this however requires additional developments in which the new generation of BIM 360 is assumed to play a significant role.

Condition #3.3 Hardware

Two barriers in the logistical process are indicated that relate to hardware. The first barrier is caused by the size of the project and the corresponding models. The total "all models model", being ***over 3.3GB with over 170 models***, is simply too heavy for the average computer to use properly, as it lags while rotating and zooming. Even Revit models are often too heavy to handle by the hardware that is used, especially on the less advanced computers used by employers outside of the BIM department. Just opening a Revit model can take up to 10 or 15 minutes on these computers, discouraging the use of BIM in the plan Phase within the different departments. Besides, the mobile devices that are used on site to run BIM 360 Field cannot handle the model size either. Putting pressure on the BIM team to cut up the model into separated models which is taking many hours by the BIM department.

Moreover, ***BIM 360 Field is only supported by IOS devices*** and not by Android, forcing sub-contractors to invest in iPads. This reduces the applicability of BIM 360 Field on site in the

Study phase, since employers with Android work phones are not able to use the application and need to (for example) share an iPad with others.

Contracts and Liabilities

Category	**Condition**	**#**	**Barriers**	**Strategic**	**Tactical**		**Operational**	
					P	A	D	S
4. Contracts and liability	4.1. Model responsibility	4.1.1	Lack of model responsibility		X	X		
	4.2. Nature of the contract	4.1.2	Contract is 2D-based but processes are 3D based		X			

Table 13. Barriers in the Contract and Liability condition

Condition #4.1 Nature of the contract

Contracts and liabilities is a fourth aspect of the applicability of BIM to support the logistical processes on the case. It was indicated by two project managers and the BIM manager that liability issues are an important aspect for not using the BIM models to their full extend to make logics plans in the Plan phase. They argued that the ***contract is 2D-based but processes are 3D based***, which is causing serious issues in the Plan phase. Even though the 2D drawing should be erected from 3D models, there are significant differences between the model and the drawings. A respondent from the BIM department stated "*Yes, so all this [having 3D work processes but construction being done from 2D drawing] is fighting against the contract, so the contract says, drawings and documents are 2D. The contract is price from the drawings and specifications. So, if the drawing says, put a table in this room, we should put a table in this room, but is the model says it, never mind, it's the drawings that counts*". Therefore, especially engineers on a tactical level use 2D drawings.

Condition #4.2 Model responsibility

It was found that there is a lack of model responsibility within the Plan and Act phase because inaccuracies in the BIM models used for logistics planning, such as the 3D-SLP, are not part of the contractual obligations. Engineers, therefore, do not trust the 3D models and are not using BIM to its full potential. One engineer stated: "*It is a BIM project ok? But in reality, everybody is working with 2D drawings*". This affects the traceability of elements in the logistics process. References and identity codes that are used in BIM and linked to tasks in the programme are not translated to 2D documents. De differences between the 3D models and the 2D drawings is often caused by ad-hoc design changes that are made in 2D by the design team. 2D changes in for example the architectural model were therefore not aligned to the structural model. A respondent stated, "*every pour I have, I have issues with mismatching drawings […] related to miscommunication*", which have had effects on concrete and rebar orders.

10.12. Appendix L

Improving knowledge requirements

This study acknowledges the importance to train staff to use digital technologies such as Revit, 360 Glue, 360 Field and the DMS and making people aware of the opportunities and benefits of using digital technologies. Enegbuma, Aliagha and Ali (2015, p.73) had similar recommendations in their research on BIM adoption as they stated, "*it is recommended to improve grey areas such as awareness, collaboration amongst construction professionals, evidence of returns on investment and training*".

It is argued by respondents that there is no clear definition about the maturity of BIM required for certain job-positions within the organisation. The BIM department is often seen as an island within the project organisation and other departments have little understanding of the responsibilities and tasks of the people working in the BIM department.

The main responsibility of the BIM department should be to set up the tools for other departments to improve practices and processes, to coordinate and check models and support other departments in the use of digital BIM tools (Barison and Santos, 2010). However, the empirical showed that the BIM departments is often asked to support other departments in basic modelling, to extract 2D documents or to adjust models and drawings. Employees in other departments should be able to perform these fairly simple handlings themselves to create the information they need without being dependant on the BIM department.

The BIM maturity of individuals within the different departments needs to be improved to be self-supporting and not dependant on the BIM department. This should increase the productivity since there is not two people working on the same issue, a person modelling and a person providing the input. Allowing the BIM department to focus on their core activities.

The case company already started with providing BIM training as is indicated by a respondent "*we have already started with an introduction of a basic Revit course to get people an idea of what Revit does. There is going to be an advanced course for people that want to go and create shapes and stuff*". However, it is yet to decide who requires what level of training and what skills employees need.

A matrix is developed based on an interview with one of the key figures of digital implementation of the case company. The matrix indicates the required knowledge base of individuals on different positions within the organisation. Based on describing the proficiency levels of learning a language. As an example *"You should have a different requirement level for different skillsets", a "BIM manager, should have an expert level of understanding of engineering, and should have a basic understanding of logistics"*. Similar can be done by describing levels of BIM maturity to job descriptions.

A matrix is shown in Table 14, which indicates an overview of the required skillset for a specific role within the organisation. The required levels of training programs to support people in the use of BIM should be based on the required knowledge related to their role. The higher the percentage, the higher the understanding and the knowledge should be on the referring role. So, for example: a senior manager in a department should possess a 100% understanding of the requirements of a junior management position. But the junior manager may only require 70% of the knowledge that a senior manager should possess.

This matrix represents the knowledge requirements of employees within the organisation. The BIM department provides the tools to use BIM, prepares models and drawings initially, but these models and drawing should be managed and maintained by the departments using them. A few examples are provided below.

A manager in the logistics department should have a good understanding of the opportunities of BIM, and a junior in the logistics department should be able to do basic modelling, position hoists, understand and move around a 4D model, take measurements and plot drawings for instance. The 3D-SLP should for example be managed by a junior of the logistics department, as most of the aspects in this model relate to logistics. This model should be used to make logistics plans as it represents the actual site layout including all the logistic.

A manager in the engineering department should also be aware of the opportunities of BIM to judge if certain BIM tools can be beneficial for his department, for instance laser scanning to BIM. Besides, a junior engineer should be able to use the model, do quantity take-offs, perform a clash detection with temporary works, take measurements, and plot 2D drawings. While a foreman may only use the model to visualise the situation and take measurements if necessary.

Table 14. Levels of required understanding

Department	Function		Egineering			Logistics			Project Controls			BIM		
		Higher management	Senior engineer	Site engineer	Foreman	Senior manager	Junior manager	Logistics coordinator	Manager	Senior planner	Junior planner	Digital construction manager	Senior digital construction specialist	Digital construction specialist
	Higher management													
	Senior engineer		100%	100%	100%	40%	60%	80%	40%	60%	80%	40%	60%	80%
	Site engineer		70%	100%	100%	20%	30%	40%	20%	30%	40%	20%	30%	40%
Egineering	Foreman		50%	70%	100%	10%	15%	20%	10%	15%	20%	10%	15%	20%
	Senior manager		40%	60%	80%	100%	100%	100%	40%	60%	80%	40%	60%	80%
	Junior manager		20%	30%	40%	70%	100%	100%	20%	30%	40%	20%	30%	40%
Logistics	Logistics coordinator		10%	15%	20%	50%	70%	100%	10%	15%	20%	10%	15%	20%
	Manager		40%	60%	80%	40%	60%	80%	100%	100%	100%	40%	60%	80%
	Senior planner		20%	30%	40%	20%	30%	40%	70%	100%	100%	20%	30%	40%
Project Controls	Junior planner		10%	15%	20%	10%	15%	20%	50%	70%	100%	10%	15%	20%
	Digital construction manager		40%	60%	80%	40%	60%	80%	40%	60%	80%	100%	100%	100%
	Senior digital construction specialist		20%	30%	40%	20%	30%	40%	20%	30%	40%	70%	100%	100%
BIM	Digital construction specialist		10%	15%	20%	10%	15%	20%	10%	15%	20%	50%	70%	100%

Table 14. Level of required understanding between roles on a construction project

10.13. Appendix M

Optimum CPLS-layout of project case

This section proposes an optimal layout for the case-project, which is based on propositions from respondents. Yet it should be noted that the functionality of this proposed layout is dependent on the availability of the enabling conditions. Therefore, the first priority should be to ensure the enabling conditions.

Figure 34. Optimum CPLS-layout

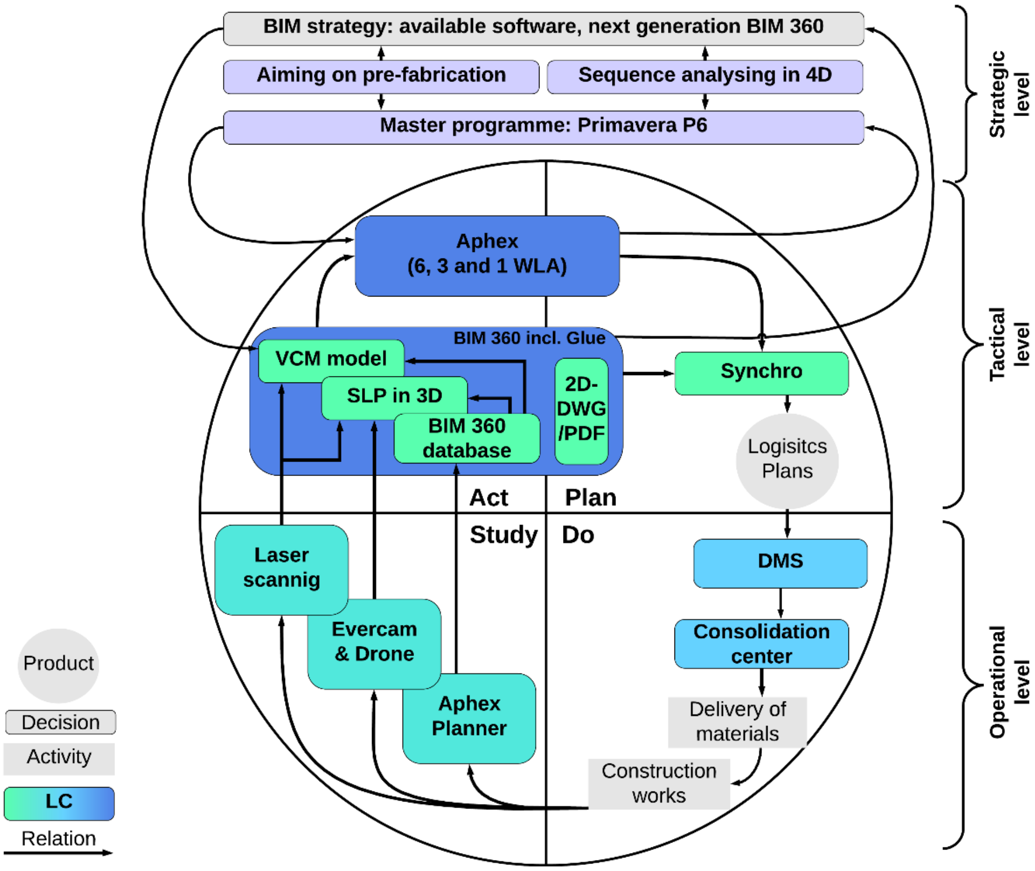

Figure 31. Optimum CPLS-layout for the case

10.13.1. Introducing Apex Planner to replace Excel

Several barriers have been indicated with the use of Excel as a planning tool for making the lookahead programmes. One of these barriers is indicated during an attempt to create a 4D-SLP for the case-project, which is performed during the field research. This barrier is primarily related to linking the lookahead programmes to objects. These lookaheads are made in Excel and, in principle, Synchro allows to import Excel programmes. However, Synchro usually offers four ways to import a program; consolidate, skip, integrate or synchronise[5]. The option to synchronise completely replaces the program in synchro with the updated external program in Excel. However, this option is not available when updating a new excel programme in Synchro, as Excel is not a planning software. Not having this option forces to manually remove tasks that may have been removed from the Excel program but still exists in Synchro, making it a labour intense and error prone process.

[5] See Synchro Pro Basic training 2019 p. 77.

Other issues in the use of excel are found in the fact that it is not linked to data that is captured in the field and therefore needs to be updated manually in stand-alone lookahead programmes. Therefore, the lookaheads programmes are not accessible for others, making it hard to plan collaboratively and to give the planning responsibility to the last planners (the supervisors and foreman depended on one another) to follow LPS. While LPS allows to plan logistics more effective as all aspects of logistics plans are considered with the responsible people.

It is for this reason that Aphex Planner[6] is proposed by a respondent. It is an advanced short-term planning application that supports the LPS working methods and allows the last-planners, to plan the work collaboratively in a cloud based and real time environment. Meaning that logistics plans can be adjusted on the latest site information. Besides Aphex Planner is able to import from and /or export to master scheduling tools such as Primavera P6 or Microsoft Project which can both be synchronised with Synchro[7]. This allows to link and easily update the process in a 4D model based on the lookahead programmes.

10.13.2. Synchro on a tactical level for logistics plan making

The use of 4D to support plan making is found to be a useful tool for construction logistics. Logistical equipment, such as hoist, are modelled in the 3D-SLP but the installing and dismantling dates are often not provided, and planned positions need to be revised due to changes in the program strategy.

Yet, deciding on new positions, installing, and dismantling dates is found to be challenging due to several reasons. If a position is chosen, it is required to check when this hoist could be installed and when it should be disassembled as it is aimed to keep hoists in place as long as possible. Therefore, it is required to check when adjacent pouring zones were planned over the different levels to be served by the hoists. However, the hoists can only be heightened to the next level once the adjacent slab is poured and the formwork and temporary site equipment, such as cantilevers, are removed. Besides, it was required to check if additional planned works clashed with the operational use of the hoists. For instance, some locations were not suitable as heavy lifting of steel elements were planned over the suggested hoist positions. Therefore, the hoist is in an exclusion zone and unusable for weeks. Also, the influence of temporary works should be considered.

All these issues are making it almost impossible to find a suitable location and plan installation. Therefore, a 4D model can be helpful, especially if site equipment and temporary works are modelled as well. Visualising the physical SLP changing over time would really allow to see all the aspects discussed above at once by going through the time in the 4D model.

Another important aspect is the impact of safety on process, which is closely related to logistical issues and can cause serious productivity issues. Simple issues such as employees who could not find the routes to their work locations as walking routes changed due to new exclusion zones were experienced daily. Especially because of the size of the project. Respondents mentioned that a detailed 4D-SLP can be useful as it can indicate walking routes and exclusion zones. A few respondents mentioned that, on previous jobs, videos of such 4D models were presented in canteens throughout the day. This was found to be very useful as workers will automatically have a look and therefore know what the site looks like on that specific day.

10.13.3. Aphex Planner to obtain field information

Field research indicates that the study part on an operational level in the CPLS framework has two main functions for logistics that were seeking to be fulfilled by BIM 360 Field.

The first is to keep track of the progress and identify deviations in the programmes, which impacts logistical operations. For instance, if four columns could not be installed today because of the weather and they are postponed to tomorrow, they should also be delivered tomorrow, and the appropriate crane should be scheduled accordingly.

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[6] https://www.aphex.co/ - http://extranetevolution.com/2018/05/detailed-planning-with-aphex-planner/

[7] It is not tested how Aphex exports to these scheduling tools, the only requirement is that unique ID's of tasks remain. Furthermore, both Primavera and Microsoft Project can be synchronised in Synchro.

Second, to collect data about the conformance of the logistical plans by keeping a record of causes of deviations to allow collaborative learning. This can be done by defining recurring causes, such as, the tower crane was blocked for an hour by a subcontractor to unload 5 elements, but 1.5 hours were required. Plans can be adjusted to improve the accuracy of the logistics plans if such issues are recurring.

BIM 360 Field was argued not to be useful for progress monitoring as there is no direct link between the status updates and the lookahead programmes. Other monitoring software, such as Synchro Field do allow such monitoring features. It allows for instance to prepare customisable object statuses to obtain a more accurate status of the site allowing last planners to adjust their schedules. Synchro Field would therefore be a better alternative to keep track of the construction progress.

However, neither of these software packages have an off the shelf tool to also collect data about the reasons causing deviations in the programme. Nevertheless, Aphex allows to collect such field data and seek to find patterns, and trends, to allow shared learnings and improve processes on the longer run. This data important as site conditions significantly impact logistics plans, and changes constantly over time. This planning software requires employees to indicate the reason of delays in the programme, following LPS. These causes of non-conformance, as available in Appendix I, are customisable, allowing to add logistical reasons as well, indicating that trucks arrived late, crane time took longer, the crane capacity was not sufficient, etcetera.