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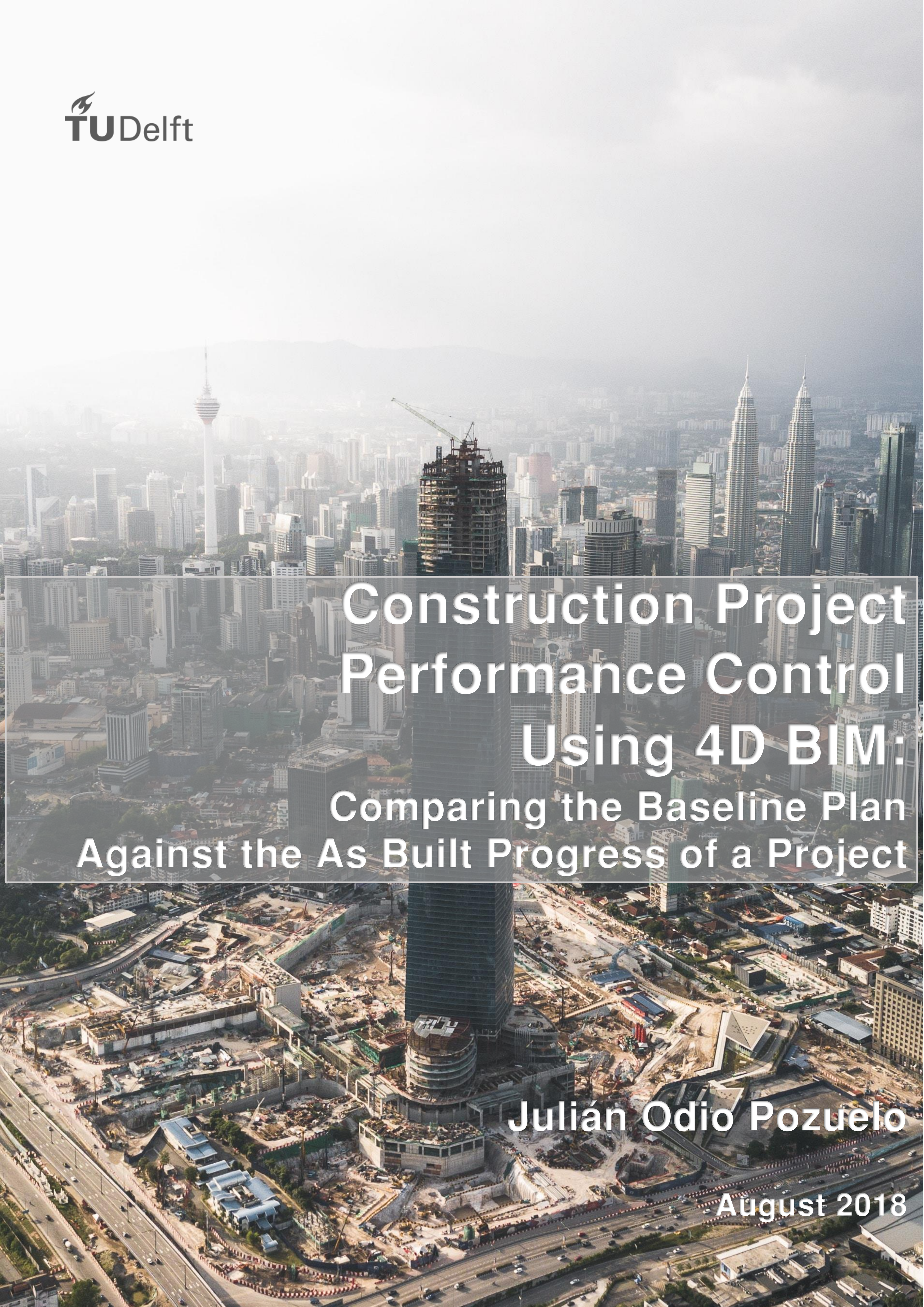

Construction Project Performance Control Using 4D BIM:

Comparing the Baseline Plan Against the As Built Progress of a Project

Julián Odio Pozuelo

August 2018

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Construction Project Performance Control Using 4D BIM:

"Comparing the Baseline Plan Against the As Built Progress of a Project"

Master Thesis

by

Julián Odio Pozuelo

Master of Science in Construction Management and Engineering

Delft University of Technology

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Colophon

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Preface

Dear Reader,

Before you lies the graduation thesis titled "Construction Project Performance Control Using 4D BIM: Comparing the Baseline Plan Against the As Built Progress of a Project" in partial fulfilment of the Master of Science degree in Construction Management and Engineering at Delft University of Technology. This document is the result of eleven months of research, data gathering and report writing.

The report was undertaken under the request of BAM International in the pursuit of implementing 4D BIM during Site Execution and Comparing the Baseline Plan, Against the As Built Progress of a Project, under university supervisors Hans Bakker, Sander van Nederveen and Louis Lousberg, as well as company supervision from Cemil Kuyululu. The research process was time consuming and demanded hard work. However, the process fed me with a tremendous amount of knowledge in breakthrough techniques and insight on the construction industry. I would like to thank my supervisors for their timely guidance with constructive criticism and knowledge sharing that enabled this document to reach a satisfactory level in my opinion.

I would also like to thank my family. They have been the best support group anybody can ask for. From them I learned to dream big in the construction industry and pursue my life goal of building World Cup Stadiums, High Rise Buildings and Tunnels, but at the same time, to make the necessary sacrifices and effort to achieve my goals. With the accomplishment of this major milestone in my life, I am one step closer to my lifelong objective.

Furthermore, I must thank Ronald De Geus, Simon Vilarasau, Eugenio Vaieretti and Randy Ugarte for their sponsorship, guidance and effort throughout this thesis. Without their support, the implementation would have not been possible. Finally, I would like to thank all those people at BAM International who shared their knowledge and motivated me to learn every day a little bit more about the construction industry.

Julián Odio Pozuelo
Delft, August 2018

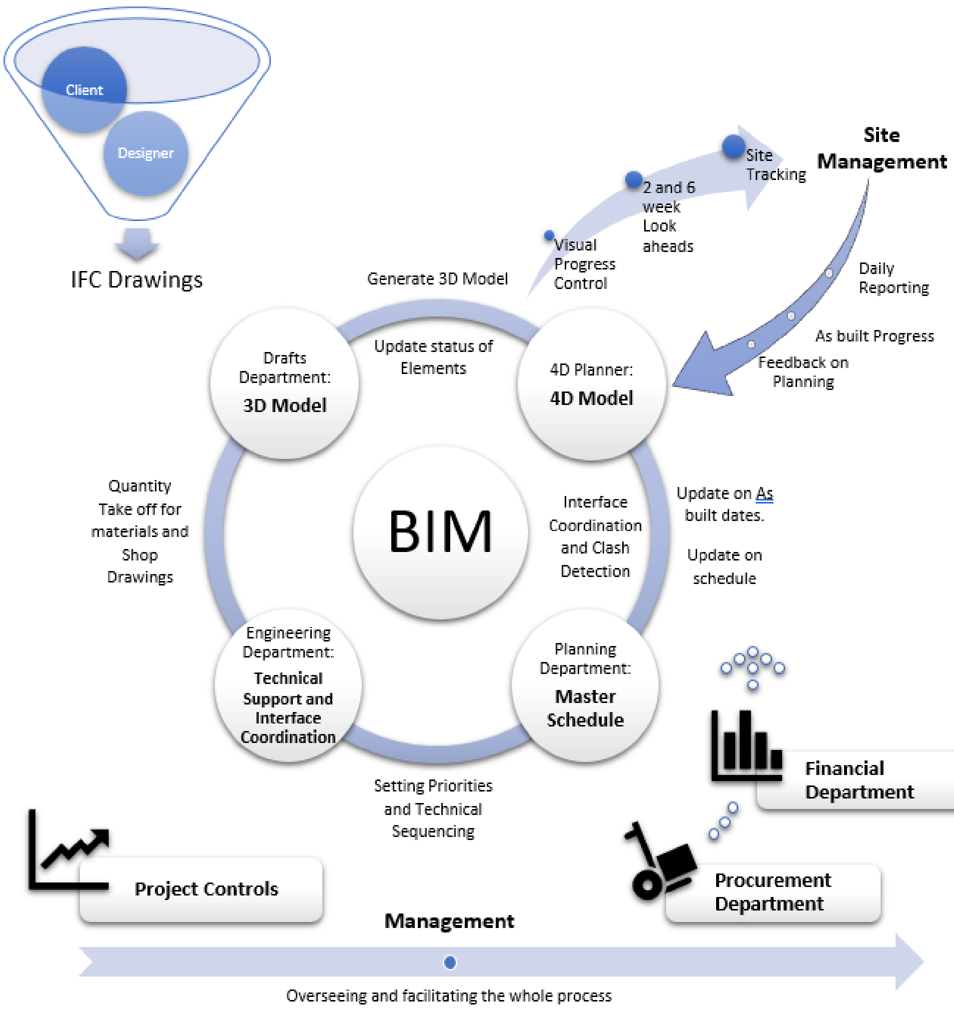
Executive Summary

Traditional construction planning and performance control tools such as Gantt Charts and S Curves fail to visually represent physical project progress, construction sequence, interfaces and the critical path, which means that decision makers carry out their job with incomplete information. Moreover, these tools motivate a quantity-oriented mindset and a project island approach. Furthermore, traditional information flows in projects are inefficient since these present a significant lag between data collection and project status reporting. With improvements in technology and enhanced visualization through 3D object-based models linked to the schedule (time being the fourth dimension), opportunities arise that enable bridging the information and communication gaps currently experienced in planning and evaluating as built performance in a Building Information Modelling (BIM) approach. 4D BIM has been seldom implemented in the execution phase of projects and has been utilized merely as a preconstruction planning tool. The end goal of the research is to make recommendations on how to apply 4D BIM during the site execution phase to improve construction performance control in mega projects and provide a conceptual model of a work methodology to be implemented in civil engineering projects.

To control performance on site, the author builds upon the capabilities of traditional control instruments such as S Curves and Gantt Charts to bridge the visualization gaps through a progress deviation signalling tool that tackles workspace and interface coordination through a 4D Model that also enables representing physically the critical path of a project by overlapping a 4D Model Baseline as a benchmark to compare against the As Built Progress 4D Model. The proposed tool represents performance prior to the data date in a colour coded display based on early or late completion. On the data date, the tool signals deviations by comparing the baseline plan with the as built progress by presenting those elements that are behind according to the colour code and contrasting between the actual production against the aforementioned benchmark. The works after the data date are represented in detail through 4D based 2 week and 6 week look aheads and interfaces as well as workspaces are coordinated up to project completion. The tool also enables visualization of the complete scope of works to dimension the remaining works in a project.

In parallel to the performance visualization tool, a BIM integration framework is presented to facilitate the information flow between planning actors and site execution staff (as seen on the figure below) by using the proposed tool to inform the site execution crews of the planning through the 4D Model based 2 week and 6 week look aheads and to evaluate their performance with the colour coded model and deviation signalling characteristics. The framework also retrieves information from the site with the aid of mobile applications linked to the 4D Model to speed up the data entry process from the site to feed the master planning and project control tools. This framework is meant for real time updating of project progress to reduce the lag between the data date and the reporting date of project status. The framework is extended towards the rest of the project organization to promote a more efficient flow of information in a BIM integrated approach.

Both the tool and the framework have been implemented in a case study in the Moín Container Terminal in Costa Rica by BAM International and tested in an intervention-oriented research. The project performance is evaluated over the course of five months prior to the implementation and the performance of the crews during the intervention is evaluated over the course of two months in which the conditions prior to and during the implementation are compared in terms of project progress and schedule performance index. The quantitative data is coupled with qualitative information from interviews with experts on the field of project planning and execution. The data collected yields from work packages that include a wharf, a building, pavements, utilities and reefer rack structures.



From the data collected it was possible to see how the implementation accelerated the effects of the learning curve in wharf deck by increasing progress values from an average of 1% to an average of 4% whilst the schedule performance index rose from 33% to 65% which evidenced an increase in the reliability of schedules and weekly coordination. In the Utilities work package, the progress values rose from 1.08% weekly, to an average progress of 1.82% during the implementation whilst the schedule performance index rose from 66% to an 86% during the intervention. Given the improved interface and workspace coordination, slot drains duplicated their progress and the busbar construction rose from 1% weekly to a 5% during the intervention. The implementation allowed visualizing the bottlenecks, as well as the lagging work fronts which enabled decision makers to take action and alleviate holdup points which are predecessor activities for the top surface activities such as pavements. 4D Model visualization enabled physically pin pointing the availability of workspaces in the coming future, which is not possible in other traditional tools and traditionally spatial coordination is neglected which results in faulty and unrealistic plans and inefficient resource planning.

The implementation integrated different work package actors in workspace and interface coordination meetings with the aid of the 4D Models to elaborate on 2 week and 6 week plans in detail to produce high reliability estimates for the remainder of the project by recalculating the remainder of activities of the project and testing for interface clashes. The implementation aided reducing the quantity-oriented mindset and project islands approach, into a whole project mentality in which some non-critical activities were sacrificed at work package level to satisfy project targets and focus on completing the forecasted quantities in the necessary locations and critical path activities.

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Chapter 1
Introduction

1. Introduction

1.1. Introduction

The present research aims at solving a portion of the problem of construction project delays through increased control of performance. The research dives into the field of construction project performance control and investigates on the limitations of present methodologies and proposes a conceptual model to solve part of the problem with the aid of 4D BIM to enable better visualization for decision makers and planners. The research is an intervention-oriented investigation in the Moín Container Terminal in Costa Rica, by the contractor BAM International.

1.2. The Problem

1.2.1. The International Construction Industry: Underperformance and Delays

The international construction industry is highly competitive and operates on considerably low margins, which make it sensitive to time and cost overruns (Loosemore, 2003). Furthermore, the construction industry has been criticized over the past three decades for its underperformance (Langston, 2014) which is evidenced by the fact that construction projects repeatedly experience time delays (Meng, 2012). Underperformance and low productivity on site are caused mainly by interruptions, working continuous overtime, fragmentation, lack of detailed planning, no focus on productivity as well as difficulties in measuring and monitoring productivity (Horner & Duff, 2001). The most effective proven measures to improve performance are continuously measuring productivity, setting targets, organizing logistics, better training, collaborative constructive workplaces and realistic scheduling (Jergeas, 2009).

Even though there have been significant improvements in technology and project management techniques, construction projects continue to fail in meeting the scheduled time completion (Sweis, Sweis, Hammad, & Shboul, 2008). According to research, at least 40 per cent of international projects are delayed (Agyekum-Mensah, Knight, & Pasquire, 2012) and 50 per cent of these delays are caused by the contractor, due to inappropriate construction methods, inaccurate time estimates, improper planning (Majid & McCaffer, 1998) and mainly, poor labour productivity (Odeh & Battaineh, 2002). Some of the most effective measures to minimise delays are employing competent project management, holding frequent progress meetings and performing preconstruction planning of project tasks and resources needed (Olajide, Timo, Onaepepo, & Idowu, 2013).

Delays and Underperformance are the two main problems to be tackled in the present research. However, it is not feasible to attempt at fully solving these two problems, but a significant portion of these such as monitoring performance and delays as well as the visualization and handover of this information.

1.2.2. Decision Making: Information Handover and Visualization

In Mega Projects, Construction Managers and Project Managers have the responsibility of making fast decisions on key complex aspects based on limited information, with the aim of satisfying the project parameters of time, cost and quality, however, this may lead to unexploited opportunities and undesirable effects (Webb & Haupt, 2003). Therefore, decision makers need information to be handed over in an accurate, timely, clear and concise manner to enable them to lead the project in the right direction (Meredith & Mantel, 2003). In terms of performance and progress control, managers traditionally base their decisions on S-Curves, Gantt Charts, Cost Reports and other visual aids to determine if the performance of a project is satisfactory or not, and based on this, make the necessary adjustments.

However, traditional construction planning and control tools such as Gantt Charts, S-Curves and Time Location Charts do not provide a clear visualization of information, since the sequence of activities is not linked to the physical objects represented by those activities (Coble, Blatter, & Agaj, 2003). With regards to Gantt Charts, progress becomes difficult to track and visualize as the number of activities increase and as parallel activities are being carried out, such as in mega projects (Mubarak, 2015). In the S Curves, the cumulative quantities of activities can be represented in the amount of money spent in the project, amount of man hours dedicated to an activity, or the amount of materials being consumed in the project (Nicholas & Steyn, 2012), yet these only represent quantities produced in time and forecasted production as well as project deviation in numerical values. The latter does not supply information about the specific physical tasks to be carried out, nor does it provide information of critical path of the project and is does not offer a visual representation of deviations, interfaces and spatial constraints (Koo & Fischer, Feasibility study of 4D in commercial construction, 2000).

The problem in short, is a visualization and communication limitation between the planners and the site execution management, on which this research will be focusing. Due to the development of technology on these fields, enhanced visualization tools have arisen, and therefore, stakeholders and researchers have seen opportunities to employ 4D BIM in the evaluation of "as built" and planned construction (Lee & Peña-Mora, 2006). The present research focuses on time performance monitoring of works performed on site and signalling where the project teams fail to meet the scheduled time completion of items (delays), specifically for use in the tools employed in decision making during progress meetings and planning of project tasks with the aid of 4D BIM capabilities.

1.3. Research Objective

The research objective is to make recommendations to improve the control of construction mega projects by evaluating the effectiveness of the implementation of 4D BIM during the site execution phase when comparing as built and as planned performance in progress meetings and preconstruction planning of tasks and resources.

The higher goal of this research is to reduce the amount of delays and increase performance. The main goal of the present project is to improve performance control and evaluation of deviations through the use of 4D BIM, by presenting progress and plans in a clear manner for decision makers. The expected result is to produce an efficient and effective framework for evaluating project performance and planning with 4D BIM. This leads to the following research questions.

1.4. Research Questions

1.4.1. Main Research Question

What measures need to be taken in an implementation of 4D BIM to improve performance control in the execution of construction projects to reduce the amount of delays?

1.4.2. Sub Research Questions

1- *What is the current common practice of controlling progress in projects and what are the possible alternatives in 4D BIM?*
2- *What stepwise coordination is required between planners, managers and site engineers?*
3- *How can 4D Models bridge the existing gaps of traditional performance control methods?*
4- *Which are the factors that hinder the implementation of 4D BIM for planners and managers?*

5- *To what extent can an implementation of 4D BIM improve construction project performance control and reduce delays?*
6- *What are the perceptions of construction managers, project managers and planners about 4D BIM and the introduction of new technologies in construction site execution for deviation control?*
7- *What are the most suitable levels of detail for each work package at each stage?*

1.5. Methodology

The logical sequence of the present document is described below with the aid of Figure 1 and Figure 2 to explain the stepwise distribution of the chapters of this research, referencing the research questions that are being answered. In terms of the methodology, as seen on Figure 1, the approach in the research is to obtain the relevant insight through interviews and literature research, in order to propose solutions that generate quantitative data in the form of numerical results, which are then analysed with the aid of further interviews to formulate valid conclusions and recommendations. The method of the research is to build upon existing knowledge and generate new insight through the case study experience and knowledge sharing of the experts involved.

1.5.1. Exploratory Phase: Literature Research and Preliminary Interviews

In order to initiate the research, it is first necessary to conduct preliminary informal interviews with Project Managers, Planners, BIM Managers and Engineers to identify the knowledge gaps in the environment of Construction Projects. Following this initial step, a literature research has been conducted to first characterize the problem in Chapter 1 (as seen on Figure 1) and then to determine the state of the art in terms of 4D BIM, as well as to highlight the research that has been carried out on the subject by others in Chapter 2. The literature research is the scientific basis to establish a benchmark of desired construction practices, that will serve to assess the initial condition of the case study. The literature research aids in determining the technical foundations of the present investigation upon which the author builds the proposed framework. The specific subjects to be covered in the literature research are project planning including Gantt Charts and Time Location Charts, project controls, S Curves, key performance indicators in construction, Building Information Modelling (BIM) and 4D BIM. This section answers sub-research question 1.

1.5.2. Case Study

An intervention-oriented research has been deemed most suitable for the present study since the practical nature of the problem requires for a pilot intervention on project controls in one of BAM International’s projects. For research purposes and confidentiality aspects, the focus of this project will adhere to general requirements of this implementation to the construction industry in a generic manner, and not solely to the company sponsoring the project. The deliverables will be oriented to addressing the common benefits and struggles of this implementation from a general contractor point of view, as well as the planning aspects that concern this topic.

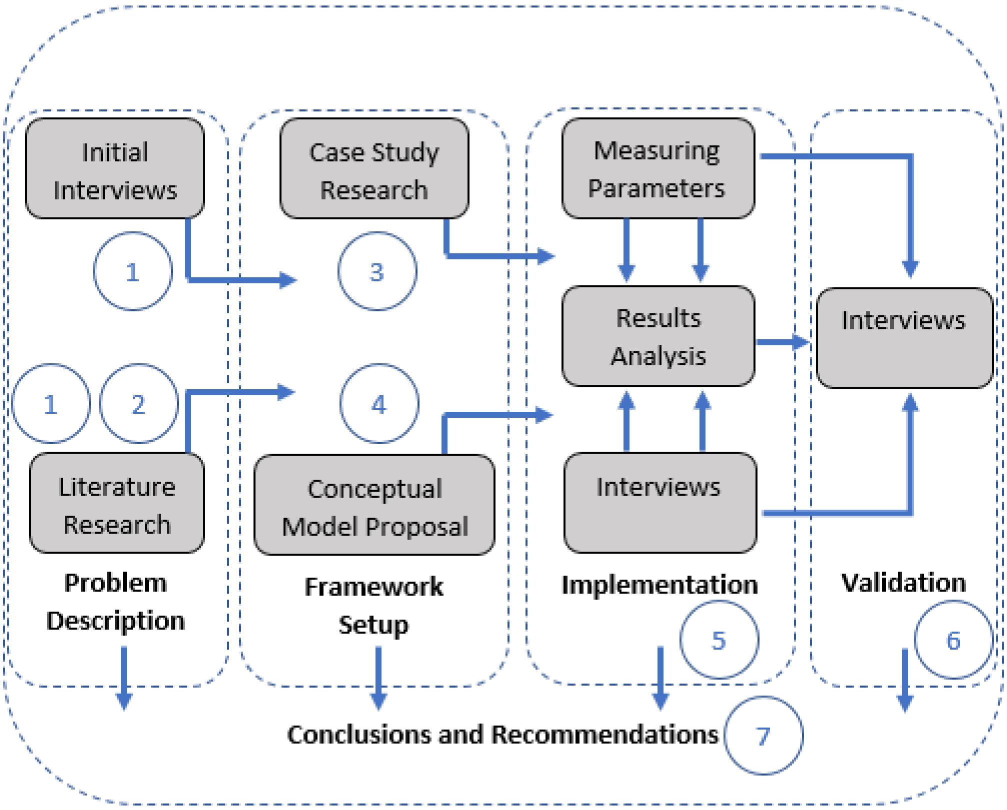


Figure 1. Research Methodology (Chapter number in parenthesis)

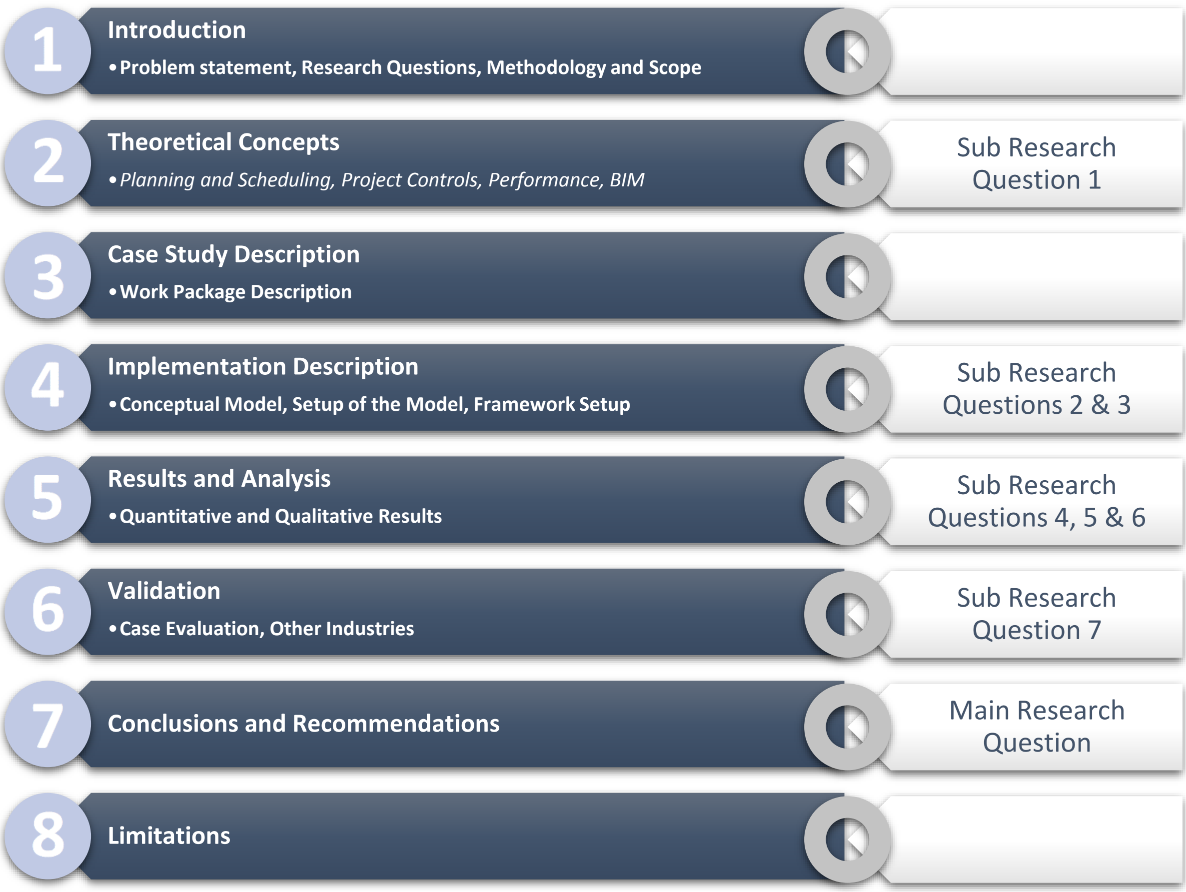


Figure 2. Overview of Research Question Discussion

1.5.3. Starting Conditions Characterisation

To be able to measure the effects of the implementation, it is necessary to establish an initial condition with which the effects of the implementation will be compared. It is paramount to establish these conditions and the circumstances that surround the initial measurements in Chapter 3, to be able to compare both scenarios under similar circumstances to obtain valid results. This process takes place over the course of five months in which the framework is being formulated in parallel to prepare for implementation.

1.5.4. Framework Formulation

Based on the initial characterisation and the theoretical foundations, a framework is created to make up for the short comings of the practice on site, in order to attempt at transitioning the execution on site towards best practices stated in the literature research with the aid of the implementation of the intervention. Understandably, it is not realistic to achieve a fully comprehensive study, however, for the sake of the current research, the framework is created in terms of achievable goals stated in the theory that are aligned with the resources present in the case study. Nevertheless, the case study selected has sufficient resources readily available to carry out the study. This section answers sub-research question 2 in Chapter 4.

1.5.5. Implementation of Intervention

The process takes place in cycles of two weeks in which the intervention is implemented and monitored to record all the results and document all the conditions that influenced the results. The whole implementation of the intervention is carried out over the course of two months. After each cycle, the Framework is adjusted based on the interviews held with key staff. The adjusted framework which answers sub research question 2 will be presented in the conclusions section. A detailed description of the intervention is also included in Chapter 4 and the conceptual model is then part of sub research question 3.

1.5.6. Data Collection

The data collected falls into two categories, quantitative data which comprehends the deterministic values of performance on site as well as the measurable environmental conditions on site, and the qualitative data which consists of the interviews of key staff on the project, that will serve as supporting information to validate and explain the quantitative portion of the data.

For this case study, the quantitative data refers to actual start and end dates for activities, activity durations, amount of planned activities for each period, baseline start and end dates for activities, weather conditions as well as other aspects that can be measured on site, such as volumes, areas and lengths of elements. From the data a "before and after" the implementation comparison can be carried out in terms of the following parameters:

- Earned Value
- Activities completed compared to Activities Planned per bi-week
- Quantity of Out of Sequence Activities
- Delayed Activities

These aspects feed the performance indicators evaluated in the research upon which conclusions can be drawn.

Both the quantitative and qualitative data are collected on a biweekly basis to understand the data collected, and to determine the shortcomings of the framework to allow for adjustments. Interviews aid in explaining the data that is not quantifiable or measurable, but relevant, such as the factors that hinder the implementation of 4D BIM as part of sub research question 4.

1.5.7. Data Analysis

The data gathered will be contrasted per work package on a before and after the intervention basis, to compare the data and pin point the benefits of the implementation based on the quantitative information. Based on the qualitative information, the possible benefits of the implementation of 4D BIM will be assessed to understand the magnitude of these benefits. This section answers sub-research question 5. Within this data analysis, interviews are held with construction managers to obtain the perceptions of seasoned staff with regards to the implementation of 4D BIM and answer sub research question 6.

1.5.8. Validation

To understand if the intervention has been successful, it is necessary to validate the process and the solutions proposed via closeout interviews with staff that is alienated from the case study which will determine if the experiment may be replicable and successful in other cases. Only if the interviewees validate the intervention, can the research be considered successful. This final interview round will be held with key staff from the planning department management and engineering from the head office to establish if the research is satisfactory. This section answers sub-research question 7.

1.5.9. Conclusions and Recommendations

The conclusions and recommendations wrap up the findings in each one of the sections as seen on Figure 1 and answer the main research question supported on the build-up created on the previous sections that validate and reinforce the measures to be recommended. Moreover, the author details the gaps detected on the knowledge and recommends further research to be conducted on the topic.

1.5.10. Scope

The present research encompasses a literature research on the topic of project planning, project controls in terms of progress and 4D BIM. The document includes the formulation of a framework and a tool for deviation control using 4D capabilities, tested during the implementation of a case study. The scope includes the data on how the framework and tool impact the case study as well as a set of interviews and recommendations to establish the proposed set of solutions to the problem of communication and visualization that traditional project control tools possess.

This document does not include in its proposed solutions, the use of advanced cameras for automated site tracking. The research includes only those tools that are readily available for the general public such as mobile and tablet applications as well as commonly used software for this discipline.

The proposed framework for BIM integration of a project organization will only refer to the information flow relevant to the planning and performance control ranging from delivery of issued for construction drawings from the engineering party, to the flow of plans towards site execution and the feedback loop from the site.

Chapter 2

Theoretical Concepts

2. Theoretical Concepts

To understand the requirements that the proposed solutions need to satisfy, it is highly important to define the theoretical concepts upon which the recommendations are built. The logical sequence of the present chapter is to first elaborate on the principles of planning, touching upon key subjects such as Schedules and tools such as Gantt Charts. A transition from planning is done towards project controls to explore on traditional control tools such as S Curves. Furthermore, to make up for the shortcomings of traditional practices, the chapter introduces Building Information Modelling (BIM) and the latest trends on project control approaches in 4D BIM. In this chapter it will be possible to answer the sub research question:

"What is the current common practice of controlling progress in projects and what are the possible alternatives in 4D BIM?"

2.1. Construction Project Planning and Scheduling

Project planning has been defined as "those processes performed to establish the total scope of the effort, define and refine objectives, and develop the course of action required to attain those objectives" (PMI, 2008). Planning covers different functions such as cost estimating, scheduling, project controls, quality control, amongst others (Mubarak, 2015). Scheduling is a subset of planning in which sequencing of activities and their timing is determined for a project to estimate the completion date of the project, calculate start and end dates for activities, coordinate personnel and subcontractors, calculate the cashflow of a project, improve work efficiency, to evaluate the effects of change, to prove delay claims and to serve as a project control tool (Mubarak, 2015).

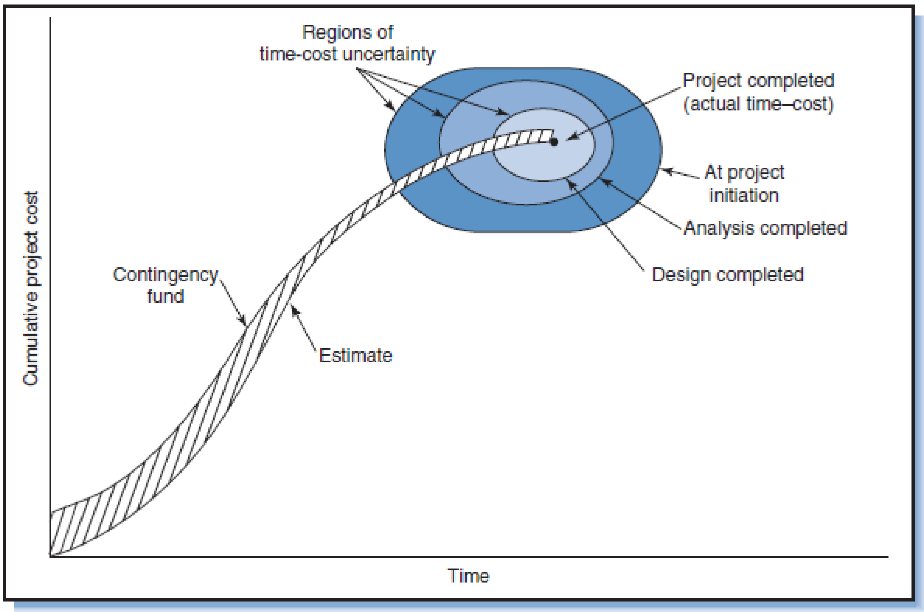


Figure 3. Cumulative project cost and regions of time-cost uncertainty (Nicholas & Steyn, 2012)

Planning and scheduling are carried out across the whole life cycle of the execution of a project. However, the process varies as the project progresses and details in the design are completed as seen on Figure 3. The major planning stages are at the Design Phase (normally done by a consultant in coordination with the client), at the Tender Phase and the Construction Execution Phase. Due to the fact that at initial Design and at Tender stages, the details are not complete, the plans are roughly estimates. However, as the project definition increases, logically information and knowledge on the project increases, reducing the amount of uncertainties and therefore, the accuracy of estimated completion dates on schedules should increase with time. Due to the high level of uncertainty at early stages of the project, it is not practical to plan in detail activities that are still on the uncertainty area further down the road. Therefore, it is more practical to employ a plan by phases approach as seen on Figure 4 (Nicholas & Steyn, 2012).

The level of detail of a schedule not only depends on the amount of information available and the stage in which a project is at, but it is also dependant on the intended audience. At managerial level, the interest is mainly on the performance and cost, as well as the integration of activities at a very low level of detail. The opposite happens with the staff in charge of the execution, which will want a highly detailed daily or a weekly schedule (Golparvar-Fard, Peña-Mora, Arboleda, & Lee, 2009). This is relevant in terms of the solution that will be proposed in this research, since the target audience is the execution staff, however, it is important to keep in mind the managers who must direct the aforementioned staff. Consequently, a balance of detail and complete information is required as well as considering a phased approach.

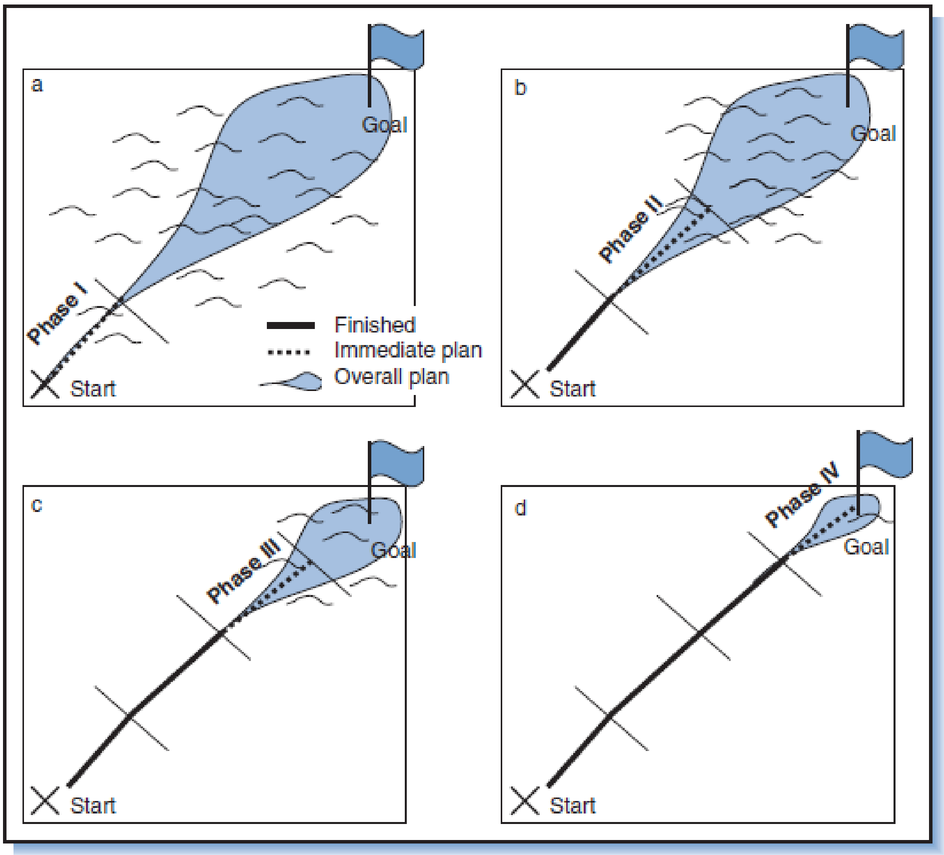


Figure 4. Phased Project Planning (Nicholas & Steyn, 2012)

2.1.1. Work Breakdown Structure and Work Packages

During the preparation of the planning, it is necessary to first identify and define the scope of the project to segment the works according to the most effective and efficient manner. It is ideal for a complex project to be broken down into several smaller subprojects. A complex project consists of major categories of work that consist of subcategories and these consist of components. This process is known as Work Breakdown Structure (WBS) (Nicholas & Steyn, 2012).

The project is subdivided by disciplines or by spatial distribution into manageable pieces of work called Work Packages so that these can be estimated, planned, assigned and controlled (Cooke & Williams, 2009). It is highly important to identify the spatial constraints and Interfaces between work packages to integrate the project and not create project islands that do not communicate with each other.

2.1.2. Hierarchy of Schedules

For the different targeted audiences there is a specific schedule that describes the information they consider relevant. This way each level of the project works with an aligned schedule that consists of the relevant pieces for each work package. At the highest level of the project, managers generally look at the Master Programme, which also functions as the baseline schedule. The level of detail for this schedule is normally one that summarizes activities and provides the milestones that will guide the construction managers and package engineers to develop a more detailed schedule at the second level at each work package as seen on Figure 5. For site execution, a higher level of detail is required on the schedule to guide the works on a daily or weekly basis to make the sequencing of activities clear. The process is a "top-down" oriented one, in which the work packages need to fulfil the milestones set by the Master Programme, as well as the schedule at the execution level which needs to satisfy the targets set by the work package level schedule. Nevertheless, it is necessary to maintain a "bottom-up" feedback to the general project planners, on the feasibility of the plans, since the staff in charge of the execution generally has more experience on the tasks to be performed (Mubarak, 2015).

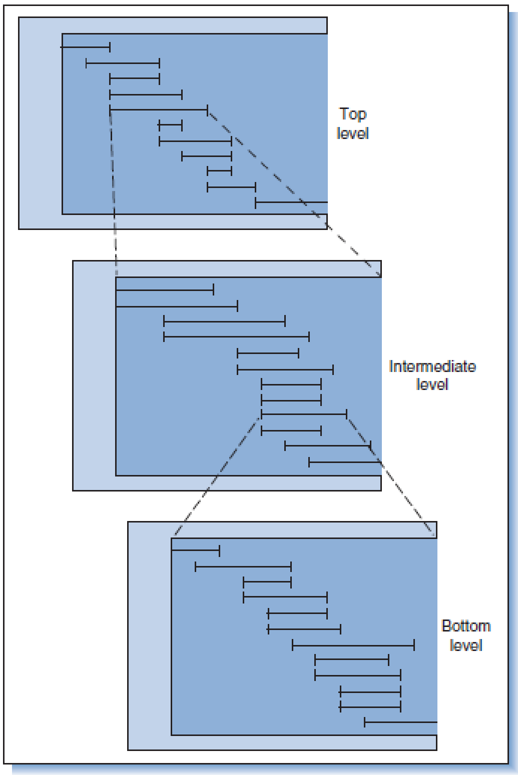


Figure 5. Hierarchy of planning (Nicholas & Steyn, 2012)

Traditionally scheduling is carried out in Gantt Charts and Time Location Charts which will be further detailed on the subsequent sections.

2.1.3. Two Week Look Ahead Plans

To transfer the information on the general planning as well as the requirements to be fulfilled to the site staff, engineers and planners formulate two and six week look aheads, which are a targeted statement of works to be carried out on said periods. These look ahead plans establish which works need to be completed to enable crews on site to have a clear understanding of what is expected from them. Two and six week look ahead plans are an extract of the general plan to in detail for site crews to focus on the specifics of the near future (Itodo, Pasquire, Dickens, & Glenn, 2016). This method is carried out to prevent from overwhelming the site execution with Gantt Charts of the whole project, as well as creating a statement of works to which the site staff commits to accomplishing. These look aheads may be a visual representation of the scope of works or may be a list of targeted elements to be completed for said period.

2.1.4. Gantt Charts

Gantt Charts are a graphic representation of project tasks and activities, shown in a time scaled bar lines with links between predecessor and successor activities. Gantt Charts can represent information in simple terms as activities or tasks with their starting end date as shown on Figure 6, however, it is common to load the activities with resources (manpower, machinery, equipment) as well as quantities, materials or even the cost of each task. Loading of activities aids in integrating different project information in a time-distributed tool which aids in visualizing the forecast of resources, production and cashflow of a project. From a loaded Gantt Chart, one may derive the S-Curves and represent the information on the forecasted performance of the project and its requirements in terms of resources. Gantt Charts are said to be the easiest tool to use for day to day communication in projects (Nordahl-Rolfsen & Merschbrock, 2016).

Gantt Charts are built up of the networks of activities and their relationships of precedence which may constitute hard logic links (a logical relationship in which one activity depends physically of another) and soft logic link (cannot perform both tasks at the same time due to a resource constraint and there is no physical constraint). Hard logic and soft logic define the relationships since the planning team must define which works can be performed and in which sequence based on the logic constraints (Mubarak, 2015). To define these constraints, it is convenient to use 2D or 3D drawings to establish the sequence of tasks and perform the Critical Path Method or the Line of Balance calculations.

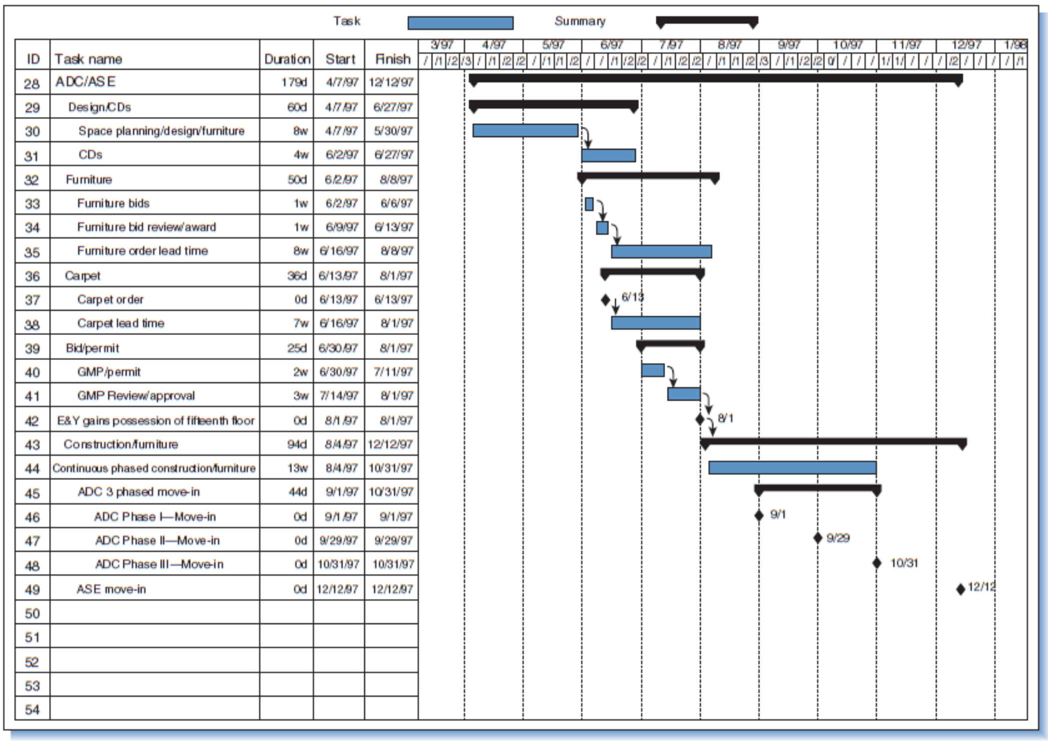


Figure 6. Sample Gantt Chart (Nicholas & Steyn, 2012)

With the aid of a Gantt Chart, it is possible to determine a Baseline, which is the reference as planned schedule with which the as-built (actual production on site) is compared in project controls to determine how the project is performing by using the Baseline as a benchmark. With the Baseline it is possible to determine if an activity is either delayed or if there are any deviations that require adjustments. It is also known as the Target Schedule. However, as stated in the problem description section, there are several issues with tracking of activities through the Gantt Chart approach:

- For mega projects as the amount of activities increase, the more complex it is to visualize the sequence, as well as the status of the project.
- When dealing with a situation in which some activities are delayed, others are completed, activities having an early start, it is difficult to visualize the real status of the project without the aid of further calculations. An example of this can be seen on Figure 7.

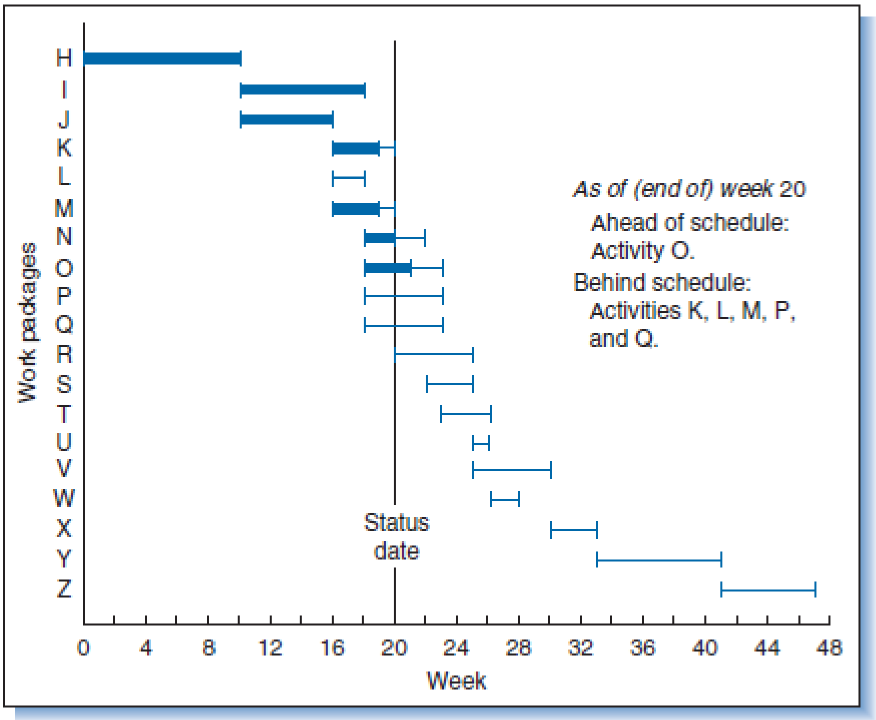


Figure 7. Progress tracking with Gantt Charts (Nicholas & Steyn, 2012)

Gantt Charts are very useful for visualizing the Critical Path and with the aid of software such as Primavera (P6), Microsoft Project, as well as other software options, it is possible to determine said path. Also, it is possible to track the progress on site and update the as built schedule with actual dates and compare these dates to the baseline schedule. Proposed solutions in this research must satisfy these currently satisfied aspects.

2.1.5. Time Location Charts

Time location charts combine the schedule with the physical component on a two axis chart (time on one axis and location on the other axis as seen on Figure 8. To generate a time location chart, one must segment the project into physically referenced portions. For example, for quantity intensive projects, such as roads, the time location graphs are segmented by linear meters. In other cases, it may be practical to use other sets of quantities or in cases where a parcel may be segmented, into areas. Having established the axis, one must plot the coordinates of time and location of the start and end dates of each set of activities joined together by a colour coded line. This can be carried out with software such as Tilos, for example. The slope of each line represents the rate of production. Time location charts are particularly useful mainly for quantity intensive projects (such as tunnels, roads, pipelaying and railways) since it is simple to visualize at which stage of the project what the teams should be performing and where. This may seem as the solution for the problem stated in the previous chapter. However, for project controls, this becomes confusing and overwhelming for the audience if one would plot the as built and the baseline plan since clarity is reduced moving away from the main purpose of making information easily understandable. Therefore, the present research investigates the possibilities of performing a time location evaluation with the aid of the 3D geometric model by adding the time component (4D).

Figure 8. Time Location Chart (Shah, 2015)

2.1.6. The Critical Path

The critical path is the longest sequence of activities in the network from start of the project until the end and therefore, define the duration of the project (Mubarak, 2015). These activities have zero float (the amount of time an activity can be delayed without delaying the succeeding activity), since any delay on the critical path represents a delay on the project. This is true if the project is on time. If the project is delayed, the project eventually has a negative float. Managers and engineers pay special attention to the activities that are critical, since these activities drive the project completion date. Therefore, identification and visualization of the critical path activities is a priority.

It is possible to have more than one critical path in a project as well as "near critical" paths that have a similar duration than the longest one. These near critical paths also need to be addressed and pay attention to the risks that may trigger and make them critical. All activities have an associated risk which may cause a delay and some activities have higher delay risks than other. To evaluate this, a Monte Carlo Simulation may be performed to determine which is the most probable critical path of all the paths and create a path ranking in which the activities are rated based on their probability of being critical (van Gusteren, 2011). Visualization of these critical and near critical path activities is key for this research.

The critical path is of great use for decision making in terms of maintaining the progress within the schedule, but also in terms of deciding on impacting a project to accelerate it or to catch up after a delay. Actions taken on the critical path towards accelerating a project will have a direct effect on the duration of the project and therefore, are the most effective way of tackling delays.

2.1.7. Delays and Claims

A delay is the condition in which the project or an activity finishes later than stipulated in the contract. Therefore, it is subject of disputes and claims in projects. The following are the types of delays:

- Excusable (stem from reasons beyond the contract work) due to either weather, natural disasters or even labour strikes and may entitle the contractor to an extension of time but are not monetarily compensable. Excusable delays may also be caused by the client or the designer and these are compensable delays both in terms of money and extensions of time, such as change orders or delays in delivering design details (Mubarak, 2015).
- Non excusable delays are those that do not entitle the contractor to an extension of time or a monetary compensation since these are deemed as delays that could have been anticipated by the contractor. Mubarak mentions examples such as slow mobilization, poor workmanship, negligence or lack of preparation which are not excusable.
- Concurrent delays are those in which a dual event occurs and there is a combination of excusable and non-excusable delays. An analysis must be carried out to determine how much of the impact on the schedule is due to a non-excusable delay and how much is due to an excusable delay.

To be able to justify a delay and therefore claim an extension of time or a monetary compensation, the contractor must make the time impact analysis on the baseline schedule since the baseline is the yardstick reference for measuring any variation. In order for an extension of time claim to be approved, the documentation needs to be traceable, regularly updated and correct (Mubarak, 2015). Even though understandably, there are variations and deviations from the baseline, these must stay within an acceptable range in which the sequence and logic of the baseline match that of the as built, for a dispute to be favourable. Therefore, in this research it is important to seek a way to maintain activities in sequence and on time.

The critical path is fundamental in delay claims since the contractor under the circumstance of a change order, if he wants to be granted an extension of time, needs to prove that the variation order impacts the critical path of the project.

2.2. Project Controls

The core of project controls is to monitor works and compare as built performance against baseline performance, to detect deviations and tackle these to bring the schedule back on track (Mubarak, 2015). Also, part of the tasks of project control teams are to identify areas where efficiency can be increased, the project can be accelerated and reduce the costs.

It is impossible to have zero deviations in a project, however, these need to be controlled and kept within a manoeuvrable range for corrective actions to be effective. Since deviations occur, schedules need to be updated to reflect the real situation on site, to keep on tracking precisely and to give more accurate forecasts. One of the most traditional control tools apart from Gantt Charts are S Curves.

2.2.1. S Curves

S Curves are a graphical representation of cumulative work progress against time as seen on Figure 9. Cumulative work may be expressed in units of work, man-hours, associated cost of the elements, percentage complete amongst others (Mubarak, 2015). As mentioned on the Gantt Charts section, S Curves are plotted by loading the schedule of activities with resources, materials and other aspects, and through these, a timely distribution of the accumulated planned progress is possible on the S Curve. The baseline reference units are plotted against time and the actual progress is periodically updated. The actual progress is also referenced as the Earned Value.

Typically works in projects begin slow (low performance and therefore almost a flat slope on S Curve), afterwards the volume of works normally increases which is seen with a steeper slope (higher performance) and finally at the end of the project, progress has a more moderate slope until it reaches completion. The actual progress is compared to the planned progress up to the data date which is the evaluation date to which progress has been reported. The progress between the data date until the completion date is a forecast based on the adjusted planning and the historical performance rates. It is highly important to capture what is on the "left side" of the data date (past performance) but equally important it is what is on the "right side" of the data date since the forecast needs to display a feasible planned performance.

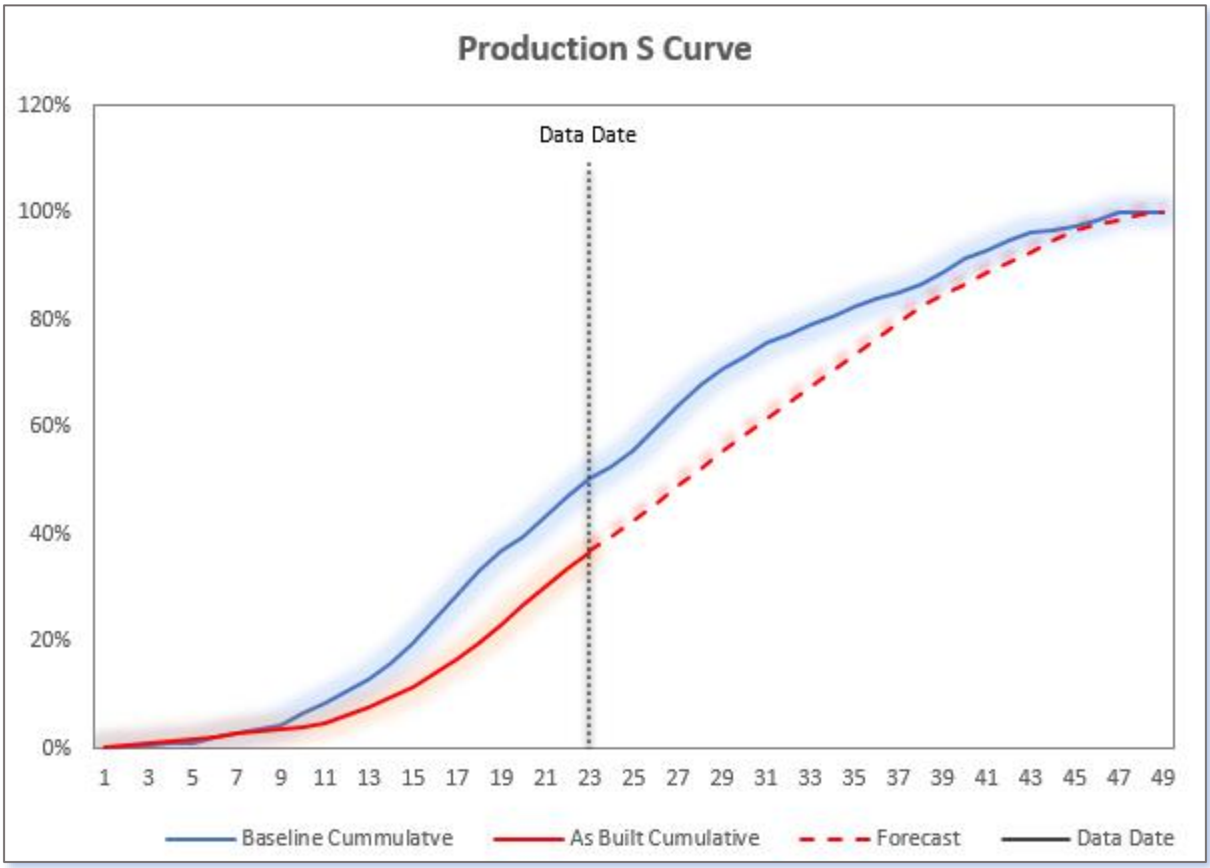


Figure 9. S Curve

S-Curves are a very good tool for upper management to see if the performance of the project is up to par or not. Visually it is very simple, either the project is performing or not. However, a construction project is a multidimensional body which is more than just simply the progress completed. Only looking at the comparison between baseline and as built progress may be in fact misleading since it does not say anything about the critical path items and its status or sequence, it does not represent anything about the interfaces and how these will be dealt with, it does not state anything about the associated elements that are on the pending list of items to be completed. Therefore, visualization needs to be aided with an object based approach and use of 3D geometric models.

2.3. Construction Performance

2.3.1. Key Performance Indicators

A key performance indicator (KPI) is a numerical value calculated to evaluate the performance of a given task. These are then contrasted to set parameters or boundary conditions to identify the level to which the KPI meets the required targets. These may be multidimensional and summarize the different sources of information into one sole value. In other words, it is a simplification analysis.

2.3.2. Earned Value Analysis and Schedule Performance Index

Earned Value Analysis (EVA) is defined as "the performance measurement to report the status of a project in terms of both cost and time at a given data date" (Popescu & Charoenngam, 1995). Through the Earned Value Analysis, one must determine how much work has been completed as well as how much should have been done according to plan, then determine how much money has been earned (from the work completed) and finally, how much has been spent. Afterwards, one must calculate the money and time deviations with the corresponding possible adjustments and then extrapolate these deviated and adjusted forecast until the end of the project (Mubarak, 2015). As seen on Figure 9, then one can estimate the schedule variance to calculate a delay as well as the cost variance. It is important to perform an EVA on a separate manner for the different work packages in a project to be able to pin point the lagging and leading teams and make the necessary adjustments. However, an aggregate EVA for the whole project is also required, since the former approach encourages a project islands and not a holistic approach.

Schedule Performance Index (SPI) is derived from the Earned Value Analysis and it is the proportion of the Budgeted Cost of Work Performed with regards to the Budgeted Cost for Work Scheduled.

$$SPI = \frac{Performed\ Progress}{Scheduled\ Progress}$$

This is a specific measuring method that will be used to compare how works were carried out prior and during the implementation in the "Before and After" analysis. In this research the costs will not be addressed, but the focus will be on progress completed in terms of percentage completed as a function of the quantities in the bill of quantities. However, a brief reference is made to the CPI which is the Cost Performance Index which compares the Budgeted Cost of Work Performed with the Actual Cost for Work Performed. This would represent an extension to the research (for further research) which is not under the relevance of this particular document. An example of the joint analysis that can be done with the SPI and CPI is seen on Figure 10.

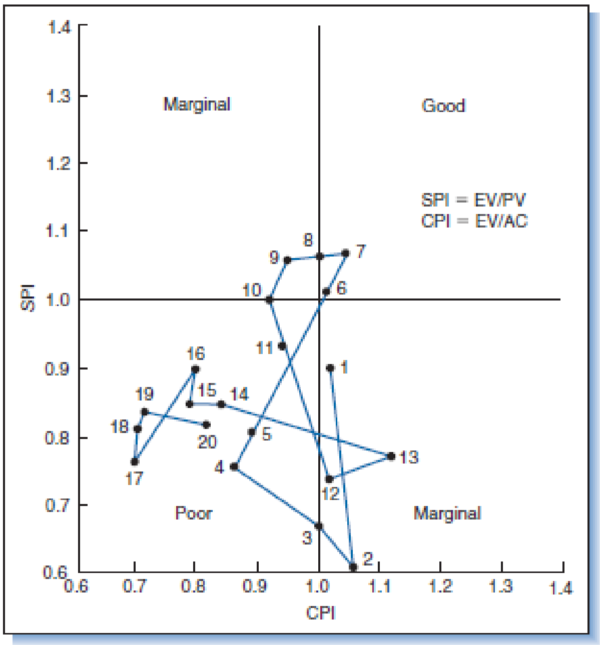


Figure 10. Schedule Performance versus Budget Performance (Nicholas & Steyn, 2012)

When dealing with a Budget driven EVA, rather than progress driven EVA (quantity or percentage completed), the schedule variance will differ from the schedule deviations seen though the CPM, since money is not the basis of CPM, and therefore these can yield contradicting results.

2.4. Building Information Modelling (BIM)

Traditional practice is characterized by 2D drawings in isolated files that require a great deal of effort in updating and revising all the systems' interdependencies (architecture, structural, mechanical) in a scattered manner with the aim of preventing clashes and inconsistencies under a handover of information approach. With the aid of technology, the construction industry has been shifting to a 3D unified approach with Building Information Modelling (BIM) as seen on Figure 11. BIM is the virtual construction of a structure built up of intelligent objects in a single source file to integrate the efforts of project team members, by increasing the amount of communication and collaboration (Hardin, 2009). With this approach, the construction practice is shifting from manipulating lines on 2D drawings to operating 3D objects with properties and combining the different systems in one sole model. However, solely using a 3D Model isn't a BIM approach, since BIM is all about implementing an integrated and centralized communication concept, where information flows in a more efficient way and all the parts in the process are aligned. This integration extends to the site operations and the planning of the activities. The BIM approach is ideal to address interfaces at organizational level as well as physical on site level since the goal is to prevent "project islands" from being created. This approach reduces the errors in design coordination, decreases detailing costs and requires for less engineering (Eadie, Browne, Odeyinka, McKeown, & McNiff, 2013).

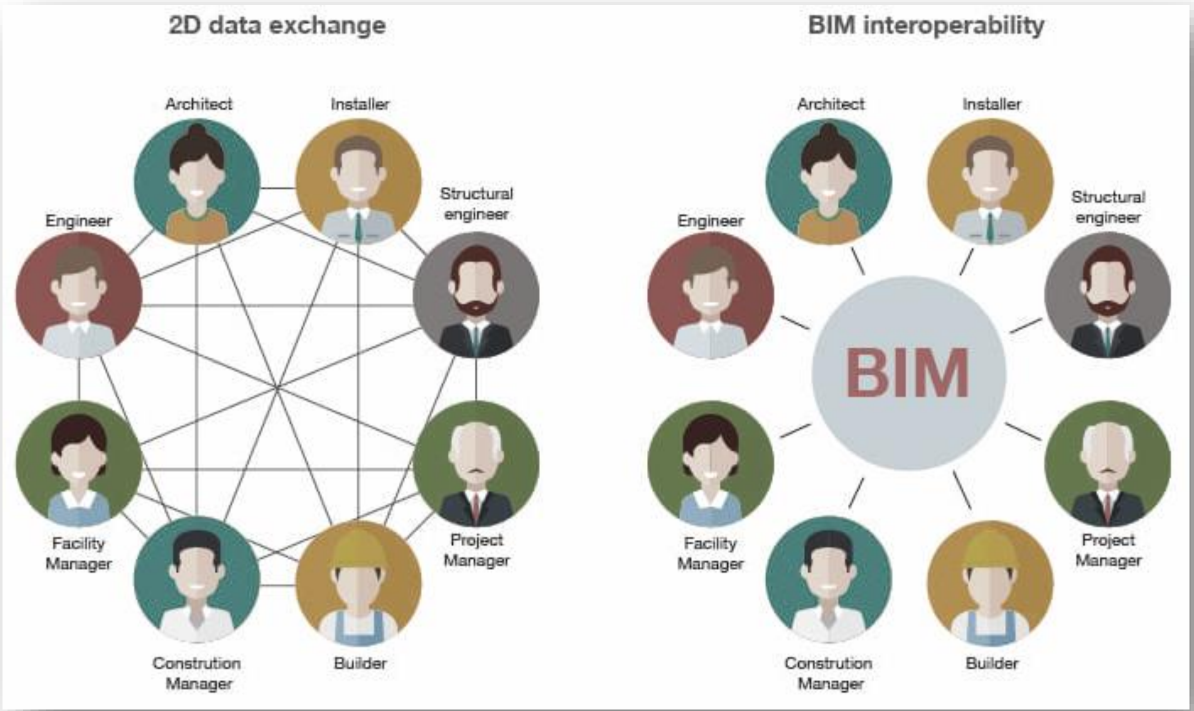


Figure 11. Traditional Data Exchange and BIM Interoperability (Saldutti, 2017)

2.4.1. 4D BIM

Traditionally construction planners have been producing sequence drawings manually to show the progression of works. However, this process requires a great deal of manual labour which is highly inefficient as well as the fact that visualization of items on paper is not optimal and spatial constraints are not represented. By linking the objects in a 3D model with the activities from the schedule (time=the fourth dimension), one can obtain a 4D model which aids in visualizing the sequence of activities and the spatial distribution of a project in a more intuitive manner (Nordahl-Rolfsen & Merschbrock, 2016).

4D Computer Aided Drawings (CAD) refer to 3D models that also contain time associations to allow schedulers to visually plan and communicate activities in space. 4D CAD tools allow the contractor to simulate the planned construction sequence (as seen on Figure 12) and evaluate hard clashes (objects occupy the same space) and soft clashes (insufficient space in between the two objects for access) (Eastman, Teichol, Sacks, & Liston, 2011).

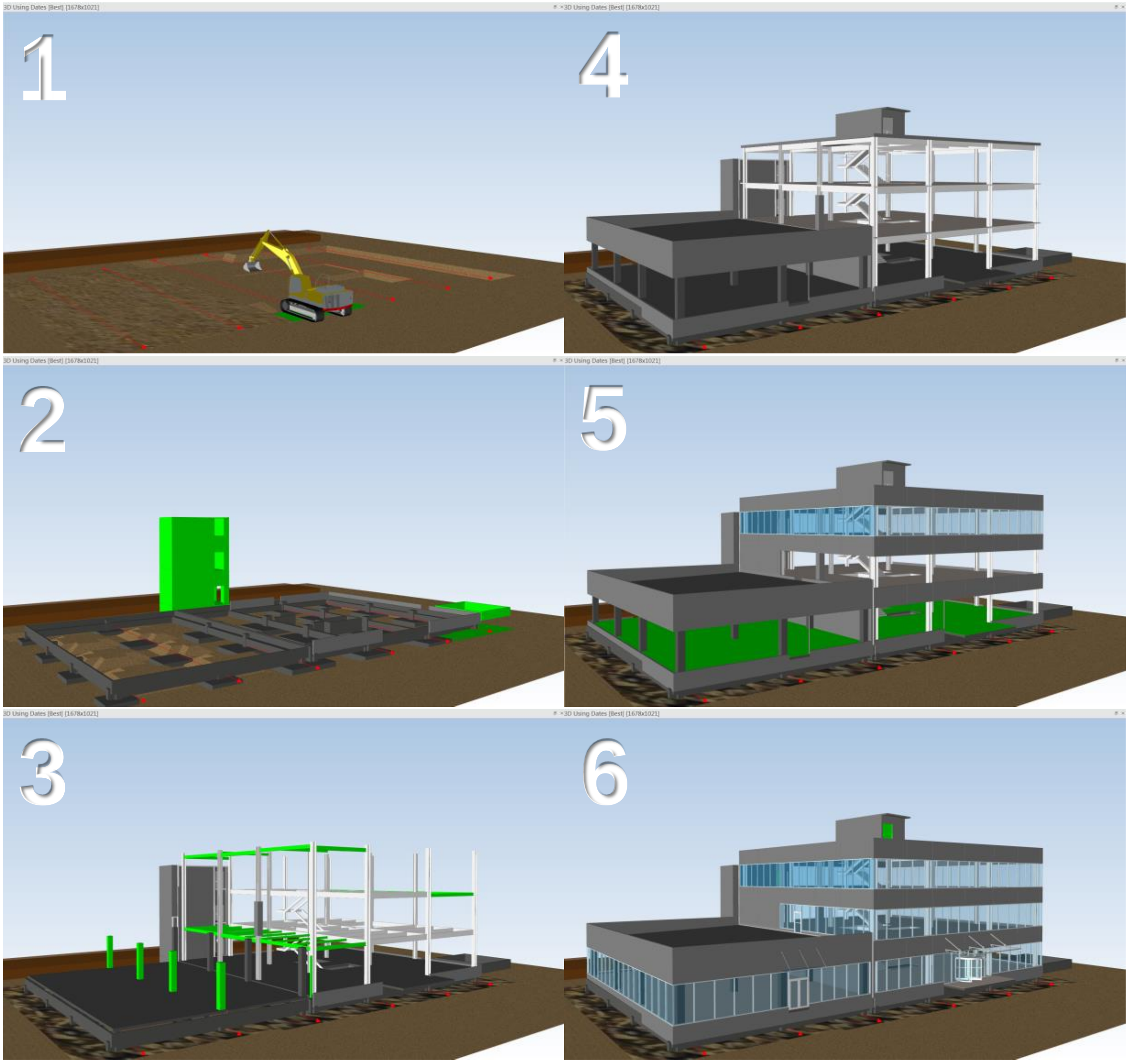


Figure 12. 4D Construction Sequencing in Synchro PRO

However, there is a distinction between 4D planning and 4D BIM. If the 3D model does not contain parametric components or relations between them, then the model is limited to clash detection, and visualization (Eastman, Teichol, Sacks, & Liston, 2011) and is deemed as 4D planning. 4D BIM tools incorporate activity sequencing, spatial and resource utilization, productivity rates in a more efficient manner since the model is synchronized with the design, the schedule and the rest of the departments of the contractor. The difference in short, is the integration between the 4D model and the entirety of the project departments. This integration leads to more reliable schedules, since the model is being synchronized with the up to date information of the project and it is possible to increase the feasibility and efficiency of the plan.

2.4.2. BIM Maturity

BIM has been categorized into three levels of maturity based on the degree of integration and collaboration that are employed. Level 0 corresponds to two dimensional drawings in which the exchange of information is carried out on paper with drawings and specifications. However, this is not considered a level of maturity in BIM, hence the number 0. Level 1 BIM refers to object based models in two dimensions or three dimensions. For this level, the financial and commercial data management are not integrated to the model. Level 2 BIM is the category in which model based collaboration is carried out on separate BIM tools with the corresponding data. This includes the 4D construction sequencing and 5D cost and resource information. Level 3 BIM is a fully integrated and collaborative process enabled by web services in which the models are integrated with each other (Ozorhon & Karahan, 2017). This is important to understand the level of integration and characterise the case study. Also, it determines the possibilities in the research. The level of integration has a direct effect on the efficiency levels of the processes in construction. Another important aspect for the case study is the level of development or detail of the model.

2.4.3. Level of Development (LOD)

Similar to the BIM Maturity, a model is also evaluated in terms of its Level of Development (LOD), which specifies the degree of information that the model must contain according to the stage of the project in which the model is being used (Boton, Kubicki, & Halin, 2015). For 4D Models, the specification of the LOD refers to both the graphical and the time component of information. In the project lifecycle, as mentioned earlier in this document, the knowledge on the project increases as time progresses. Therefore, similar to the knowledge acquisition process, the LOD is expected to increase as the project progresses since the LOD obeys to the amount of information on the project.

There are five levels of development ranging from 100 to 500. The first level (LOD 100) refers to a generic representation of the building in which the analysis is conducted at conception stage of the project based on cost per square meter as well as building orientation. The second level (LOD 200) corresponds to a more elaborate development of the model than LOD 100 since it includes approximate shape and size, as well as quantities. When the project has been defined more thoroughly, and the model can be used to generate construction documents, it is said to have a third level of development (LOD 300). However, contractors and manufacturers require a higher level of detail than that given by the engineer in charge of the design, and therefore, an LOD 400 is achieved by increasing the details of manufacture and assembly. The literature recommends an intermediate level of development (LOD 350) which has the sufficient amount of information to support interface coordination (Boton, Kubicki, & Halin, 2015). The fifth level (LOD 500) refers to the as built model of the project which is required for operation. This is not relevant to the present research since the specific detailed location of certain elements does not influence the overall performance of a project. It is highly important to understand the level of development of a model since this parameter explains during the project lifecycle, how accurate one can be with the estimates given the level of information at each stage. Also, it is important to evaluate the case study in terms of this parameter to be able to characterize the model being used and replicate the research, also, the overall inputs can be evaluated given these pieces of information. A high LOD enables for detailed visualization and interface coordination, which are part of the factors that affect the productivity (Boton, Kubicki, & Halin, 2015). During construction, the LOD also refers to the resources that are included in the model, which also gives a better visualization of spatial coordination.

On the initial phases of the project (with a low LOD due to the lack of definition of the project), the 4D model is used for preconstruction analysis and constructability reviews. The analysis is based on cost per area. However, for detailed day to day coordination, it is logical that a higher LOD is required to be able to carry out interface coordination and clash detection. This is particularly important for this research, since the progress on site is compared to the baseline plans. Therefore, in the analysis the level of development has a special role since the LOD also refers to the time component (schedule), in theory as the LOD is higher, the plans should be more detailed as well, stating clear instructions both on the schedule and the object based model, which is the planned sequence of works.

The LOD selection is dependant of the knowledge level of the project, however, it is also highly dependent on the complexity of the works to be carried out. For highly complex operations which either have a congested array of elements, or that it requires for interface coordination, as well as precision works which require special coordination, it would be necessary to increase the level of development to spot the specifics and enable the adequate visualization of the process. It is a common practice in the industry to utilize a level of development between LOD 300 and LOD 400, and the spectrum of works spans from the less complicated works on the LOD 300 edge to the complex works on the opposite limit of LOD 400 (Boton, Kubicki, & Halin, 2015). This strategy is put in practice to prevent from wasting effort on elements that do not require further development.

When dealing with interface coordination, it is important to understand the hard logic stated in the planning section and this can only be spotted with a precise level of development (LOD 350-LOD 400) in the model, to state which object is the priority in the sequence. A common strategy in 4D Planning is to solve interfaces by looking at the hard and soft logic, however, another strategy for concurrent activities that are synchronized, is to desynchronize the tasks to enable the process favouring that activity that has a hard logic priority based on its level of criticality (Boton, Kubicki, & Halin, 2015).

2.4.4. Aspects that influence the Quality of the Model

The quality of the model depends on the fitness for purpose in terms of the scope, the level of detail, the temporary components it includes as well as the decomposition and aggregation of it that make it both accurate and efficient for manipulation. These characteristics are further detailed on the paragraphs below.

- Scope: When dealing with a 3D model that has been created by the client with the aid of the engineer, it is most likely that the model is intended at a different audience (potential clients) since the goals that the contractor has with the model are different than the client. The client will prefer a summarized model that is visually appealing, and the contractor will focus on constructability aspects and how he can segment into an efficient sequence. The way a designer organizes a model is not detailed enough to enable relating objects to activities. Therefore, contractors tend to initiate a new model that is suitable for construction purposes.
- Level of detail: The level of detail depends on the target audience and the period of that is required to be represented in the model (Golparvar-Fard, Peña-Mora, Arboleda, & Lee, 2009). For management, it is preferred to summarize information as much as possible since it is intended as a status overview of the project and for site management crews it is preferable to increase the level of detail since the model is targeted as an instructional video. Another aspect that influences the level of detail is the size of the project, since for mega projects it is already a challenging task to tackle the model, then the teams tend to adjust to the situation

and understand that it is not worthwhile spending too much time in some details because the model has to be light enough for the users to collaborate in the whole project. Another aspect that influences the level of detail is change management. The higher the level of detail, the more time consuming it is to adjust the model, therefore, flexibility towards change is necessary. Therefore, teams need to reach a suitable level of detail that is efficient in the event of changes.

- Temporary Components: The model is required to be an accurate representation of reality in which relevant aspects need to be portrayed in the model. Therefore, temporary components such as formwork, machinery, scaffolding and excavations amongst others, need to be included. Otherwise, the model is flawed because it does not represent the spatial distribution of works accurately and it does not aid in depicting interfaces and constructability issues. In terms of animation, in certain complex tasks it is important to be able to simulate specific movements of machinery and plan the spatial distribution of the operation.
- Decomposition and Aggregation: When manipulating the model, it is necessary to segment and aggregate in an efficient manner according to the condition that is going to occur on site. Therefore, it is necessary to have early involvement of experts of each work package when creating the model to have a smart decomposition from the beginning. Also, it is important to have a work package separation which is checked constantly for clash detection with other work packages. By separating the model into work packages, users then need to merge multiple files into a single model and update portions of the model and the data can be reorganized to fit the model.

2.4.5. Visualization of Construction Progress with 4D: The state of the art in 4D BIM

The steps taken in the industry in 4D BIM have started from preconstruction constructability analysis on the 4D Model and have advanced to various applications still in development, such as the visualization of construction progress as seen on Figure 13. The initial steps in visualizing progress have been on depicting the current status of elements to translate the site progress into a model representation in 4D.

Research has been carried out in the line of visualizing the progress of a project through 4D Models such as in the research performed in "Visualising the status of building elements in construction projects" (van Breukelen, 2016) as well as other research such as "Visualization of Construction Progress Monitoring With 4D Simulation Model Overlaid On Time-Lapsed Photographs" (Golparvar-Fard, Peña-Mora, Arboleda, & Lee, 2009). The former addresses the manner in which the status of elements is represented and the ways in which information flows in the organization. The latter proposes a time lapsed picture approach in which a colour coded model (according to the status of elements) is superposed on top of up to date imagery on site. Both researchers address the status of the previously constructed elements on site. The strategies to represent progress are different to those in traditional project controls since the S Curves and Gantt charts make use of the axis to represent the time scale for both, and also quantities in the case of the former. Given the lack of scaled axis in the 4D Model, it is highly important to make use of visual aids such as colour coding of elements (to visualize information as criticality of activity, past performance according to key performance indicators), yet is important to represent the right amount of information and not overwhelm the targeted audience. Some of the limitations in the 4D approach are that one cannot visualize certain key information such as a schedule overview, activity duration and the relationship between activities. As stated in previous research, unless these limitations are overcome, the 4D Model cannot be a substitute of the conventional methods (Benjaoran & Bhokha, 2009).

Visualizing the status of completed elements is enabled through colour coded approach. However, according to research, in practice it is more complicated because when dealing with high LODs, objects have different layers and different stages of construction (Benjaoran & Bhokha, 2009). For example, in the case of a cast in situ wall, the process includes activities in the rough works such as rebar placement, formwork placing, concrete casting and formwork stripping. Added to this, in the final stages, that wall requires in several cases finishing works such as plastering and painting. Therefore, it is important to define the standard in which progress will be recorded as completed since it may be misleading to observe an element as complete at an initial stage when the wall is casted and afterwards as ongoing during the finishing works. The same challenge applies for the works that need to be carried out in layers such as the structure of pavement and backfilling works. This poses a challenge to the present research and requires recommendations based on the implementation process and the interviews conducted.

2.4.6. Visualization of As Built Performance Compared to Baseline Performance: The State of the Art in 4D BIM

The development of BIM as seen on Figure 13, coming from the conception of BIM during the decade of the 1970 has been implemented in the design phase, passing through the development of 4D BIM for preconstruction, and following the developments of visualizing the on-site status of elements with the aid of 4D on the execution phase, the next step in research has been on comparing the as built performance with the baseline performance. The present research digs into the area of controlling progress by replicating the as built versus baseline comparison as the project controls do through the S Curve, but bridging the visualization gaps from the conventional methods, through a 4D Model comparison. In the latest investigations on this topic researchers have focused on two approaches relevant to this document, one is to compare the baseline progress against the as built progress without overlapping the models and the other trend consists in automating the data gathering of progress in projects by overlapping site imagery with the 4D Model.

Recent research conducted by Golparvar-Fard and Peña-Mora has focused on overlapping the as built 4D Model with the baseline to compare progress carried out prior to the data date. However, the research carried out has focused on portraying the actual on-site status, through an automated imagery system. The emphasis has been on the quality of the imagery and recognition of construction materials, occlusion (objects that are not collected due to them being out of focus from the pictures taken on site or due to an obstruction) and how this process can be automated either in an aerial approach, or a ground level approach. The research is focused on monitoring the progress prior to the data date. There is a gap in the research as to propose solutions to the performance control from the data date until project completion. Also, there is a gap in terms of the execution point of view since the deviations between the baseline plans and the as built are not being addressed in terms of performance control and decision making, but only on data gathering with cameras.

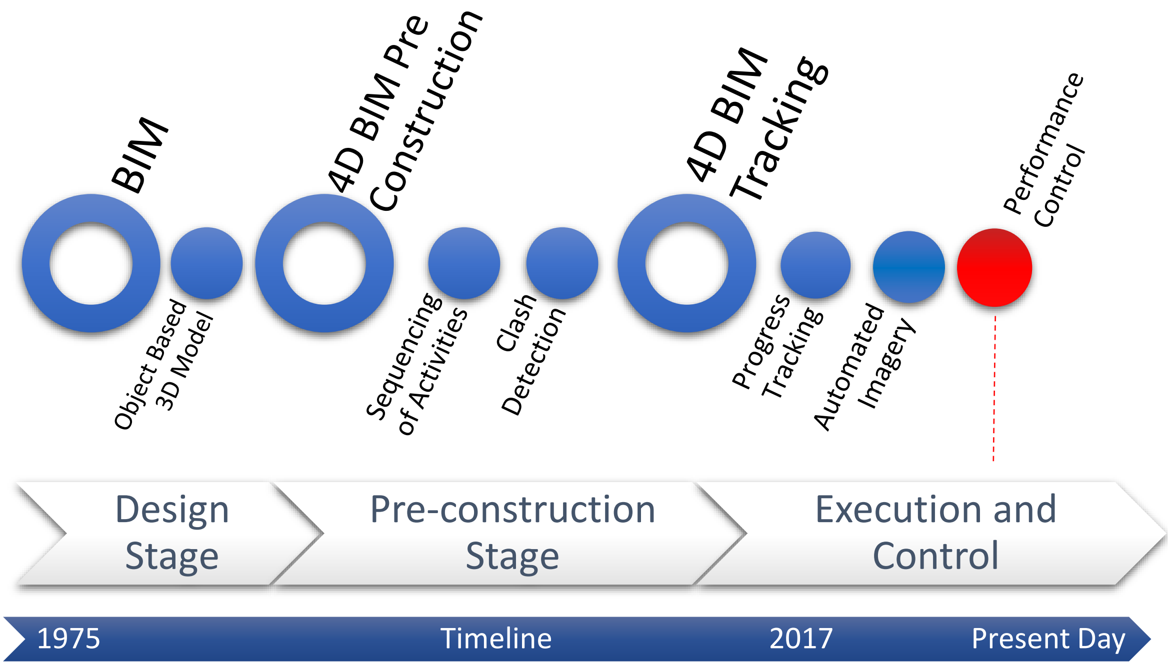


Figure 13. BIM Timeline and State of the Art in 4D BIM

The current practice in projects worldwide reflects a low adoption of 4D BIM during the execution phase (Mahalingam, Kashyap, & Mahajan, 2010). However, those projects that have introduced 4D BIM during execution phase, compare the baseline progress against the as built progress in a side-by-side approach and not in and overlapped manner. This means that the 4D model comparison is carried out without a clear benchmark in each model. This practice is similar as if the S Curve analysis would be carried out with the baseline and the as built curve on separate graphs as seen on Figure 14. It would not give a clear indication as to how the project is performing since it is difficult to spot the differences in performance. Therefore, it would be ideal to overlap the baseline model with the as built model in the present research as it is done on the S Curves to be able to pin point easily in which objects the project is lagging or it is ahead.

However, there are several aspects that need to be addressed since the goal is not to overwhelm the audience with numerous elements that distort the visualization (Song, Pollalis, & Peña-Mora, 2005). Therefore, if the two models are overlapped, these need to be simplified with the essential aspects, to make the information clear and understandable. Moreover, overlapping models may be counterproductive if the project has activities out of sequence and it is ahead of the baseline plan but also lagging in other planned activities. The latter is since those activities that are falling behind the schedule will appear as pending, yet those activities ahead of schedule in an out of sequence manner will not be accounted for as progress ahead of schedule. As a result, the project may be ahead of schedule but may appear as delayed.

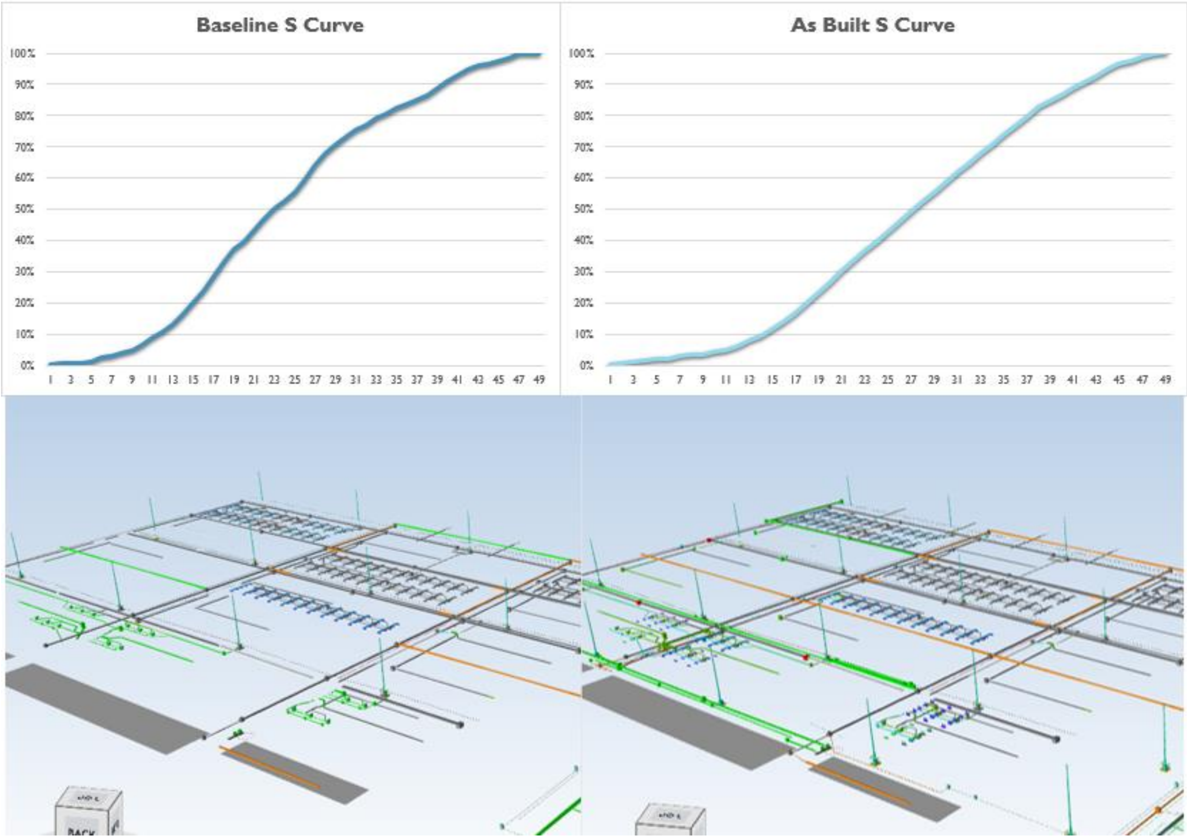


Figure 14. Need for Benchmarking and Overlapping

Through 4D Models it has been possible to bridge the gap of the visualization of the performance of a project. However, this has solved only what is on the "left side" of the data date by comparing the baseline to the as built. The gap of knowledge in research is to tackle what is ahead in the future on the "right side" of the data date. Previous research does not refer to the visualization of the forecast or adjusted plan for schedule deviations for the remainder of the project. The present research builds upon previous research and proposes a performance evaluation of the elements built by comparing the baseline with the as built plan, and also takes the next step in research on this topic by tackling the way in which the remainder of the project will be sequenced and executed by coordinating the interfaces and work spaces in response to deviations in the schedule. Chapter 4 will elaborate on the proposed model guidelines for deviation signalling and tackling the problem of remainder of works.

2.4.7. On site use of BIM

Planning alone does not ensure the success of the project. On site verification needs to detect deviations and report them in a clear and timely manner. However, the industry currently has reprocesses that lead to redundant efforts of manual data entering which is a form of waste (Bosché, Guillemet, Turkan, Haas, & Haas, 2014). This may become an information overload of mismatching information if the planning and the site execution are not synchronized. The integration effort needs to be aligned with the site coordination to enable the process to be successful, therefore, the files and formats need to be compatible.

Through BIM integration it is possible to extract relevant information such as shop drawings for on-site execution but also for tracking purposes. This way, the information can be updated on site periodically by the site teams and it can be readily available on a compatible format that can be uploaded by the planning team that enables to update their models and generate other relevant information. Therefore, reporting of progress on site can be done in such a way that reduces the uncertainty as to which object is referred to on the daily reports and progress tracking tools since it is linked to the object in the first place and both the teams on site and the planning team are clear on which element is being referred to.

As a result of this alignment of technology, files and formats, other capabilities are available for the teams since information from models can be extracted to allow for machine guidance technologies that can be uploaded to machinery on site and allow for reference points to be available for crews with GPS technologies as well as laser scanning technologies. However, these capabilities are not inside the scope of this research but are benefits that contractors need to see in this integration through BIM.

2.4.8. Workspace Planning with 4D and Interface Coordination

Performance and productivity are highly dependent on spatial coordination. Inappropriate planning of workspaces between parties in a project results in interference and inefficiencies which lead to a loss of productivity (Kaming, 1998). These inefficiencies have been quantified to produce up to a 30% loss of productivity (Mallasi, 2006). This situation aggravates with new business models that have emerged in which the companies reduce the space buffers (Kassem, Dawood, & Chavada, 2015). Therefore, it is necessary to incorporate in the conceptual model the spatial coordination of interfaces in the sequence of activities on a forward look.

Currently the industry makes use of time location graphs which do not provide insight of the spatial configuration. Another traditional practice are sequence drawings on paper which are highly inefficient due to the dynamic nature of the construction industry that calls for constant adjustments in the planning. In the case of Gantt Charts, these have been considered as a to do list that does not offer a visual explanation of how the activities are to be carried out nor do they represent aspects of physical space coordination between parties in a project. Other current practices involve LEAN principles that tackle this spatial coordination in a two axis (time-contracting party) grid. However, this method does not offer a preview of the spatial distribution and only allows for one contracting party in each workspace simultaneously (Itodo, Pasquire, Dickens, & Glenn, 2016).

Given the 3D geometric model, it is possible to bridge the visualization gap of traditional methods of workspace clash detection (Mallasi, 2006). Previous research has proposed the insertion of a rectangular boundary volume that encloses the workspace required for each element. One may visualize the workspace clashes by introducing these volumes in the 4D Model and observing the intersection of these over time as seen on Figure 15 (Kassem, Dawood, & Chavada, 2015). The use of these intersecting volumes is quite useful for the present research, however, the aforementioned research focuses on automating the clash coordination and giving a preferred sequence by introducing conservative volumes without any specific criteria related to the actual situation on site and the resources required. The present research must include these volumes and build upon them by tailor making these to adapt to the needs of the case study with the aid of expert knowledge on the site.

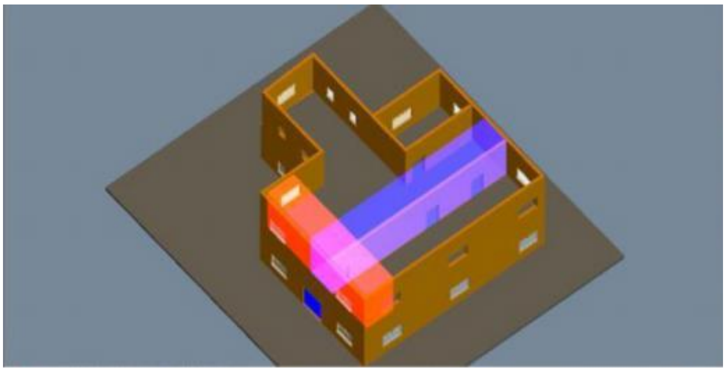


Figure 15. Visualisation of congestion levels using colour coding. (Kassem, Dawood, & Chavada, 2015)

2.4.9. Benefits of 4D Capabilities

As stated previously, the goal is to improve communication by capturing both the spatial and temporal aspects of a schedule in the model and communicate more effectively than Gantt Charts. As a result, multiple stakeholders have a better understanding of the project and can express their concerns in a timely manner, not when the process is already ongoing, which could cause a delay (Candelario-Garrido, García-Sanz-Calcedo, & Reyes, 2017).

Site logistics and interface coordination are improved since one can coordinate the space usage when dealing with trades as well as when works are required in small spaces. Moreover, stakeholders may foresee clashes and then coordinate the method of works to tackle this interdependency. Equally important for the purpose of this research is the fact that it is highly important that project teams can compare construction progress against the baseline and visualize where it is on track or behind schedule. Also, 4D planning is particularly useful for evaluating alternative sequencing and apply value engineering.

In traditional practice, objects and activities are not linked one another. Therefore, the process is manually intensive which lags with the design since it is not synchronized and hence, error prone. Additionally, through BIM tools it is also possible to extract updated quantities of objects, areas, volumes and materials.

The synchronization of information is highly valuable to the components matched one another, therefore, when the schedule is updated, the 4D model is updated through the auto-match function. Also, detailed building information, temporary components, specification information associated with each building component, analysis data related to performance levels and project requirements design and construction status are compatible one another and these functions can be exploited to reduce redundancy of manual works, as it happens in the traditional practice.

2.4.10. Drawbacks of 4D BIM

Even though 4D BIM has plenty of capabilities, it is important to state some of the drawbacks of the state of the art 4D BIM presented on previous research such as the lack of visualization of the schedule overview, activity duration and relationship as well as progress tracking which is part of the topic of this research.

The 4D Model is presented in a movie format which gives a picture of the current status of the project at each point in time whilst the movie plays continuously. However, it does not provide a clear overview of the project as Gantt Charts since one may view the whole array of activities to the left and to the right of the data date. In 4D models one must watch the entire movie to visualize the status at each point in time (Benjaoran & Bhokha, 2009). Therefore, the audience looking at a 4D model cannot get a glimpse of the forward and backwards look. The 4D model has been used to visualize the sequence of works and not as a schedule overview tool.

Since the 4D model does not have a time scaled axis and it does not provide information in a table array as Gantt Charts do, it is not possible to visualize activity duration and the activity relationship. Activity durations are fundamental in the process for execution since the crews on site need to know how long their works should take and assess the feasibility of it. Activity relationships are also of high importance to visualize for sequencing purposes to understand if it is a Start to Start, Finish to Start, Start to Finish or Finish to Finish relationship (Benjaoran & Bhokha, 2009). Since these two aspects are not yet visualized in 4D models, Gantt Charts cannot be replaced, but complemented with further visualization tools.

With the increase of capabilities for visualization, a 4D model faces the risk of over representing information and overwhelming the audience. One of the challenges in the implementation process in this research are that the model provides sufficient information that enables a better understanding of the sequence, as well as to promote critical evaluation of the progress carried out prior to the data date.

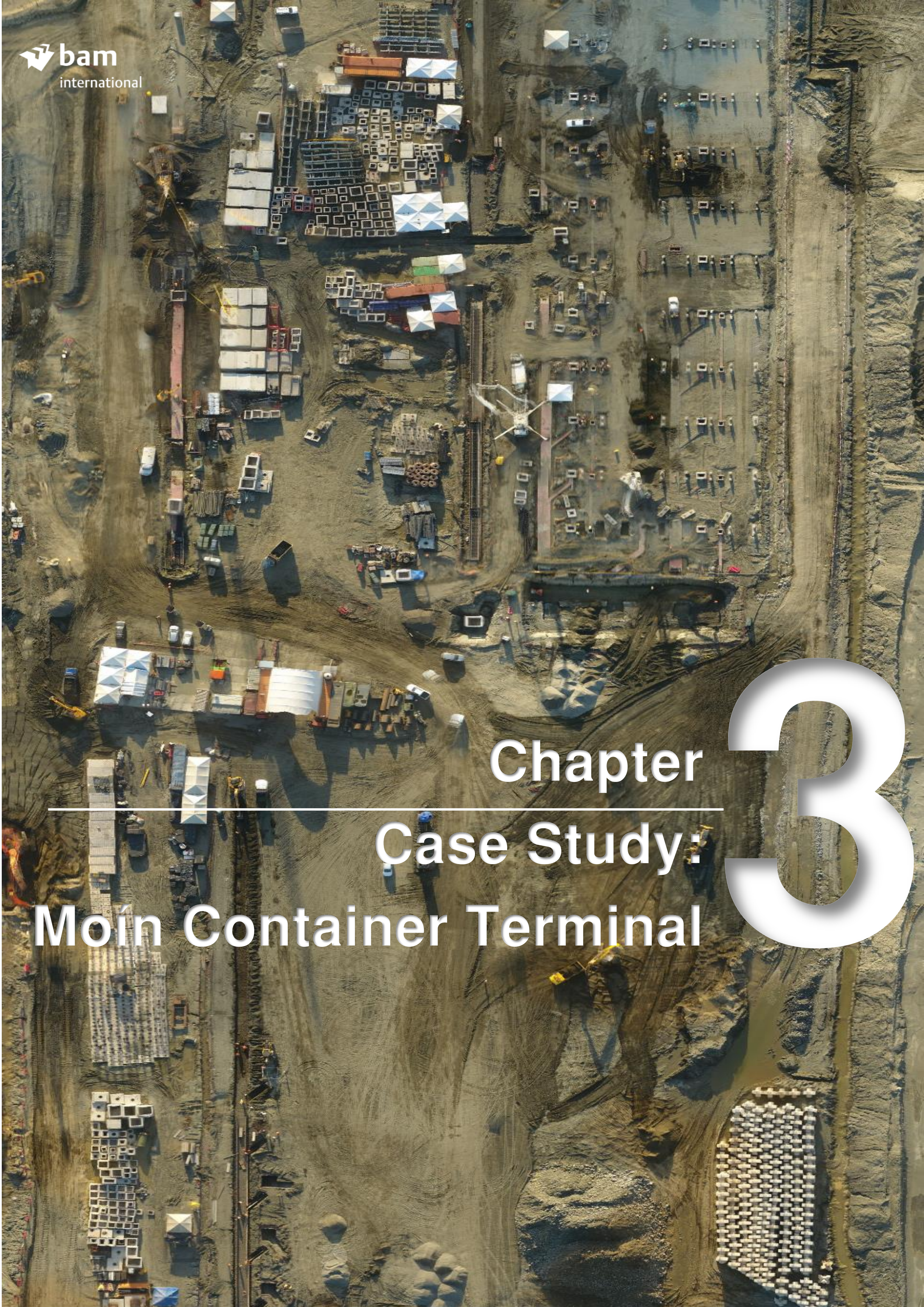
The current chapter offers a wide array of shortcomings of traditional tools and practices, as well as limitations in current uses of 4D BIM. The greatest weakness of 4D BIM is the lack of implementation during the site execution and therefore, a lack of knowledge as to what it can be applied for. To bridge this gap of knowledge, a case study is carried out on an intervention on the Moín Container Terminal project, in which 4D BIM is taken out to the field in a pilot attempt.

2.4.11. Conclusions on the Theory

The present chapter offered a glimpse into current project planning and control tools and trends to lay the foundations for the proposed solutions by looking at what has been done traditionally in the industry and where it is going in the future. With this information it is possible to answer the sub research question:

"What is the current common practice of controlling progress in projects and what are the possible alternatives in 4D BIM?"

The construction industry has been oriented traditionally towards a set of tools that are based on measurable numerical values, such as S Curves, Gantt Charts, Time Location Charts and Key Performance Indicators such as Schedule Performance Index and Cost Performance Index, which enable decision makers to quickly understand the general performance status of a project and easily calculate parameters (performance, delays, deviations, completion dates and others). However, these tools are a collection of clustered information that in many cases are not explicit nor fully representative of a project, since projects are multidimensional bodies that require a deep understanding in order to make an educated decision. The main drawbacks of traditional control tools are the lack of visual representation of physical elements which the industry has attempted to bridge through Building Information Modelling and 4D Models. However, 4D Models fail to provide a numerical value representation. Therefore, through 4D Capabilities it is possible to complement the current traditional tools through workspace and interface visualization, as well as pin pointing where the deviations are present and obtain numerical values from current graphical representations. 4D models and the implementation of these techniques are still undeveloped, which is evident since the industry has seldom applied 4D BIM during the execution phase and it has remained as a preconstruction tool for planning and clash detection.



Chapter 3

Case Study: Moín Container Terminal

3. Case Study: Moín Container Terminal, Costa Rica

3.1. Case Description: The Project

The client of the project is the container terminal operating company APM Terminals. The design and inspection of the project is carried out by former English company CH2M Hill, now Jacobs (American). The project has been set up as a Design Bid Build Contract, or in other words, a traditional contract.

The Moín Container Terminal in Costa Rica is a civil engineering mega project which has been awarded to dutch contractors Van Oord (in charge of performing the Dredging and Reclamation works) and BAM International (in charge of doing the Civil and Building works) in a joint venture. The consortium also includes in the Civil and Building work packages, the local contractor MECO.

Figure 16. Construction site for the Container Terminal (BAM International, 2018)

The container terminal is built upon an artificial island, product of dredging sand from the sea bed adjacent to the construction project and placing the reclaimed material on the final location. On the surroundings of the island, a breakwater has been built made of X Blocs to protect the 400.000 m² of artificial island under construction as seen on Figure 16.

The Dredging, Reclamation and Breakwater works have been completed already, and therefore, the largest portion of this research will focus in the Civil and Building work packages, which include the construction of a Deck on Piles Wharf, the Revetment, construction of Utilities, Civil Works, Buildings, Reefer Rack Structure Installation, and Pavements. The scope of works represents an attractive case to study since there is a diverse spectrum of civil engineering works that each call for different measures in terms of the usage of 4D BIM and Planning. Furthermore, the array of work packages is of high interest for this research since there is an abundant amount of interfaces to be coordinated between work packages. A key aspect for this research is the availability and quality of 4D BIM tools and models in the selected case (as seen on Figure 17) since it is a determining starting point for this study. The case has been studied on site on a daily basis over a period of seven months in which observation, data gathering and interviews are carried out. This allows the author to have a better opportunity at documenting the environmental aspects that surround the implementation.

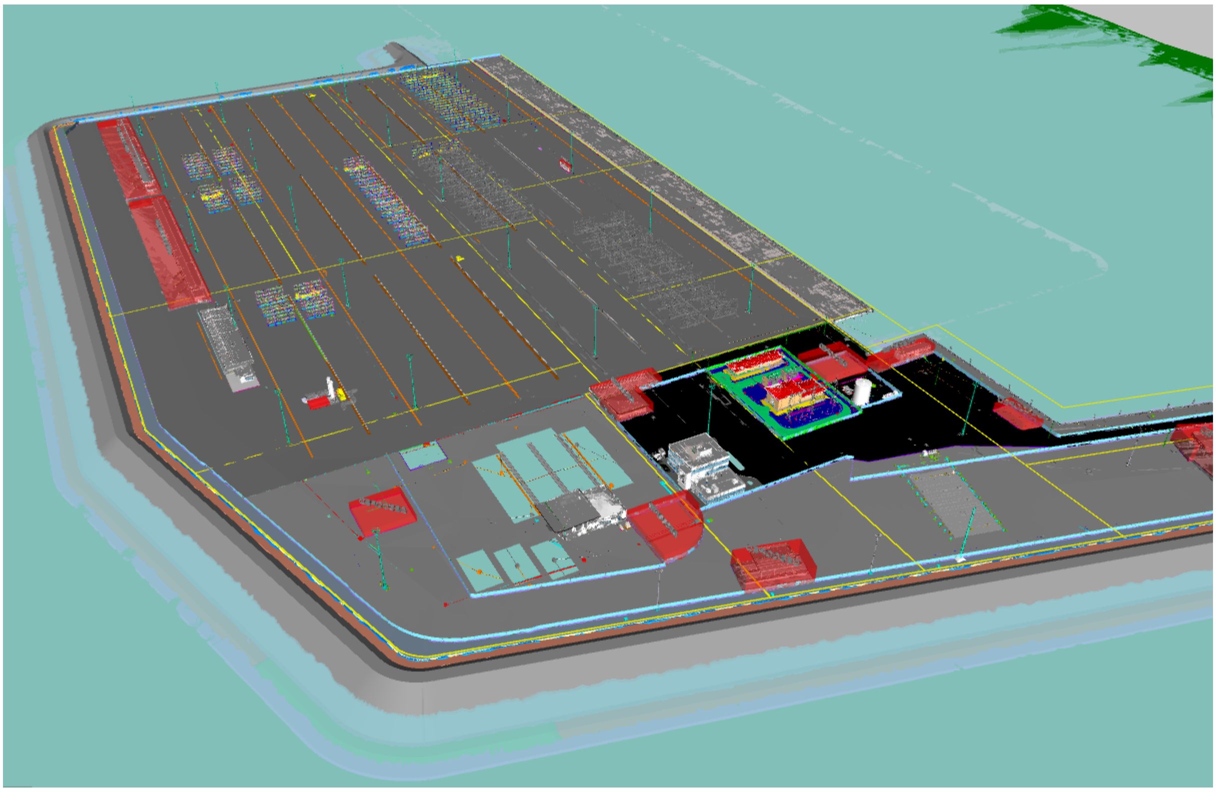


Figure 17. 3D Model used in Research Project

3.2. Case Study Work Packages

The following work packages are within the scope of the present research. A description of the type of activities is provided to provide insight on sequence, the performance hindering factors, interfaces with other work packages, as well as within the same work package which are the interdependencies.

3.2.1. Wharf

The scope of works consists of a deck on piles (as seen on Figure 18), a concrete mattress revetment as well as a stem wall with its corresponding approach slabs and bollards. The sequencing of activities on this work package start with the pile driving, followed by the construction of the beams of the deck. These works are done in a dry condition. For the construction of the revetment, the excavation of the slope precedes the pouring of the concrete mattresses in a submerged condition. Following these revetment works, it is possible to carry out the deck plank placement and slab pouring.

The works on the wharf follow this same sequence along the whole length and therefore, the progress is communicated by gridline completed. The wharf works represent an interface challenge, since the cranes and excavators used in the process require a great deal of space, as well as the tipper trucks that need to be loaded with the revetment material, and all this operation interferes with the adjacent civil works and utilities. The transit in the workspace of the heavy machinery can become a problem for the installed utilities in the area, and therefore, a great deal of coordination and communication is required, since for example, several drainage and sewage pipes go through the revetment so works need to be synchronised in parallel and work packages need to work together.

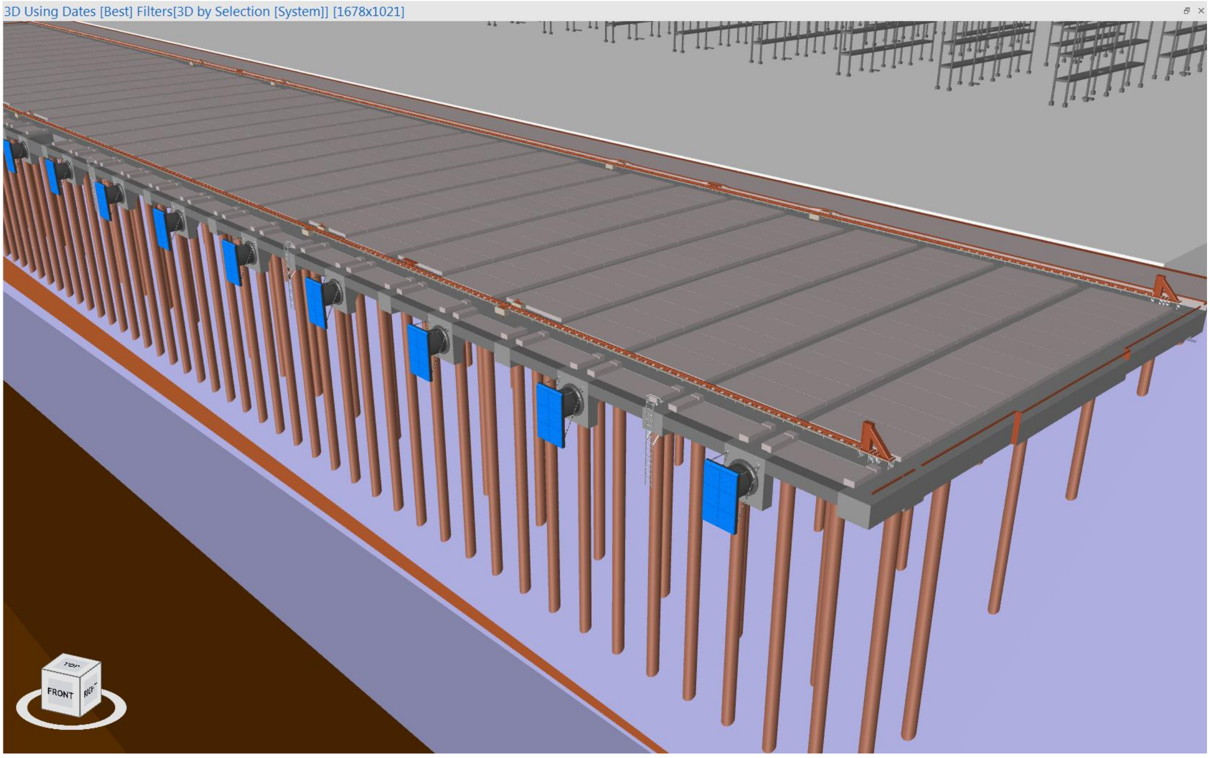


Figure 18. Deck on Piles Wharf Model on Synchro PRO

The main constraints for the performance on the wharf works have been the wave action in the case of the revetment, and in general the operation relies heavily on the transit along the temporary roads of the project to get the required materials in and out of the wharf workspace. This work package is machinery intensive, therefore, breakdowns represent a considerable threat to performance.

In terms of interfaces, several utilities works could be carried out after the machinery has exited a workspace ideally, however, the pressure on several deliverables and milestones, force parallel works to be carried out in order for the Ship to Shore (STS) cranes to be offloaded and begin trials and operation on the wharf.

3.2.2. Administration Building

The Administrative Building is a three-story steel frame building as seen on Figure 19. The construction of the steel members, the electrical and mechanical installations, the window installation, the dry walls and floor tile placement have been all awarded to separate subcontractors. The role of BAM International is to manage these subcontractors as well as to perform the concrete works.

The sequencing of works starts with the concrete foundation slabs, followed by the erection of the steel frame of columns and beams with the aid of mobile cranes. Once this is completed the placement of the steel deck floor follows and afterwards, the pouring of the floor slabs is done. Electrical and mechanical installations are carried out in parallel to these activities and are ongoing throughout the entirety of the construction. Next, is covering the facades with the glass frames and windows to provide a water tight environment, yet it requires for the installation of a perimetrical scaffolding. In dry conditions it is possible to install the drywalls and ceilings as well as the subsequent activities such as the floor tiles and other finishings.

Figure 19. APM Terminals Administration Building Model on Synchro PRO

The interfaces between subcontractors and the supply of materials for the installation on site are part of the hindering factors. Weather conditions are mainly relevant until the roof slab is poured for grey works. For finishing works the weather is an important hindering aspect, until the windows are placed and the building is water tight. The building requires external powering and therefore, the interface between the underground utilities that feed the building and the surrounding scaffolding are the main issues to be solved.

In terms of critical path, the building may be considered an isolated project, except for its dependency with the connecting utilities and final pavement works. Therefore, the works require less interface meetings with the rest of the work packages, but it is intensive on internal interfaces between subcontractors whose interests need to be aligned by the general contractor.

3.2.3. Utilities and Civil Works

The Utilities include excavation, pipe laying, backfilling and compaction works for drainage, sewage, firewater and potable water pipelines. Drainage and sewage pipelines are gravity systems and therefore, are normally placed deeper than the rest of pipes. Moreover, these two systems include the installation of manholes for inspection of pipelines. Pressure lines (firewater and potable water systems) are constructed generally on top of the gravity systems. Additional to the pipelines, the work package includes the construction of concrete duct banks (conduits for electrical cables), slot drains that channel superficial storm water into drainage manholes, substation pits (medium to low voltage transfer pits) and busbar foundations for the electrical feeding of the Rubber Tire Gantry (RTG) Cranes.

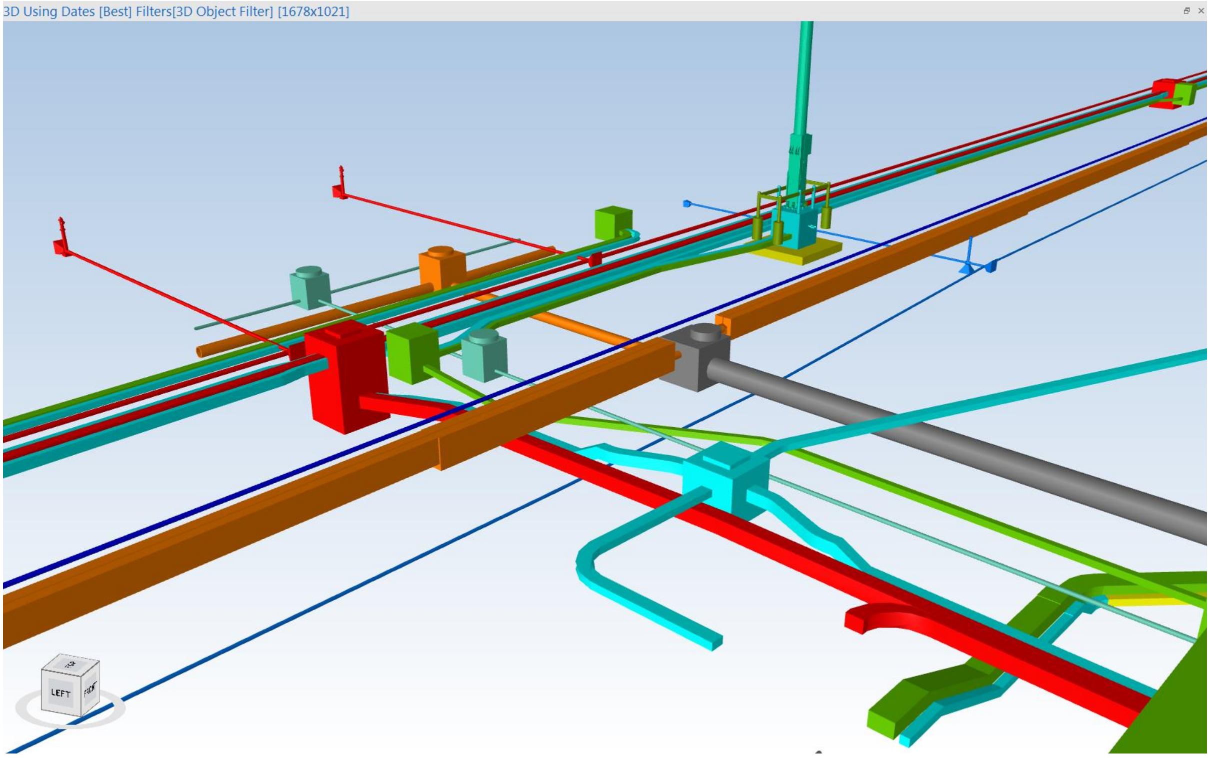


Figure 20. Underground Utilities Model on Synchro PRO

In terms of planning of activities, the logical sequence is a “bottom-up” construction starting with the deepest utilities (normally drainage and sewage), followed by pressure lines or other elements which require to be constructed in a more superficial position. The progress is measured in terms of linear meters of pipelines completed with a distinction (as a function of depth of installation) in the weights of each system, since gravity systems require more work in compaction and groundwater table control and therefore have a higher weight.

Part of the external hindering factors that reduce the productivity of the crews are the high groundwater table (specially for deeper excavations for manholes and gravity lines), the intermittent rainfall that prevents compaction works to be carried out and last but not least, interface coordination and availability of workspaces, since the utilities are built on the whole footprint of the artificial island, this work package has interfaces with the entirety of the remaining work packages. The first two aspects are not tackled in the present research; however, the third factor is key in the analysis.

Even though the Utilities work package does not represent a large portion of the project, it’s nature of being underground works introduce it on the critical path and becomes a driver for the successor activities since the superficial works such as pavements, electrical cabling and some interface points of buildings and wharf revetment depend on the completion of the utilities first (hard logic). Also, since the utilities feed the buildings with electricity, the coordination of the utilities must be done in such a way that the buildings meet the required deadlines for powering of equipment.

3.2.4. Pavements

The scope of works for the 400.000 m^2 of pavements (as seen on Figure 21) includes two types of surfaces: block pavers and asphalt pavement. However, below the surface the pavement structure is comprises a layer of subgrade preparation which is measured in performance control by area (m^2) as well as a layer of Dense Graded Aggregate (DGA). On top of these inferior layers, two layers of Cement Treated Base are placed, and this is prepared by a batching plant on site and it is controlled by weight and area completed. After the areas have been covered with these structure of pavement, the contractor can proceed with the block pavement, or the asphalt pavement, depending of the area.

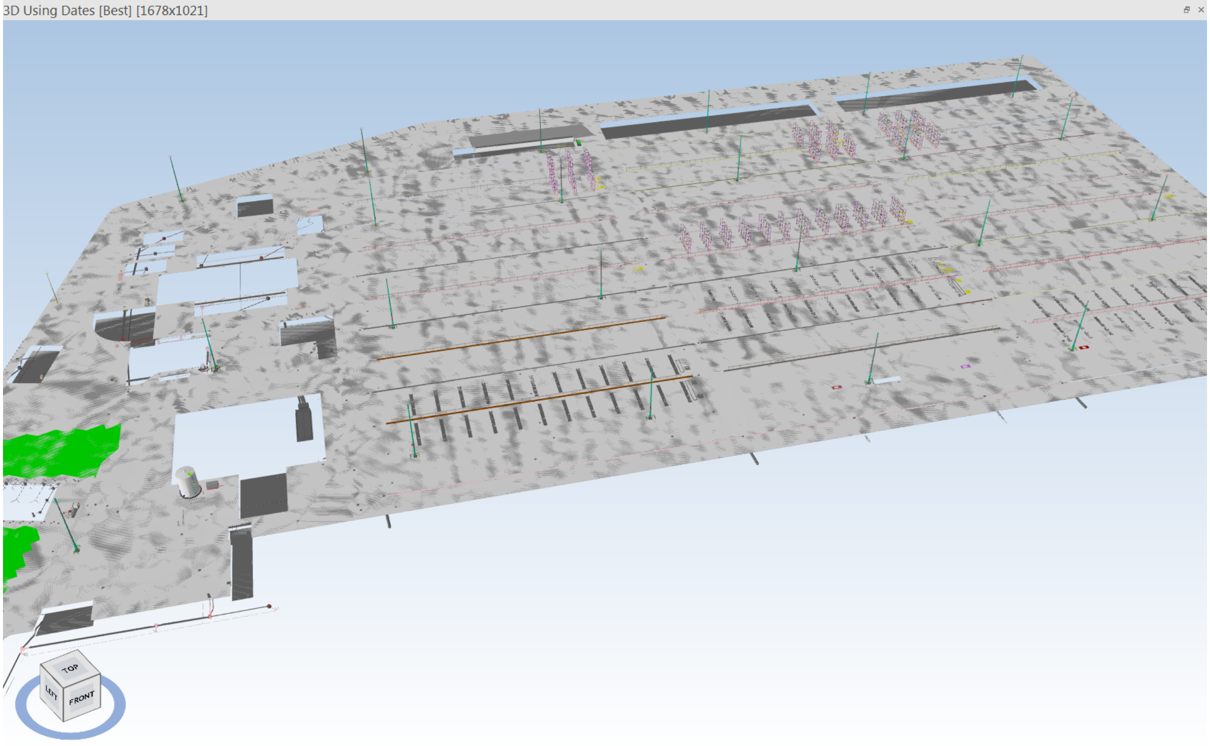


Figure 21. Pavement Footprint Model on Synchro PRO

This work package is highly dependent on the rest of the work packages, especially on Utilities and Civil Works since the former enable workspaces and the latter provides the necessary confinement of the pavement structure. In terms of performance hindering factors, are the completion of the predecessor activities, as well as the rainfall, since compaction is highly sensitive to moisture. This work package will be coupled with the utilities and civil works since there is a high dependency and these open the workspaces for pavements.

The pavements are on the critical path of the project, since these are the closing activities of the project. Therefore, it is highly important for the Utilities and Civil Works crews to avoid any delay, since it will result in a delay of the entire project. Due to the criticality and the repetitive nature of these activities, this work package is highly quantity oriented. However, it is key to complete the quantities on the priority areas set by the milestones.

3.2.5. Reefer Rack Structures

The reefer rack structures are prefabricated steel frames, floors, staircases and handrails to be assembled on site and erected on top of their concrete footings and pedestals (as seen on Figure 22), connected by embedded bolts on the concrete pedestals.

The sequence of works starts with the installation of the steel frame on each set of reefer racks, followed by the installation of the walking platforms, staircases and handrails. The works are carried out with the aid of a crawler crane and man lifts to tighten up the bolts of the structure.

The main interfaces that these structures need to deal with are first their precedence of the pouring of the concrete footings and pedestals, which follow the concrete ductbanks of the surroundings of the reefer structures. Another important interface is in the space that the crawler crane requires for manoeuvring which interferes with the locations where the slot drains need to be casted.

The main hindering factors are the handovers from the predecessors as well as the possibility of breakdowns of the crawler crane which is critical for this operation.

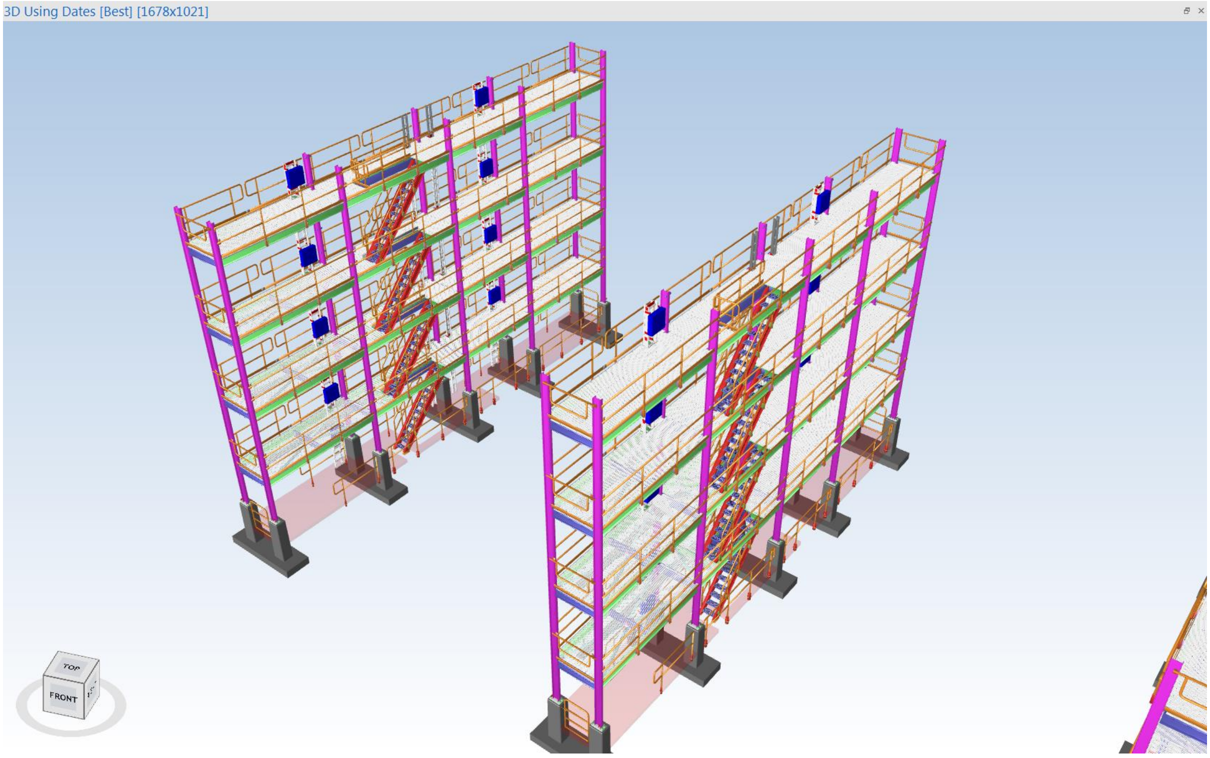


Figure 22. Reefer Racks Structures Model on Synchro PRO

3.3. Project Status Prior to Implementation of the Intervention

Prior to the implementation, the project presented several areas of improvement in which the crews on site could further exploit their potential. These aspects included incomplete 4D BIM on site implementation, site execution inefficiencies present in any mega project, which offer an opportunity for improvement, as well as the flow of information in a handover of information approach.

The 4D model was generated on Synchro PRO software for pre-construction purposes in detail to solve for interfaces and coordinate activities. However, as in other projects mentioned in the literature, the model was not intended for the site execution phase. Therefore, the model was not updated and the deviations in the project would result in an inaccurate representation of the events on the site since first, the deviations caused by weather events (hurricane and tropical storms) resulted in an outdated version that was inaccurate in terms of the time component (delayed and lagging in terms of dates) as well as the shift of some activities to a later stage which resulted in changes in the interfaces that were initially considered. Therefore, it is not logical nor possible to compare the baseline against the as built, since these are out of synchronisation (due to the weather event). This requires for an adjustment of the baseline plan.

In terms of the site execution, work packages were working in a project islands approach and works lacked a holistic view. This resulted in inefficiencies in works that required interface coordination in order to achieve the optimum performance. For quantity intensive work packages, such as utilities, there is normally a quantity oriented mind set, in which gross elements are completed first, leaving the fine details and finishing touches unfinished, since the approach is generally to complete quantities and meet the quantity requirements set on the S Curves. This causes several work fronts to be pending for completion, and therefore, successor activities are not able to enter several workspaces and as a result, there may be several idle work fronts. These aspects can be determined as inefficient use of resources. This evidences in some cases a lack of project view and suggests a project islands approach which is a common challenge in mega projects. For quantity intensive work packages, it is also common to see out of sequence activities that are not aligned with the critical path, which result in delays.

From the aspects mentioned above, it is clear that work spaces offer a coordination opportunity in the execution with the use of 4D visualization tools. Normally, given the interface and workspace coordination challenges, the start date of some works can be delayed, since the workspaces would not be readily available for start of works (these could be occupied by temporary works or props).

The conditions prior to the implementation offer an opportunity for 4D planning to integrate the project islands and coordinate workspaces, interfaces and traffic management, in order to improve the KPI's of the project.

3.4. The 3D Geometric Model

The 3D geometric model can be determined as a high-quality input for the implementation, since the LOD is high (LOD 400), which is detailed up to the specifics such as bolts, nuts and washers of structures as seen on Figure 23. The model was generated by the contractor for clash detection as was used in software such as Navisworks Manage also for workspace visualization. The model offers a great level of detail for interface management and requires a limited amount of partitioning for coordination.

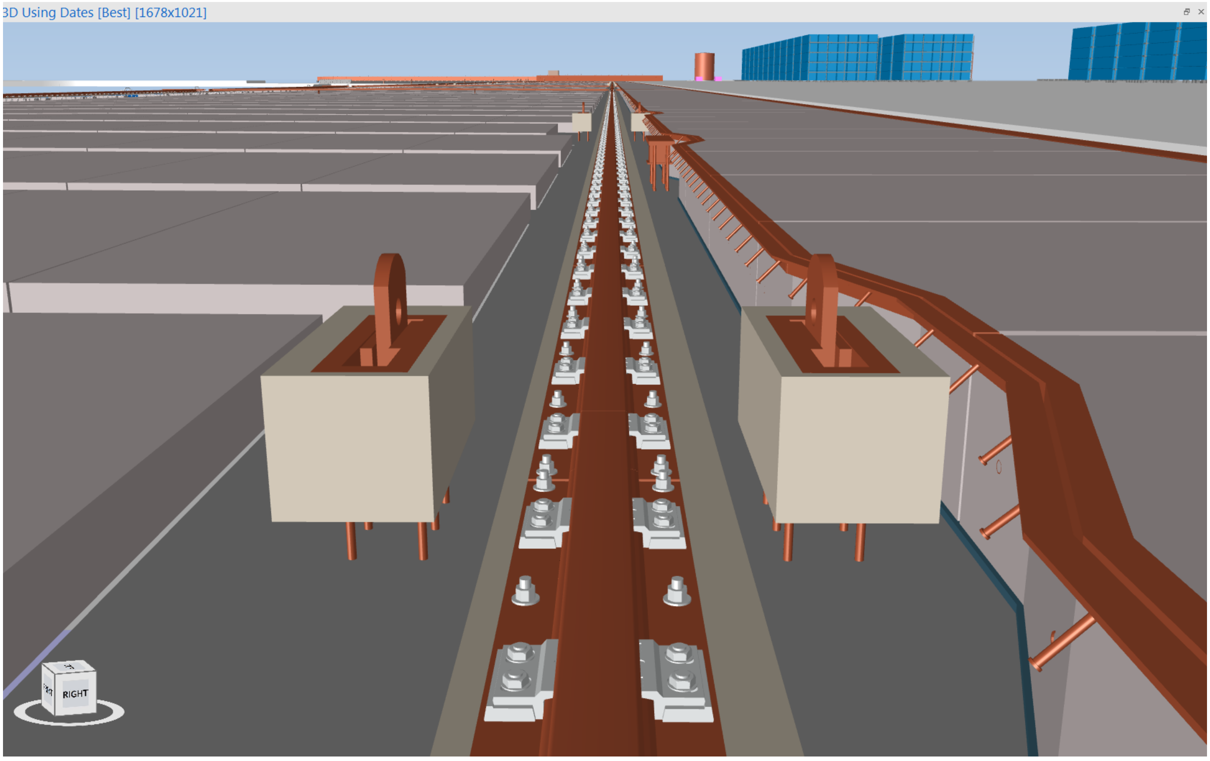


Figure 23. Level of Development of 3D Geometric Model

3.5. Handover of Information

For the purpose of the present research, only the flow of relevant information towards and from the site execution are studied. The flow of information towards the site execution includes the issued for construction (IFC) drawings, specifications and general plans. The latter was handed over to the site execution crews with the aid of screen shots of the scope of works and drone pictures highlighting the works to be carried out on the following two weeks. The level of BIM maturity can be determined as number 1, since the geometric models were shared around the organization, yet these lacked BIM integration since these were separate unlinked models.

Information in the project on the progress was handed over through spreadsheets from daily reports and this was scrutinized and loaded into the planning, to update the project status. This process was inefficient, since it required for planners to interpret information and then load it on the schedule on Primavera P6, which resulted in a lag of two weeks between the data date cut-off and the date of presenting the status which means that decision makers receive information that is already two weeks behind.

Chapter 4
Implementation of the Intervention

4. Implementation of the Intervention

4.1. Introduction

Given the initial conditions, the implementation is designed to align the practices to feasible ideal best practices stated in the theory to both bridge the gaps for the sake of research, as well as to propose solutions for the conditions mentioned above. In the present chapter, the implementation is described to help solve the initial symptoms. The intervention includes a two-phased conceptual model which comprises a deviation signalling tool, interface and workspace guidelines, as well as a framework to channel the tool in a project organization to send the information on planning to the site and to collect the information on progress status from the site in a more efficient manner.

4.2. Critical Success Factors in the Implementation of 4D BIM

Technology is not the sole driving element that will lead to the success of a project. It requires certain factors to be aligned to ensure the success in its implementation. According to research on critical success factors of BIM Implementation, there are five categories of critical success factors which are related to human, industry, project, policy and resource factors. Statistics show that in terms of human related factors, key elements are effective leadership which supports the implementation through the senior management, as well as proper training of employees to increase the level of experience on BIM (Ozorhon & Karahan, 2017). With regards to the industry, the awareness level is the utmost important factor. The more awareness there is on a new technology, the less risky it becomes to implement. When dealing with project related success factors, research states that the most important variable is the coordination among project parties since the integration that BIM pursues is not possible unless the actors in the project are willingly collaborating in a synchronized manner. With regards to policy, the most important element is the company's policy of implementation of BIM. If the company has adopted a culture of shifting from traditional practices in construction, to an innovation in their execution, then the implementation stands a better chance at being successful. The implementation requires a strong institutional and managerial influence since there is an understandable resistance to change in traditional practices as well as lack of experience and interoperability issues (Ozorhon & Karahan, 2017). Without this sponsorship, the success of the implementation is unlikely. In terms of resources, the availability of qualified staff, information and technology are key aspects to increase the probability of success. The implementation relies on a qualified staff that can put together a suitable model that can enable the pursued integration and accuracy in the estimates. Moreover, it is highly important that the new technology implemented has a clearly perceived relative advantage over the currently used technology (Rogers, 2010).

4.3. The Conceptual Model

4.3.1. Introduction

The conceptual model is split into two phases, the first is the content of the Model and the second phase is the way in which this Model is Implemented. The former encompasses the proposed project controls 4D Model (the tool) to compare baseline and as built performance. The latter includes the method in which this model is integrated with BIM in the organization (the framework or the process) to enable the implementation in an efficient manner. This proposal follows the recommendations on section 4.2 on the critical success factors in an implementation of 4D BIM.

4.3.2. Model Objectives

The main objective of the intervention is to bridge the gaps in terms of visualization and performance control that traditional project control tools currently display by building upon traditional tools and covering the main functions in project controls from S Curves and Gantt Charts. In terms of results, the objective is to achieve an improvement in weekly progress, as well as to improve the schedule performance index and reduce the amount of out of sequence activities during the implementation, compared to the initial state as a by-product of the aforementioned improved visualization of performance control. Another objective is to test those success factors in the implementation model and how integration through 4D BIM is achieved in the process to make the recommendations on how to carry out an implementation in further projects.

4.3.3. Characterisation of Phase 1 of the Model: Visualization of the 4D Model

The logic of the model is to replicate the capabilities of an S Curve with a 4D Model by overlapping the baseline performance of the project with the as built performance to analyse the deviations between the two. To simplify the understanding of the logic behind the Model, portions of an S Curve will be used depending on which aspects are required to focus on and a demonstration through screenshots will be presented from the 4D Model. This section is organised on a "left to right of the Data Date" transition by showing first the performance prior to the data date, followed by the performance evaluation on the data date itself and finally the forecasted performance ahead of the data date. This section (4.3.3) answers in detail the sub research question:

"How can 4D Models bridge the existing gaps of traditional performance control methods?"

The present section elaborates on the research question in detail and in the Conclusions (Chapter 7), a summarized version and closeout of the research question will be presented.

4.3.3.1. Benchmarking

In any control, a reference point or a benchmark is required to be able to compare initial assumptions to measure the deviations detected between the initial scenario and the actual situation and it is necessary for identifying inefficiencies and controlling project costs (Liao, et al., 2012). As stated in the theoretical concepts, as done in the S Curve analysis, the Baseline Performance and the As Built Performance 4D Models will be overlapped to be able to visualize the deviations in a simplified manner without the need of shifting from one model on one side of the screen to the other model on the other side to be able to spot the differences. In the S Curve analysis, the deviations between the baseline and as built performance are spotted in a straight forward manner by observing and measuring the differences in quantities or completion percentage between the two lines on the graph at each point in the time scale. On the 4D model to be able to visualize deviations, a colour code is employed.

4.3.3.2. Appearance Profile and Colour Coding Based on Planned Performance

Due to the absence of a quantity and a time scaled axis on the 4D Model, other visual strategies are required to portray the main aspects displayed on an S Curve. Through a colour coding it is possible to represent the status of elements as seen on previous research. Therefore, an appearance profile is modified on the model to fit the needs of the present research. A different profile was done for the baseline, the as built and the critical path activities. For each one, a specific colour coding is provided as seen on Table 1. The model is built upon three separate models that consist of the same scope of works stacked together differentiated by a colour code to visualize the performance of the project.

When the focus time is before the task, Baseline objects will serve as a visualization of the scope of remaining tasks in the project (in a white transparency) before each task begins on the planning. This gives a good overview of the project and aids in benchmarking how far along is the project. For this focus time As Built objects are invisible since the scope has already been covered by the Baseline items. Prior to the activity taking place, those objects in the critical path on the baseline will show up on the model in a purple transparency.

During the task, the baseline objects will serve as a visualization of the two week look ahead by representing the tasks that the crews on site should be performing at that precise moment in a yellow transparency. In terms of the as built objects, once the task is being performed, these objects will be visible in a solid green appearance. The solid green As Built objects will supersede the yellow Baseline objects since the two week look ahead activity is being performed accordingly. Those elements from the critical path that are being performed are represented in a solid purple appearance.

After the task has been completed, the baseline objects will shift their colour coding to a red transparency. This will aid in signalling the deviations between the baseline and the as built. Upon completion of a task on the site, the As Built object will change its appearance to a grey solid. These solid grey objects will cover those red Baseline objects. In case of a delay, one may visualize outstanding red objects which represent the deviations of the project. This will be further explained in section 4.3.3.5.

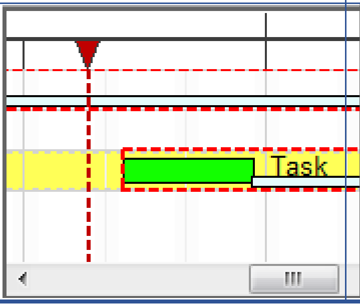
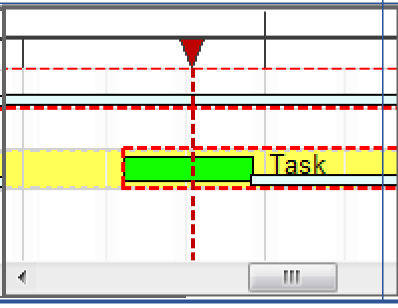
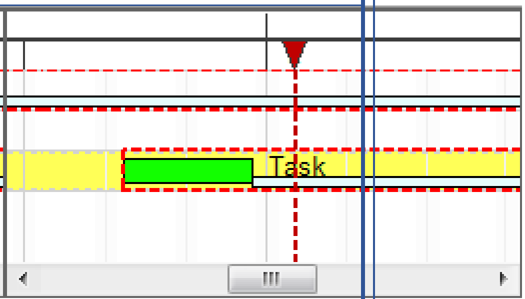
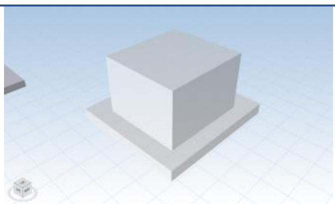
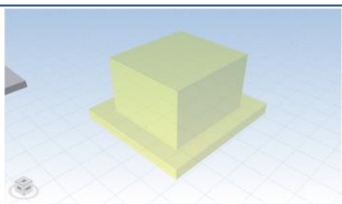
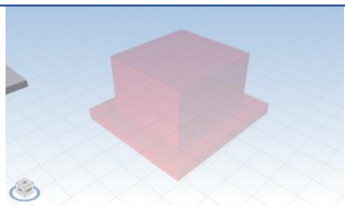
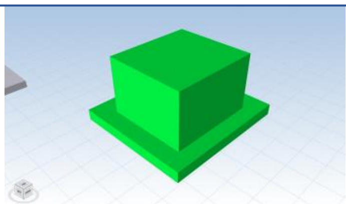
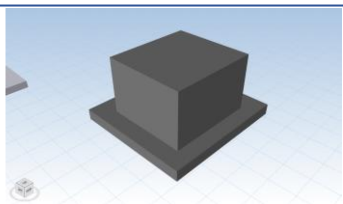
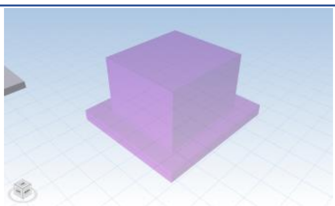
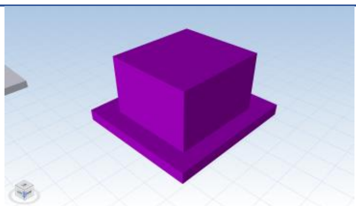
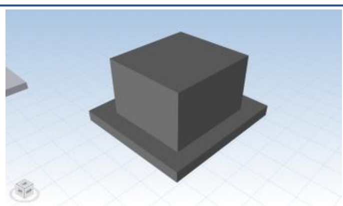
	Focus Time		
	Before Task	During Task	After Task
Profile			
Baseline	 White Transparency 60%	 Yellow Transparency 70%	 Red Transparency 80%
As Built	 Transparency 100%	 Solid Green	 Solid Grey
Critical Path	 Purple Transparency 70%	 Solid Purple	 Solid Grey

Table 1. Appearance profile of elements according to the focus time

Each completed object is evaluated according to the performance on the site compared to the planned performance and is assigned a binary colour code when each one is finished. To prevent from overloading the model with distracting colours, the as built performance-based colour coding (green for on time or yellow for delayed objects) is done on top of grey elements. This way, the deviation visualization can be performed without any interferences and one may focus on the performance evaluation colour coded objects at any given time.

Once objects in the critical path are completed, these are evaluated and represented like the rest of the objects either green if completed on time, or yellow if the object is completed in a longer period than planned. To be able to spot the deviations when evaluating on the data date, those activities that have not been completed, are signalled in red.

Figure 24. Colour Code Legend Used on the Intervention

The aspects on Figure 24 have been selected since these are the essential pieces of information for decision makers whilst evaluating the performance of a project. The colour coding mentioned above is a mild visualization for the performance control of elements completed prior to the data date.

4.3.3.3. Whole Scope of the Works

One of the most advantageous characteristics of S Curves are that one may visualize what has been the performance (planned and executed) in the past, the situation of the project on the data date and, the forecast of production in the remainder of a project compared to the baseline plan. This advantage is also understood as being able to visualize the whole scope of works in one sole graph. However, in 4D Models the audience must watch the whole movie to see the totality of the works to be performed as well as the completion date. The present research aims at representing those works that have already been carried out (Section 4.3.3.3), the situation of the project in the data date (Section 4.3.3.5) and in this section the research aims at visualizing the scope of works ahead.

Benchmarking is highly important to visualize deviations; however, it is also important to dimension these in the whole scope of works to understand how big these deviations are, compared to the whole project. The scope of works in the proposed conceptual model is shown in a white transparency as seen on Figure 25 in which all the objects are visible, but do not distract the audience from the main focal points that need the attention.

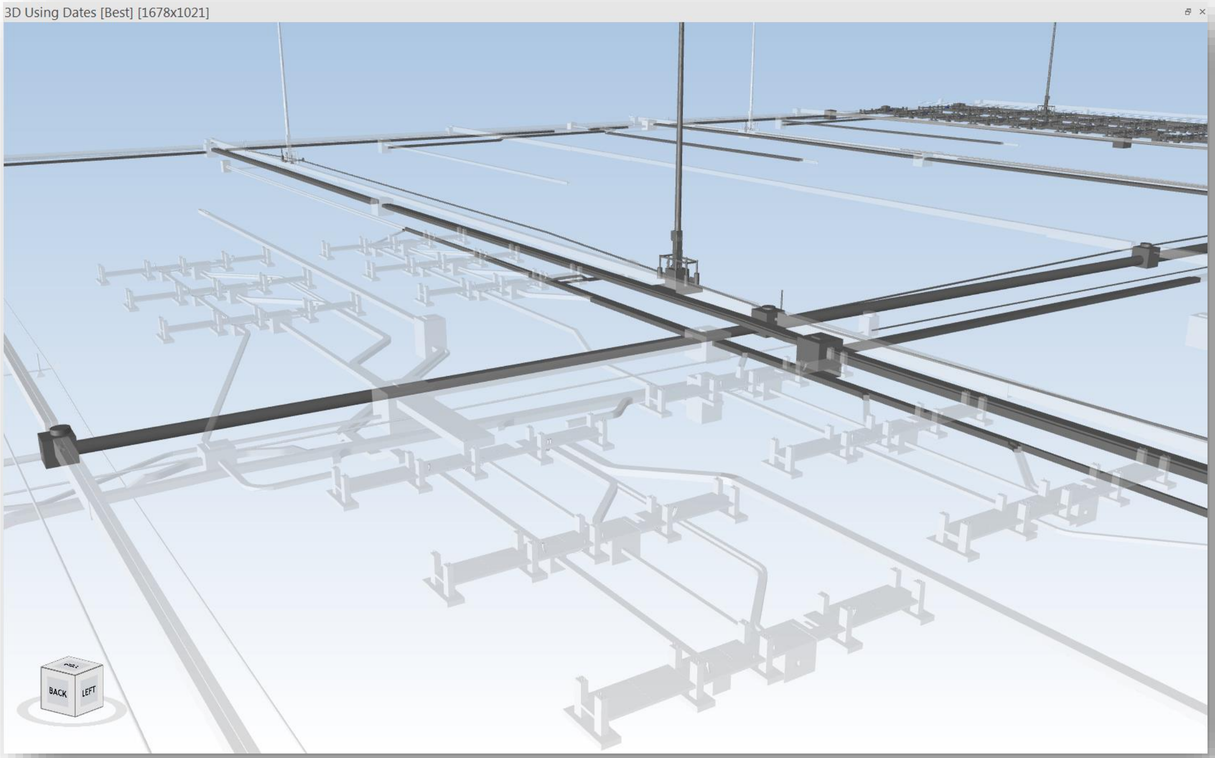


Figure 25. Visualization of the Remaining Scope of Works.

4.3.3.4. Performance prior to the Data Date

Given the colour code from the previous section, the performance prior to the data date can be represented in the 4D Model for evaluation. The initial condition in the model is such that all the elements are in a transparency appearance, except for the purple objects from the critical path. As the elements are completed, these will be visible with the appearance based on the criteria stated in the previous section. As the project progresses, one may visualize how the objects on the left side of the data date are being completed as seen on Figure 26. One may look back at the whole scope of works completed and detect in which elements the project performed accordingly or if there were deviations. This is a similar approach to the S Curve Analysis in which one may visualize the slope of the curve as well as the difference between curves and understand in which points the project performed accordingly or failed to do so. However, the model that this research proposes allows to grasp how the crews are completing those objects and it allows the management to understand if there is a trend in which a certain kind of object has problems in the process. In this way, managers can act on the specific elements to prevent deviations and make corrections in the process.

This approach of representing the as built status of elements in a 4D Model is based on previous research, that tackles the visualization of progress prior to the data date. Figure 26 can also be understood as the state of the art in 4D BIM, since what has been researched on is the status of a project on the left side of the data date. Figure 27 shows the visual evaluation of as built performance with the colour coding of the objects in which it is clear to see which elements underperformed and those that were delivered on time. The model aids in answering where the deviations have occurred.

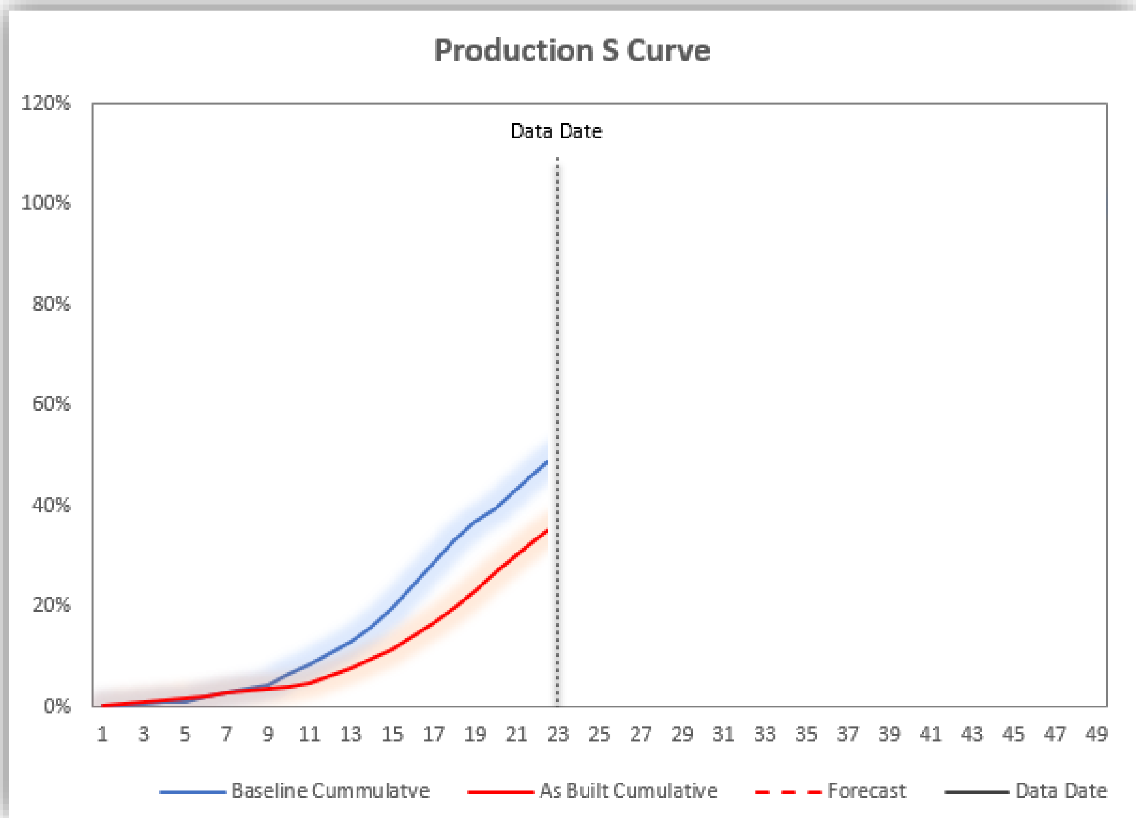


Figure 26. Performance Visualization Prior to the Data Date

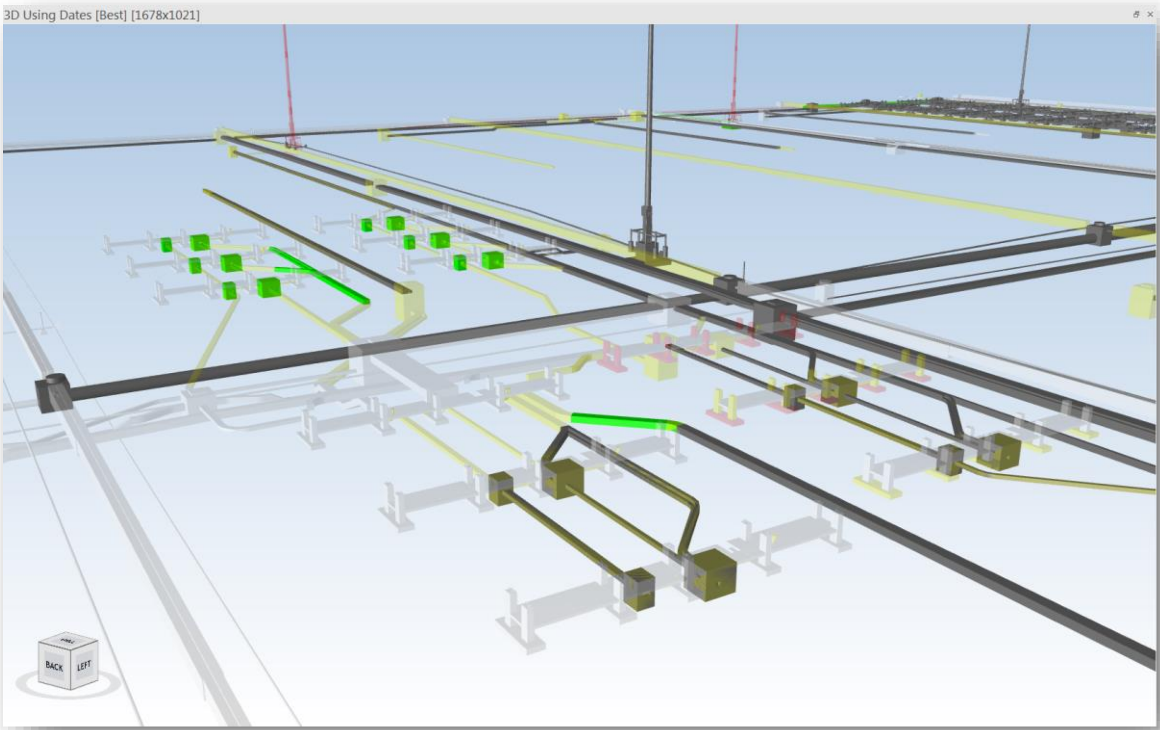


Figure 27. As Built Review Prior to the Data Date

4.3.3.5. As Built versus Baseline Comparison on the Data Date: Deviation Control

One of the main aspects to evaluate on the S Curve Analysis is how the project is performing on the data date compared to the baseline plan. The comparison between the baseline planned production and the as built production is done normally on a weekly or a biweekly basis to understand the situation of the project on the data date. Therefore, the focus shown on Figure 28 shifts every week or two from left to right on the data date. In this analysis, experts look at the difference between the quantity planned and the actual quantity produced to detect deviations. On S Curves, it is fairly straight forward to estimate this difference as seen on Figure 28 in which one measures the difference between the two curves both on the “X” axis (to calculate the time deviation or delay) and on the “Y” axis (to calculate the Quantity or Percentage deviation). On the proposed model, for the comparison of baseline versus as built performance, one may observe those objects that are planned to be constructed in yellow and one may easily spot the objects that are lagging in a red appearance. These objects in red are then the deviations between the baseline plan and the as built performance upon which one must act.

On an S Curve analysis, one may easily spot the amount of deviation in terms of quantities between the two curves as seen on Figure 28. However, one may not understand where these deviations are physically occurring in the project. The conceptual model proposed in this research aims at bridging this gap. For every point in time, one may visualize these differences by focusing on the red elements as seen on Figure 29.

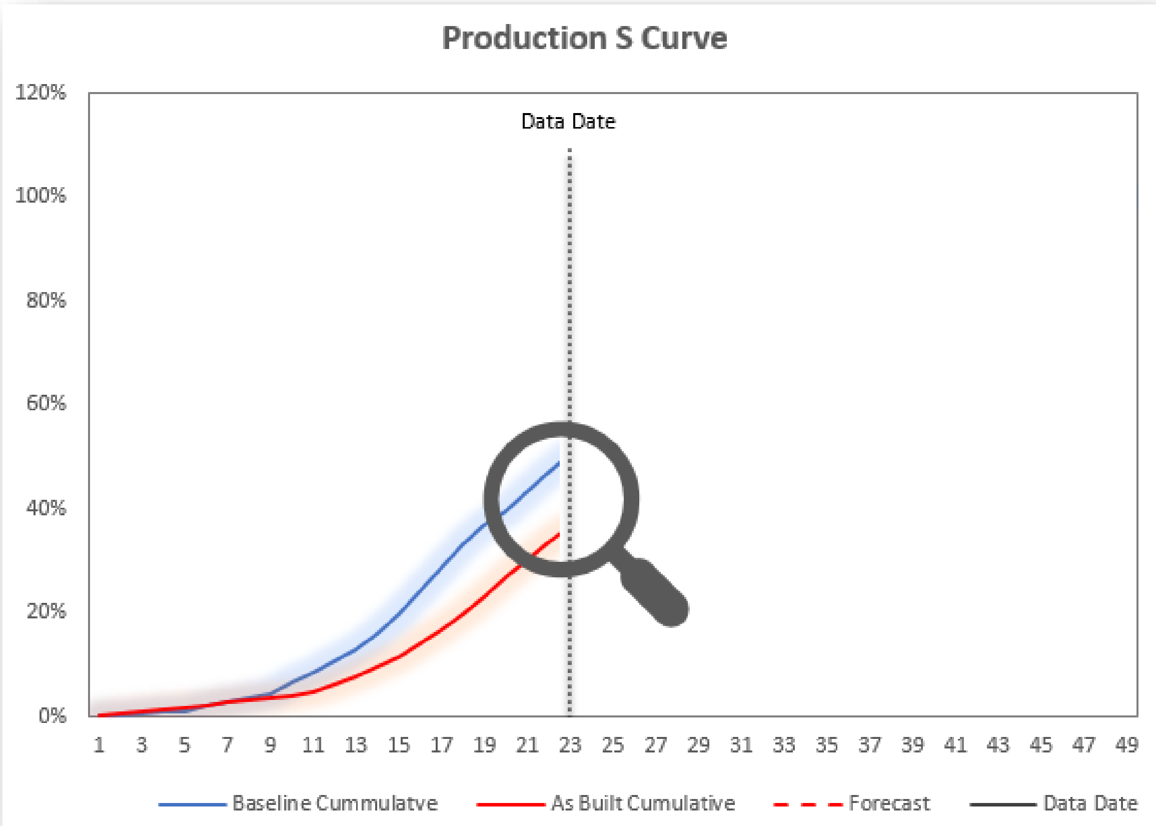


Figure 28. Visualization of the Baseline and As Built Performance Comparison

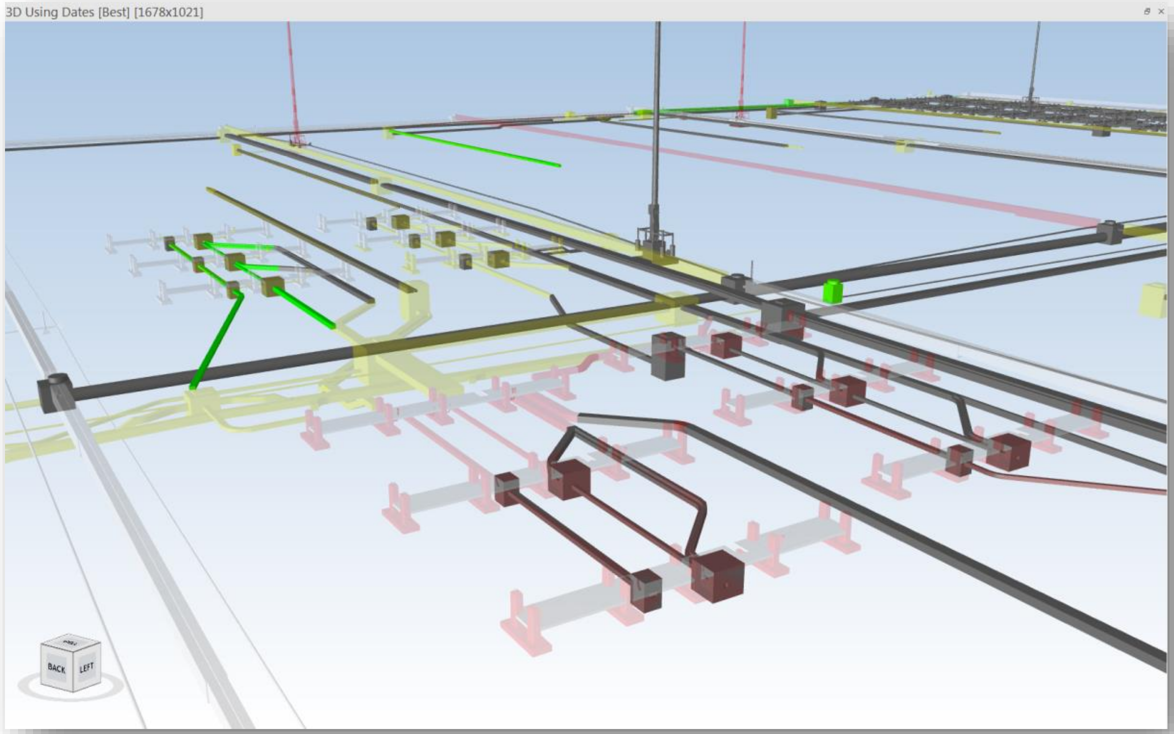


Figure 29. Deviation Visualization in the 4D Model

Based on the elements that are flagged as deviations in a red appearance, decision makers may correct in a timely manner where required. The aim of this method is to reduce delays by making the deviations (the symptoms of an unhealthy project) more visible and enabling a close control as well as increasing accountability. By enabling this deviation visualization, one may answer the question about where the teams are under performing.

Deviations may be negative (performance is lower than planned) or a project may encounter a positive deviation (performance higher than planned). The former has already been addressed by depicting these elements in a red appearance. The latter needs to be tackled as well since it is not the aim to promote a culture of performing close to the lower limit.

One may encounter a situation in which the crews on site are performing the gross works (in which it is easier to achieve the targeted quantities per period), but at the same time leaving the final details (which are more time consuming) and as a result, the project may deliver the quantities targeted on the baseline, but not delivering the targeted quantities on the planned objects (critical path for example). The situation described above results in open work fronts that do not allow for successor activities to start since the preceding activities have not been finished. As stated by interviewees, this is an "unhealthy" situation for projects because it may seem that the project is performing accordingly but may result in delays further down the road. The situation stated above cannot be identified by merely looking at the S Curve, since the lack of progress information for some objects is hidden by those in which the crews have completed earlier than planned. With the aid of the model proposed in this research, one should be able to detect the aforementioned deviations and understand if the project is performing in an in-sequence manner.

4.3.3.6. Two Week Look Ahead and Six Week Look Ahead Comparison: The Forecast and Interface Coordination

Visualizing the scope of works in a transparency appearance does not cover in its entirety what is on the right-hand side of the data date, since S Curves provide the baseline curve as well as the forecast on this side as seen on Figure 30. Therefore, it is important to integrate the planning of the remainder of the works into this model and make use of the performance measurement prior to the data date.

Given the lack of a time and quantity scaled axis on 4D Models, it is not yet feasible to fulfil the capability of S Curves of visualizing the remainder of works on the baseline plan compared to the forecast as seen on Figure 30. However, given the capabilities of 4D software, this can be addressed by generating two and six week look ahead sequence movies (as seen on Figure 31) with the baseline benchmark as done in sections 4.3.3.3 and 4.3.3.5. The aim is to provide the site crews with a detailed two week look ahead which must be aligned with the six week look ahead target that follows the master plan. In case of underperformance in a bi-week, it is possible to adjust the plan to enable the crews to achieve the targets by the end of the six weeks. To make up for the shortcomings of 4D Models in which one cannot visualize in one snapshot the entirety of the remaining works, the method of two week and six week look aheads in detail combined with the visualization of remainder of works in the whole project is proposed. This way, a constant revision of the forecast of remaining works is motivated in an object-based visualization which should enable planners to evaluate the feasibility of the estimates.

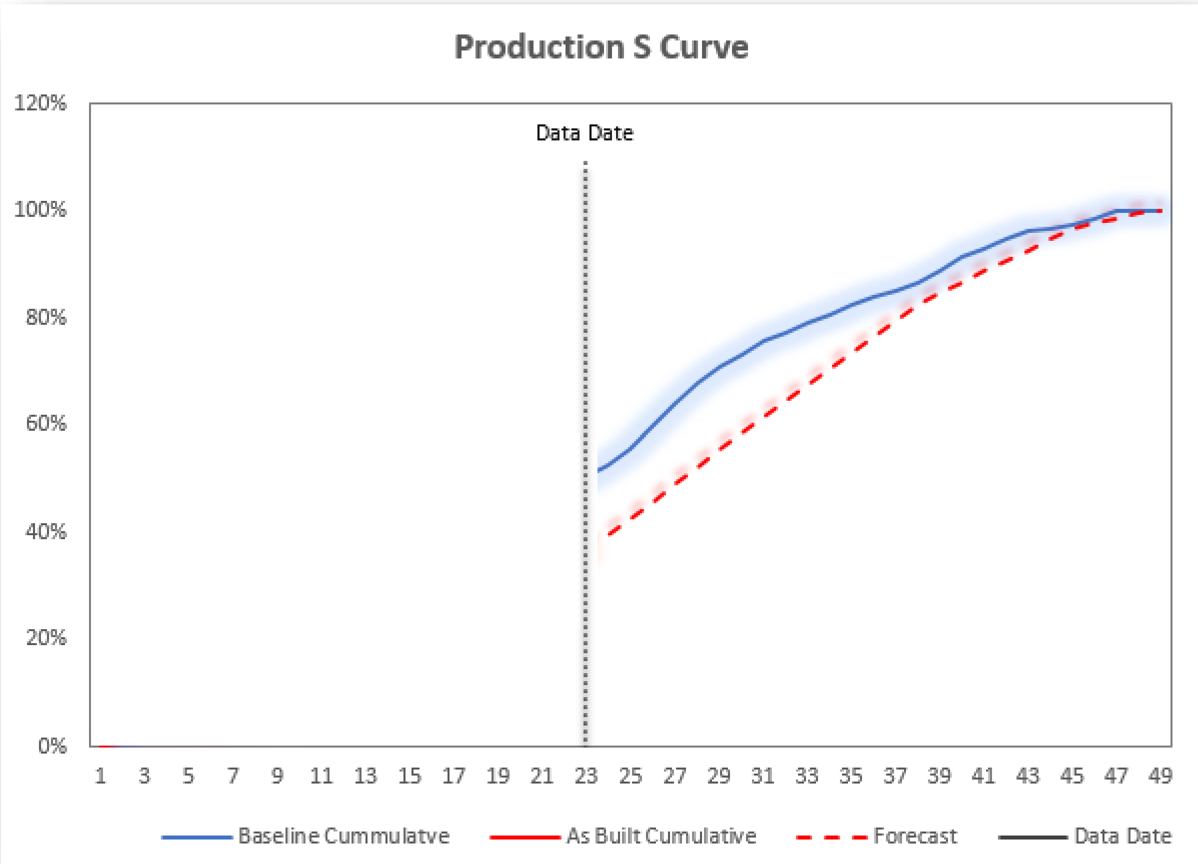


Figure 30. Visualization of Scope of Works after the Data Date 2 Week and 6 Week Look Aheads

The current practice of using the 4D Model is merely for preconstruction analysis, however, a project is not static. Therefore, for projects in which several work packages interact, it is highly important to evaluate how the deviations measured prior to and on the data date, impact the interfaces on the remainder of the project. On S Curves, it is not possible to visualize how the deviations affect the interfaces, and therefore, the forecasts are based on the assumption that everything remains unchanged. With the aid of 4D Models it is possible to bridge the visualization gap and deliver a forecast that is tested for interfaces and therefore, is more accurate and feasible

Normally, each work package has their own S Curve under which their crews are evaluated. In terms of accountability, it suits the purpose. However, this approach promotes a project islands philosophy and a quantity-oriented mindset. As a result, crews tend to look solely after their own interest and do not collaborate with each other and due to the lack of coordination, works are sometimes obstructed and logically, performance decreases. To prevent this from happening, the conceptual model proposes merging the whole scope of works in the 4D Model and evaluate for clashes and interfaces. By doing so, the interfaces are dealt with enough time provision and crews commit to enabling work spaces to other work packages. Even though this topic is related to interface management, as seen on the case study, it influences performance directly and it is one of the shortcomings of project controls whilst carrying out the S Curve analysis.

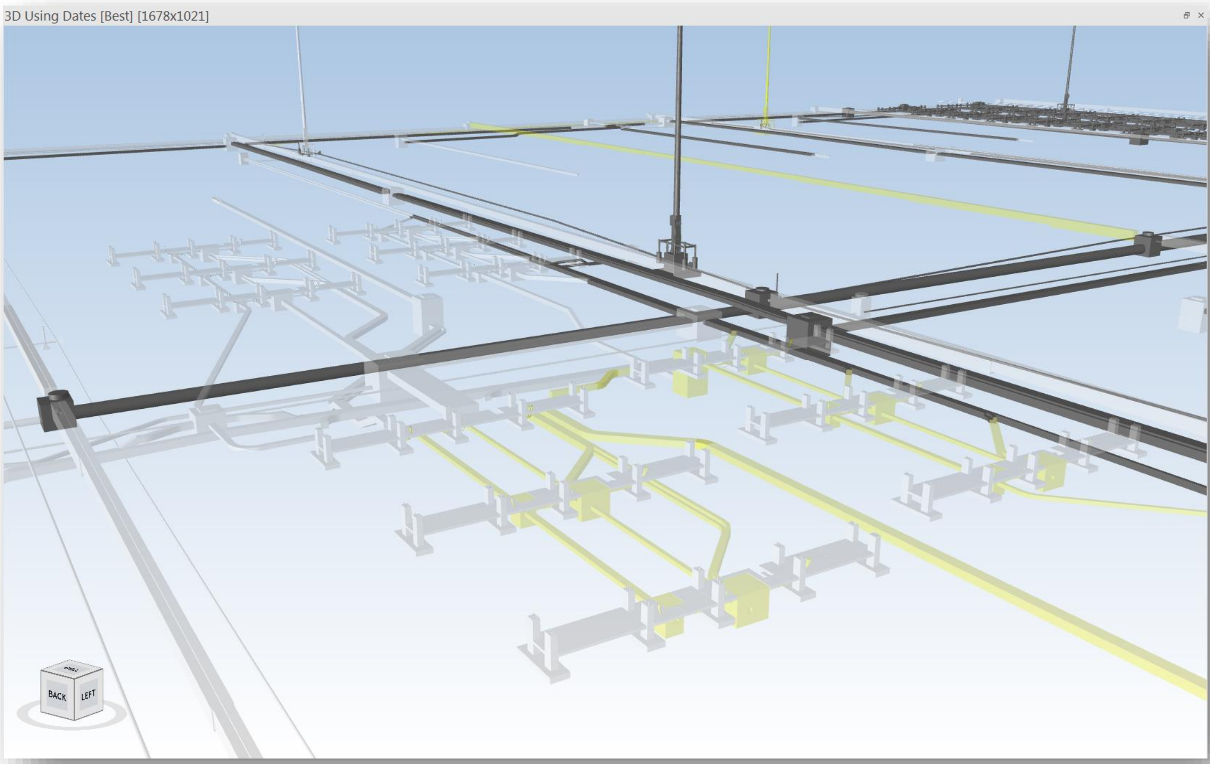


Figure 31. Visualization of 2 Week Look Ahead on 4D Model

4.3.3.7. Iterative Nature

As stated in section 4.3.3.6, the nature of the project is dynamic, and therefore the 4D Model needs to be updated and adjusted to be used during the execution phase in an iterative manner on a biweekly basis. Given the input from the performance during the two weeks of planned production, the information feeds the planning and the estimates are adjusted for issuing of a new two week look ahead in an iterative nature. This process takes place for the whole duration of the project. Given that there is an increase of information as the project progresses, the iterative nature of this process should make the estimate more accurate with each iteration.

4.3.3.8. Traffic Management

Similar to the influence that interfaces have on performance, from preliminary research it has been evident that traffic management is a key aspect that impacts the performance of the project. Therefore, it is necessary to incorporate the traffic coordination on the site whilst carrying out the interface coordination to ensure that supplies and resources transit through to the site in an efficient manner. By looking at the interfaces and the traffic management, it is possible to detect which areas are most suitable for temporary storage, site offices and other aspects that may hinder the performance. By addressing this in advance, it is possible to determine which are the designated drop off zones and reduce the amount of time wasted carrying out double handling of materials and resources. According to preliminary research carried out on the case study, wasting resources on double handling of materials and equipment reduces the performance since resources need to be allocated to double handling when these could be used to produce progress for the project.

4.4. The Process of Setting up the Model

4.4.1. Initial Inputs

The quality of the model is highly dependent on the inputs one has for the implementation. In this intervention, the inputs are the 3D Model, the Schedule and the As Built data generated on site that is used for the elaboration of the As Built Sequence in the colour coded representation. Also, there are sufficient aerial drone pictures of the whole project taken on a weekly basis that serve as corroboration images for the model. In case of having poor quality inputs, the accuracy of the outputs may be reduced.

The 3D model employed consists of several inputs depending on which software is most suitable for each work package. In the case of the Buildings Work Package, a Revit model was used due to the architectural details on the Administration Building that made the Revit Model most suitable. Due to the grading details of the Pavements and the amount of objects on the Utilities, it was deemed most suitable for the 3D model to be created on AutoCAD CIVIL 3D. If the Pavements and Utilities work packages would have been modelled in Revit, the model would have been too heavy to manipulate as it occurred at the beginning of the model generation in which the program crashed repetitively. In the case of the Wharf Work Package and Revetment works, the 3D Model was generated on AutoCAD Civil 3D due to ease of use. The Revit model for the Administration building (generated by the design engineer) is not as detailed as the rest of the models generated by the contractor, since it is created to depict architectural aspects and not for construction purposes.

The Master Plan was generated on Primavera P6 by the planning department in which they set the outline of the project with the corresponding milestones for the work packages to generate a detailed execution schedule on Microsoft Project. The reasoning behind the different software being used is that for project management and higher planning, Primavera P6 is most suitable due to the capability of handling larger amounts of activities without the software crashing, as well as the increased amount of reporting options available on Primavera. For the work packages, Microsoft Project was used due to fact that the crews on site were more knowledgeable on the use of this software.

The initial As Built data was extracted from Daily Reports in which the data was introduced manually into Excel Sheets which are an object inventory in which progress is computed. During the implementation, the data was extracted from the Synchro Site application in which progress was captured on an object-based model. Prior to and during the implementation, input verifications were carried out through visual comparison with drone imagery. The as built input data is a key element in this analysis, and therefore requires a high level of accuracy.

4.4.2. Level of Development

The level of development of the inputs is evaluated in terms of the 3D Model, the Master Plan and the Schedules at work package level, to establish the standard under which the present research elaborates its recommendations and conclusions. For the Pavements, Utilities, Reefer Racks, Civil Works and the Wharf, the 3D models were created by the contractor on AutoCAD Civil 3D with and LOD 400 since these models amount to a high detail level which is used for assembly and manufacturing. In the case of the Reefer Racks, the structures are standard assembly modules which have been built repetitively by the supplier and therefore the models have been developed further than the rest of the work packages, since this work package is highly assembly intensive. In the case of the Utilities, the 3D Model was used frequently for clash coordination between the different services, and therefore, required a high level of development when coordinating pressure pipe distribution with the gravity systems. The Wharf, Pavements and Civil Works offered a similar level of detail, however, this was more related to the grading of the revetment and pavement surfaces. These details enable for the contractor to carry out a highly detailed sequence of works. For the case of the Administration Building, the model was under constant modification by the client on Revit, and therefore, the model was implemented directly, instead of beginning a new model from the contractor side. The level of development of the model was lower than the rest of the work packages since it was mainly for construction documents and architectural design and therefore it was considered an LOD 300.

As stated in the theory, level of development not only relates to the physical 3D Model, but also to the time component. In the case of the Master Plan, it was considered to offer level of development that fits the category of LOD 300, since it made reference to clusters of objects which were accurate in terms of quantities, yet these were not sufficient for coordination and sequencing on site. It is understandable for a Mega Project such as Moín Container Terminal to cluster objects due to the fact that the large number of objects in the project would not be manageable at Master Plan level. Therefore, the clusters were further detailed by the work packages to elevate the level of development at a suitable level (LOD 400) for sequencing, interface coordination as well as assembly and manufacturing. It is ideal that both the time component and the model are at a similar level, since it is more straight forward during the integration of these.

4.4.3. Setting up of the Baseline and the As Built in the Model

The process of setting up the baseline in the 4D Model is mainly a match between the schedule and the objects on the 3D Model on the Synchro PRO software. Logically, it requires certain partitioning (slicing) of objects to match the specific sequence of works, as well as for interface coordination. The forward-looking starts off with a transparent appearance of all the scope of works. As the movie progresses, when the baseline objects are being constructed in the model, these are visualized according to the appearance profile on section 4.3.3.2. This aids in the visualization of the sequence.

For the As Built evaluation, a second model is generated with the same scope of objects as the baseline. This model is introduced in a file in which both the baseline objects and the as built objects are overlapped. When evaluating the performance on site compared to the baseline, the appearance of the objects completed prior to the data date will depend on the colour mentioned on section 4.3.3.2.

For the as built arrangement of the 4D model, a two-phased approach is required in which the first is assigning actual start and end dates to each object completed prior to the data date and on the second phase, the forecast plan is carried out similar to the baseline setup since it is the same logic of forward planning.

4.5. Capabilities of the Model

With the setup completed, the model is now capable of functioning as a forward and backwards looking tool (as seen on the visualization summary of the conceptual model on Figure 32) which needs to be updated on a weekly basis. To illustrate appropriately, on top of the S-Curve on Figure 32 are the properties that are being proposed in this research in which the 4D Model will aid in the "backwards look" with progress and performance control in the comparison of the Baseline against the As Built by illustrating it in a colour coded scale which represents the performance level at which the elements have been constructed. On the "forward look" on the right side of the data date an adjusted 4D Model represents the activities with a highlight for the critical path and takes into account the schedule adjusted with the interface coordination. The process is carried out in 2 and 6 week sprints in which the plan aims to adhere to the baseline and it is communicated to the execution crews on site. The latter is adjusted on a biweekly basis. This conceptual model is the main course of this research since it is the proposed intervention.

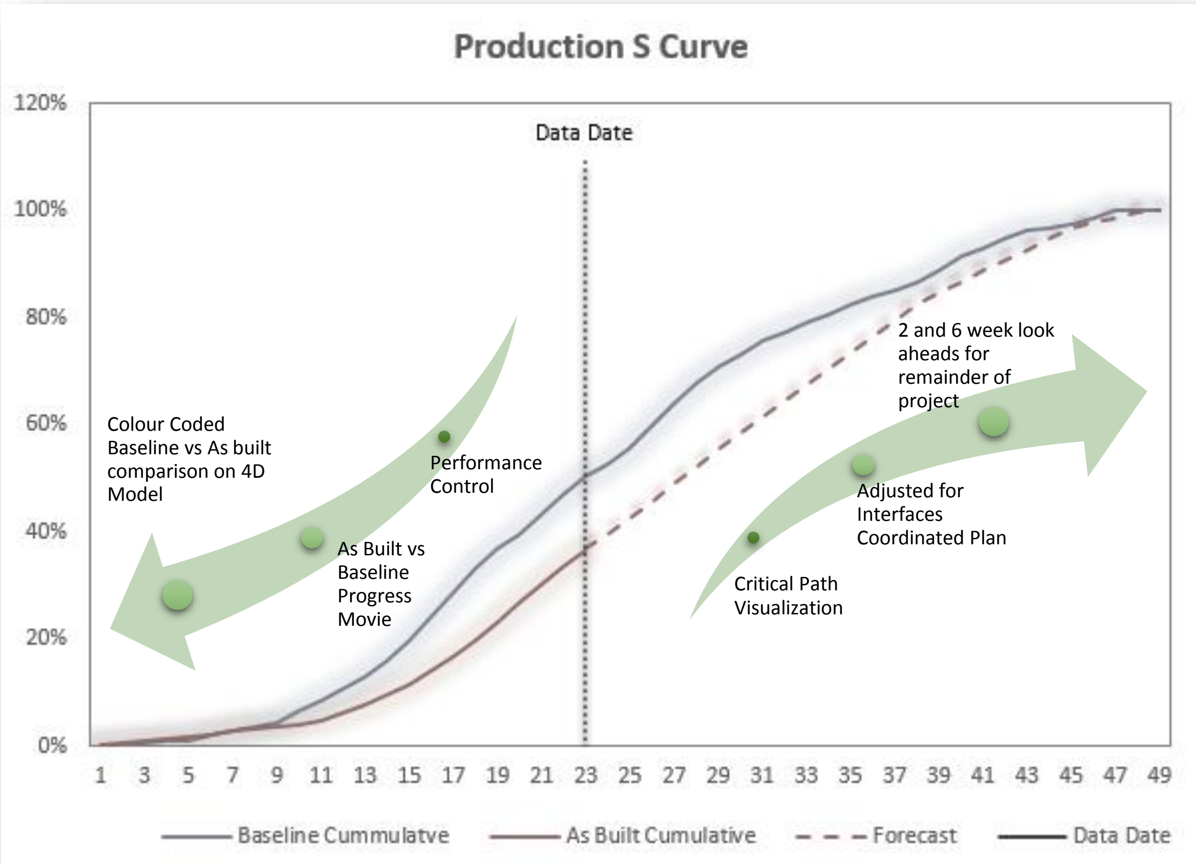


Figure 32. Model Capabilities of Visualization of Progress Control, Interface Coordination and Planning with the 4D Model

4.6. Implementation Process Description: Phase 2

Based on the historical data and the analysis carried out of the previous in situ conditions compared to the theoretical ideal situations, a conceptual model has been generated to bridge the gap between the current situation with traditional tools and the targeted status. However, an implementation plan needs to be put in place to satisfy the critical success factors stated in Section 4.2. Phase 2 describes the framework (process) in which the tool should be implemented in a 4D BIM environment in the organization. This implementation plan should satisfy the following sub research question:

"What stepwise coordination is required between planners, managers and site engineers?"

This question will be answered in sections 4.6 and 4.7 in an extended and detailed manner. A revision of this will be made with regards to its behaviour during the implementation and the revised version will be presented in the Conclusions (Chapter 7) at the end of the research as an executive summary.

The intervention takes place for the duration of two months in which the effects are measured both at the performance level of the teams on site, as well as the organizational effects experimented on two week cycles over whole period of evaluation. The cycles follow the two week "sprints" carried out on the site in which the planning develops a two week look ahead and a six week look ahead plan. The former serves as an immediate target, and the latter serves as the foreseeable near future.

On the intervention, each work package has carried out their own planning for the remainder of the project that aligns with the master plan and with the collaboration of the planning department, a 4D Model has been generated for each separate work package. After this first step, the work packages are merged in a sole 4D model in which interfaces are checked and clashes are discussed. Afterwards, re-planning is carried out with regards to the input that the work packages share since some workspaces are a priority for successor activities and the model is adjusted accordingly to satisfy the requirements of the project as a whole.

In the intervention, the traditional practices are reinforced with the implementation of the performance control with 4D BIM. These have been carried out in parallel since the managers did not want to jeopardize the construction operations by exclusively experimenting with an alternative method. Therefore, S-Curves have remained as a tool for the biweekly meetings, however, 4D Models have been implemented with the performance comparison between as built progress and what was planned on the baseline schedule. Additionally, the two week and six week look ahead have been generated with the aid of the 4D model to represent in detail the upcoming works to be completed.

Over the course of the two months, after every two week cycle finished, adjustments were made to align the progress to the six week look ahead plan since the six week look ahead has more time for adjustments to be carried out to make up for any shortcomings in the performance of each cycle. Over the two week cycles (as seen on Figure 33) the execution is ongoing on the site and tracking of activities is done on a daily basis and this is reflected on the daily reports. On the second week, the biweekly reports are completed in which the data feeds the S-Curves and Schedules. The progress is compared to the baseline on the 4D model and it is then adjusted with the necessary contingency measures and the interface coordination. Afterwards, the two and six week lookaheads are extracted from the adjusted model. Finally, the progress is presented and evaluated during the biweekly progress meeting and afterwards, the two and six week lookaheads are communicated to the teams on site. After this cycle, the process starts again with the execution and tracking on the first week as seen on Figure 33.

Over the course of each cycle, on the second week, interviews have been held with the staff on site and management to adjust the framework to prepare for the final recommendations. During these interviews, the interviewees state what they reflect has improved, worsened and evaluate the impact of the results seen due to the implementation of the intervention.

Figure 33. 2 Week Cycle Overview

4.7. Framework Setup

In the previous section, the iterative process of the implementation has been described. In this section the intervention framework is described and the substance of what has been implemented in the model is tackled at each level of the organization. In a functional level for site coordination and control, the logic of the intervention is to include the 4D model in performance control, interface coordination and look ahead planning for the remainder of the project. The process in Figure 34 starts off with the master schedule which sets the requirements for the project. The internal schedule is merged with the 3D model to generate a detailed sequence at work package level to establish an internal baseline that must satisfy the Master Planning requirements and milestones. In the 4D model, the look aheads are carried out in an independent manner. Then, the independent models are merged into a project 4D model in which the interfaces are revised and the requirements from one work package to another are solved. The 4D models are communicated to each work package site team. During execution, progress is tracked, and this progress is fed to the Master Plan for updating and adjusting the status of the project.

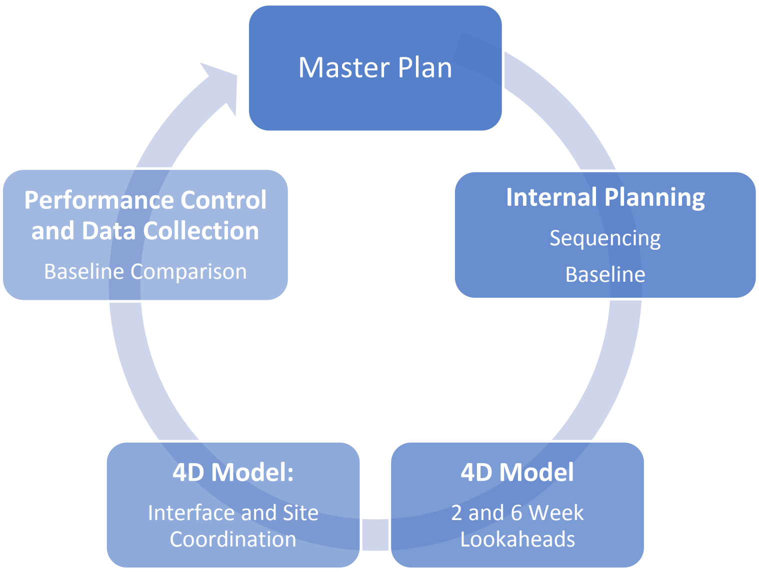


Figure 34. Iterative Planning Cycle

4.7.1. Stepwise coordination

However, the aim of this research is not only to improve the performance control and planning of remaining activities, but to integrate the efforts in a smart way through BIM as presented on the flow of information on Figure 35.

The process on Figure 35 begins with the Issued for Construction (IFC) drawings delivered by the client and the design engineer. These are first manipulated by the Drafts Department under the supervision of the Engineering Department and the 3D object based parametric model is generated. The drafts department creates workshop drawings which are then linked to the 3D model and the properties are accessible in the model. The 3D model is now ready for the 4D Planning Engineer to sequence the works along with the planning department and the package engineers to satisfy the initial Master Plan that usually comes from the tender stage in less detail.

Afterwards, the sequence is trialled and ran to revise the interfaces. Until this point, the process is not yet an integrated BIM process. Moreover, up to this stage, the practice on site in the case study went as on the model before the implementation of the intervention. The first steps have been deemed efficient and the research has built upon them since these are aligned with the ideal practice of the theory in the case of a traditional contract. However, the remainder of the aspects of integration and usage of the 4D BIM model were not as proposed below since the model had only been used for preconstruction purposes and the project was not tracked with the model. The aim is to integrate and update the planning through the BIM capabilities by linking and auto-matching the model with the master schedule. To increase integration and efficiency, a mobile application can be used in which the 4D model is used for updating the progress on site (Synchro Site) and then this data can be used to update the master plan without the need of manual tracking on Excel spreadsheets which prove to be inefficient and visually constrained in most cases. Therefore, the site management is fed with 4D model visual progress control evaluations, 2 and 6 week look aheads and a visual tool for site tracking (as well as a specification and drawing loaded model) and in return, the site management feeds the 4D planners with compatible format daily reports, as built progress and feedback on the planning to share their expertise and improve the plans.

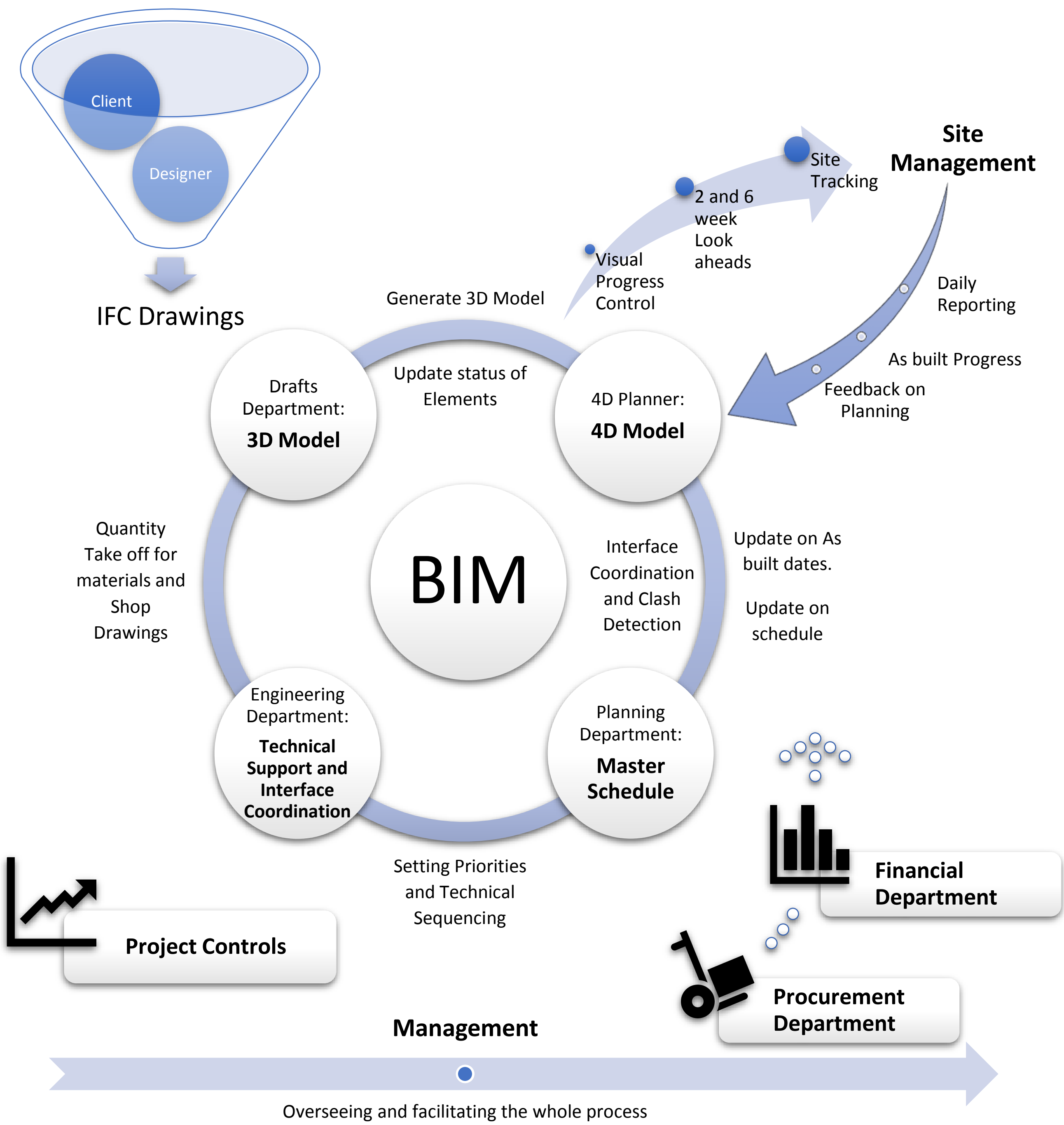


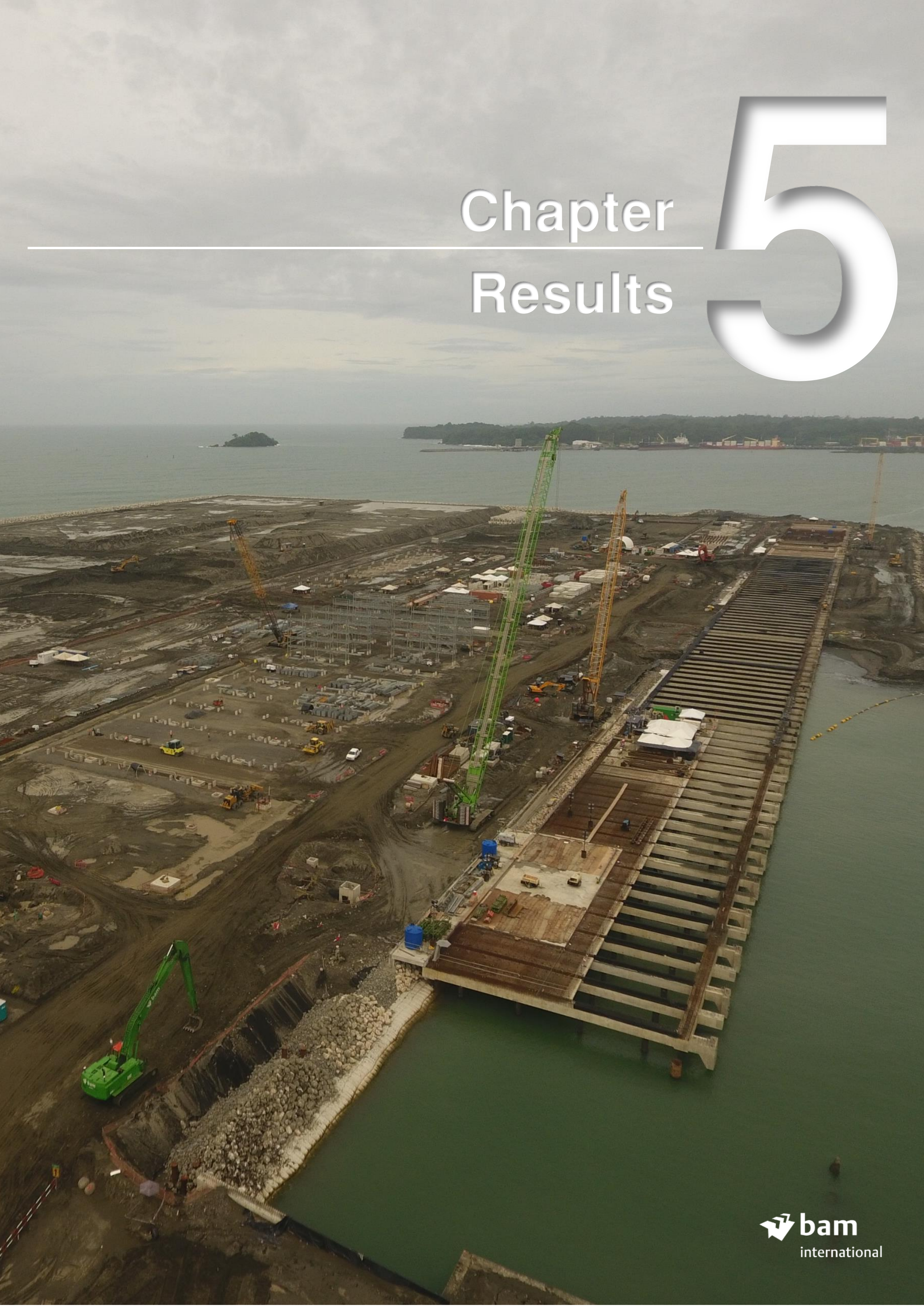
Figure 35. BIM Framework Setup

4.8. Influencing Factors

The aim is to compare the results under similar circumstances both prior to the implementation and during the implementation (a fair comparison). Factors such as quantity of personnel in the work package, weather conditions, machinery, ongoing works (both during the implementation and prior to it), if the period has a bonus offered to personnel (additional incentives to finalize works in an accelerated manner) amongst other aspects have been deemed as influencing factors and therefore, have been recorded throughout the whole process. The objective is to capture all of these aspects both prior and during the intervention, in order to select those periods that have similar conditions to those during the intervention. Those periods which do not match the conditions during the implementation have not been included in this research since these distort the analysis and do not offer a fair comparison. Also, new work fronts that have been opened during the implementation such as the placement of paver blocks (which was not ongoing prior to the implementation), have not been included in the analysis, since these would make the progress appear artificially higher than it was prior to the implementation.

The following chapter shows the results of this implementation, both at tool level, as well as framework level. The tool and framework will then be adjusted accordingly, depending on the feedback received from the interview sessions.

Chapter 5
Results



5. Results

The Results chapter presents the outcomes of the implementation as well as the reactions to the intervention in an interview approach. However, first it is necessary to establish how the data was collected, followed by the quantitative results at work package level for each work package. Following these results, a qualitative evaluation of the behaviour of the tool framework is included and how the actors perceive the results obtained. The present chapter answers the sub research questions:

"Which are the factors that hinder the implementation of 4D BIM for planners and managers?" *(section 5.3.2.2)*

"To what extent can an implementation of 4D BIM improve construction project performance control and reduce delays?"
(sub-sections within section 5.2)

"What are the perceptions of construction managers, project managers and planners about 4D BIM and the introduction of new technologies in construction site execution for deviation control?"
(section 5.3.2.3)

5.1. Data Collection Process

During the two months of the implementation, the data was gathered from updates on the daily reports and tracking on site to capture the earned value figures for each work package and contrast it with what was recorded prior to the intervention. The weekly progress on each work front has been recorded as a percentage of the total scope of each work package.

Moreover, it was necessary to capture the alignment of the activities on site with the planned sequence, therefore, on a weekly basis these were contrasted between the baseline (2 week look ahead) and the as built and then quantified to establish a performance indicator for "in and out of sequence" activities. From this, it was possible to estimate an SPI of activities completed compared to activities planned. Also, one can visualize and calculate the amount of activities that are delayed compared to the baseline.

It is important to highlight the fact that the key performance indicators calculated in this research are in comparison with the 2 week look ahead which becomes the reference point since it would not be practical or it would be of little value to compare and control activities with a baseline in case there are significant deviations on the schedule. However, the aim is for the production to adhere to the project baseline.

5.2. Quantitative Results

The present section addresses the quantitative results obtained during the implementation to quantify the benefits of the intervention and answer the sub-research question:

"To what extent can an implementation of 4D BIM improve construction project performance control and reduce delays?"

5.2.1. The Wharf

5.2.1.1. Earned Value

Due to confidentiality reasons, the earned values will be presented in progress percentage on a weekly basis and not on quantities that may derive performance rates nor monetary figures. Traditionally, the wharf deck and other slabs are controlled by area or in other cases volumes. The wharf deck has had barely eleven weeks of progress prior to the implementation.

From Figure 36, it is possible to see that the average progress values prior to the implementation were approximately 1%, and during the implementation these values rose to an average of 4%. One of the reasons for this increase is the acceleration in the process of maturing in the Learning Curve, since the process was made clear in which is the optimum sequence that needs to be followed, consequently, the efficiency has increased.

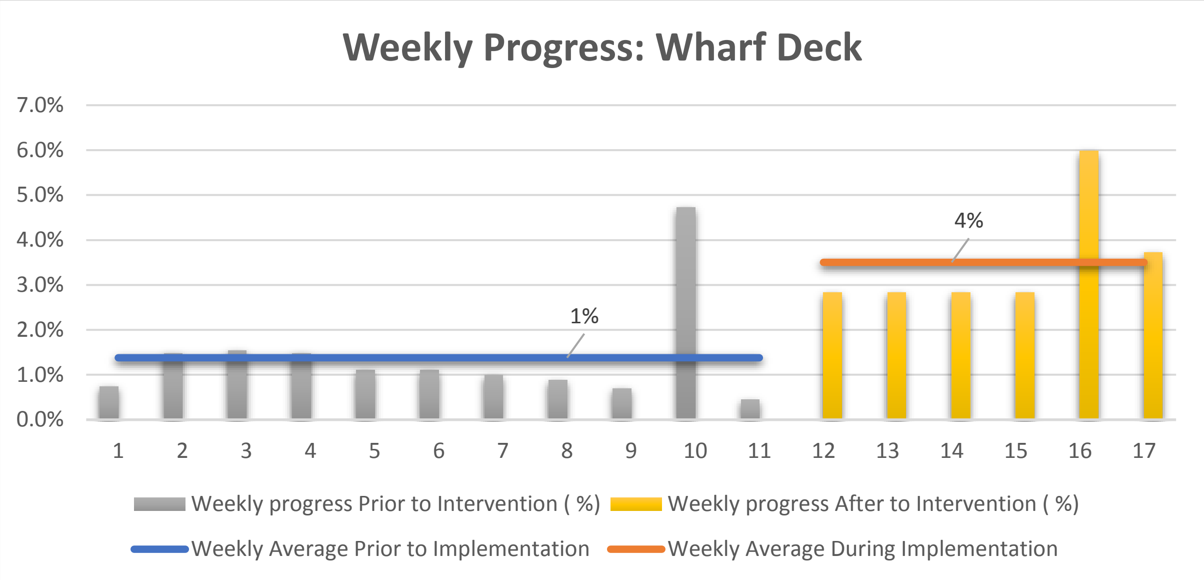


Figure 36. Weekly Progress Wharf Deck

From Figure 36 it is also clear that the minimum values during the implementation (2.8%) are higher than both the minimum values prior to the implementation (0.7%) and the aforementioned average values prior to implementation. It is therefore possible to determine that the general production level during the intervention has risen (the minimums and maximums are higher).

To be able to understand the reasoning and the link with the implementation, interviews were held with the area operations manager and local operations manager which share the opinion that the visualization carried out with the aid of the 4D model makes the goals more tangible and as a result, in terms of accountability it was easier to state whether the goals were being met or not. Through the 4D model, the crews on site knew specifically which elements were being requested to be completed over the course of two weeks.

5.2.1.2. Schedule Performance Index (SPI)

For the wharf deck works it is possible to observe on Figure 37 that the average level of the Schedule Performance Index rose from a 33% prior to the intervention, to a 65% during the intervention. Even though the average progress rose on a ratio of 1:4, the reasoning behind the increase in the SPI in a 1:2 ratio is due to the fact that the plans requested an increasing production rate. This is why on Figure 37 one may clearly visualize that prior to the implementation, the SPI trend had a negative slope (downwards slope). This can also be seen on the graph on the values during the implementation in which the trend is also downward sloping since the planned estimates have an incremental trend, but production has plateaued as seen on Figure 36.

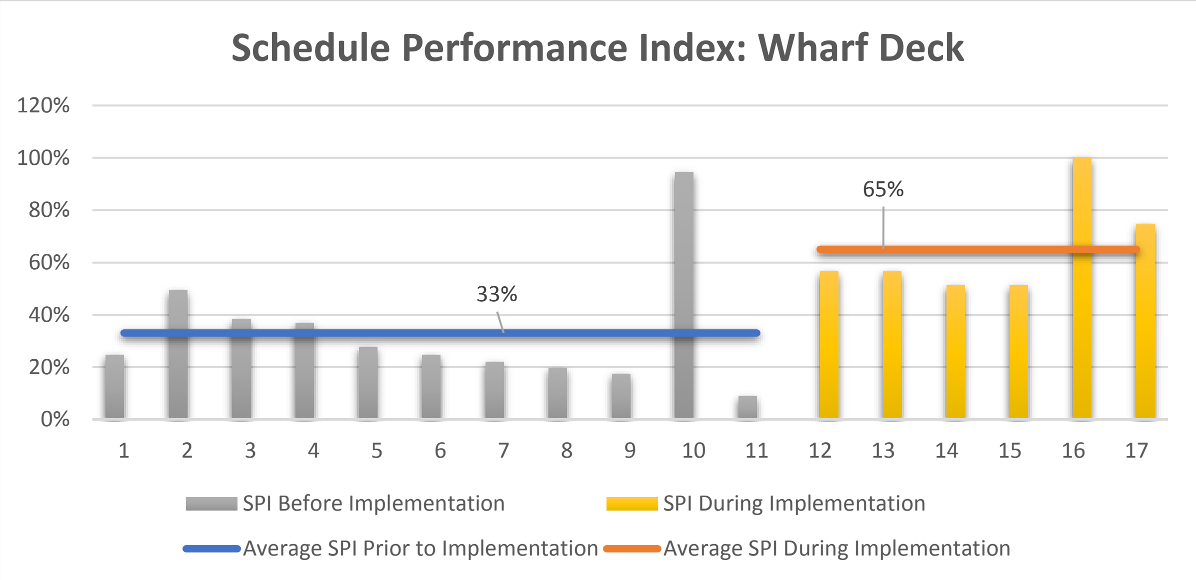


Figure 37. Schedule Performance Index Wharf Deck

From Figure 37, one can understand that during the intervention, plans are accomplished at a higher rate, which means that the reliability of the estimates, even though is still low (average 65%), it has risen. This information is aligned with research that states that productivity is not improved by completing as many tasks as possible, neither from increasing workload or hours worked, but by making work flow more predictable (Liu, Ballard, & Ibbs, 2011). The increase in the case study may be explained by the fact that the schedules and 4D Models improved their quality by updating these on a regular basis which increased the reliability of estimates. Since the wharf deck works have had only 11 weeks of production prior to the implementation, the crews on site should be expected to increase these values and experience further maturing on the learning curve.

5.2.2. Utilities

5.2.2.1. Earned Value

Traditionally, the utilities are measured by linear meter of construction and then the systems are weighed based either on cost or effort required. For this report, the utilities are not weighed and all the corresponding linear meters are stacked together as one sole work package for confidentiality purposes.

From Figure 38 it is evident that the average progress has an increase from 1.08% (prior to implementation) to a 1.82% (during the implementation). In terms of minimum values, it is clear that the values during the implementation have risen (0.60% to 1.46%). The Production has stabilized relatively during the implementation on a higher range of values (higher minimums and maximums). According to the interviewees, the main aspect that allows for a significant increase in progress is the coordination of works in a smart manner that enables the crews on site to follow a more efficient sequence, following the logic of completing the works in terms of depth and working by layers, instead of progressing with the different layers in parallel.

Prior to the implementation the works were carried out on the available works spaces left by the rest of the work packages. During the implementation, the aim was to maximise the lengths of the work spaces available by coordinating with the rest of the work packages and clearing these work spaces. This allows for an increase in productivity which is seen on Figure 38, since the crews on site can perform repetitive tasks over larger distances and increase the progress rates and achieve a continuous flow, with the aim of decreasing disruptions which lead to low productivity (Enshassi, Mohamed, Mayer, & Abed, 2007).

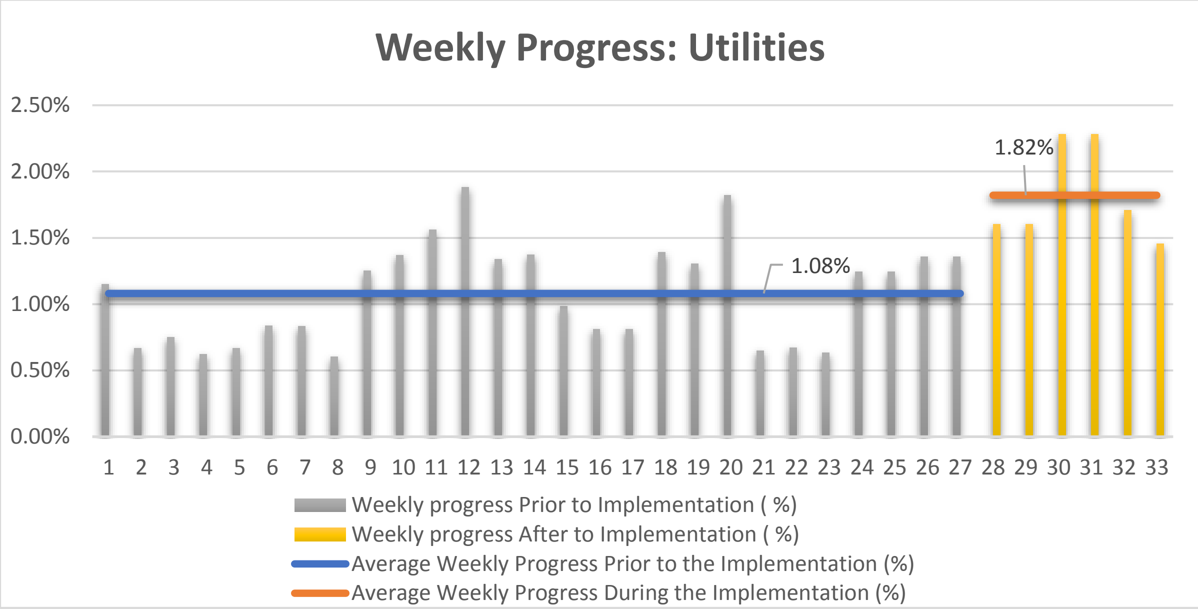


Figure 38. Weekly Progress Utilities

5.2.2.2. Schedule Performance Index (SPI)

Contrary to the wharf deck works, the Utilities works had been ongoing for a larger period of time prior to the implementation (approximately 43 weeks). However, the works and interfaces had not been coordinated in such a way that the crews could take advantage of repetitive tasks that would enable them to become more efficient on each activity since there was a constant shift between one discipline and another prior to the intervention. Therefore, there was still area for improvement and maturing on the learning curve on this work package. This is evident on Figure 38. However, on Figure 39, one may understand that the average SPI prior to the implementation was of 66%, which is higher than the average achieved during the implementation by the crews in the wharf. On this same figure it is possible to observe how the average SPI rises from 66% to 86%.

Interviewees state that through the 4D Model they can easily pin point out of sequence works and underperforming crews through the colour coded array of objects, as well as portions of works that were being left behind. According to the management, an increase in accountability has been experienced since there is a visual evaluation tool of the work fronts that has motivated the crews to deliver what they are being expected on a biweekly basis.

By coordinating in a spatial manner through the 4D model, it was possible to foresee the work spaces that needed handling of obstructions (containers and materials). According to the interviewees, in this spatial coordination (two and six weeks in advance) lies the key to the increase in productivity since work spaces were cleared in advance, contrary to the previous situation in which the crews would enter limited work spaces since these obstructions had not been removed in a timely manner. As a result, this has increased the rate of success (SPI) in the plans per bi-week. According to interviewees, there was more of a project view, than a work package view. The supervisors stated that the works progressed in a smooth way without wasting time waiting for other work packages to move containers or other materials from other's workspaces.

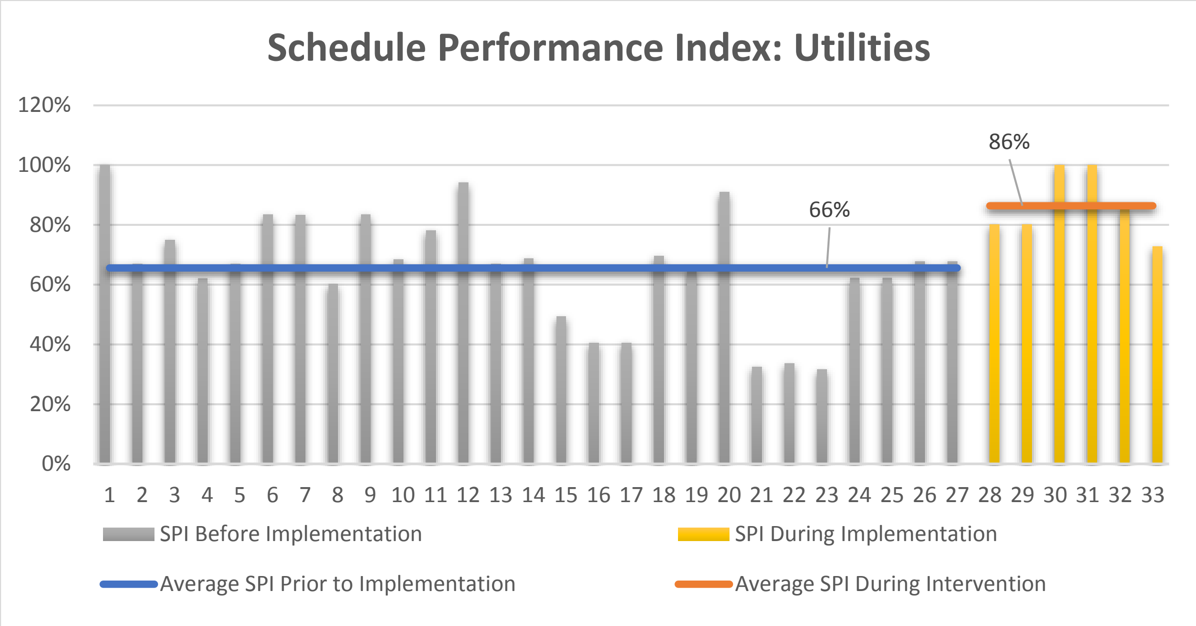


Figure 39. Schedule Performance Index Utilities

The construction manager stated that as a product of a deviation, it is necessary to recalculate all the remaining works, since it is possible that the interfaces have shifted to a later time which may involve a clash with machinery from another work package. The lack of performance in the past impacts the performance in the future if new interfaces arise and were not foreseen. Interfaces are not static.

5.2.3. Civil Works

5.2.3.1. Earned Value

The following disciplines (Slot Drains and Busbars) are commonly controlled in linear meters. For the present research these are analysed separately, since stacking them together would give misleading results, since the interface coordination of each of these relates to two different work packages as well as the nature of each work.

In the case of the Slot Drains, on average numbers, the progress was duplicated (from 1% to 2%) as seen on Figure 40 and it is clear that the rate of production stabilizes during the implementation. According to staff on site, this is due to the coordination of traffic along other routes that would enable the completion of these works. Prior to this coordination, the slot drains were seen as an obstacle for transiting in the island since it is on the main corridors to access the Wharf.

For the Busbar Foundations, as seen on Figure 41, a greater increase in progress was experienced since the average progress rose from 1% to approximately 5% during the implementation. This is the element with the greatest increment and it is explained by the coordination that was lacking with the mobile crane that was used in the reefer rack area and as a result, there was not a steady stream of works being carried out, which leads to a need for reorganizing personnel elsewhere. In terms of performance, these works do not see a great deal of change in accountability or sequencing of works since these are straight forwards works that are completed in one concrete pour and decision makers understand that it suffers a problem of workspace availability.

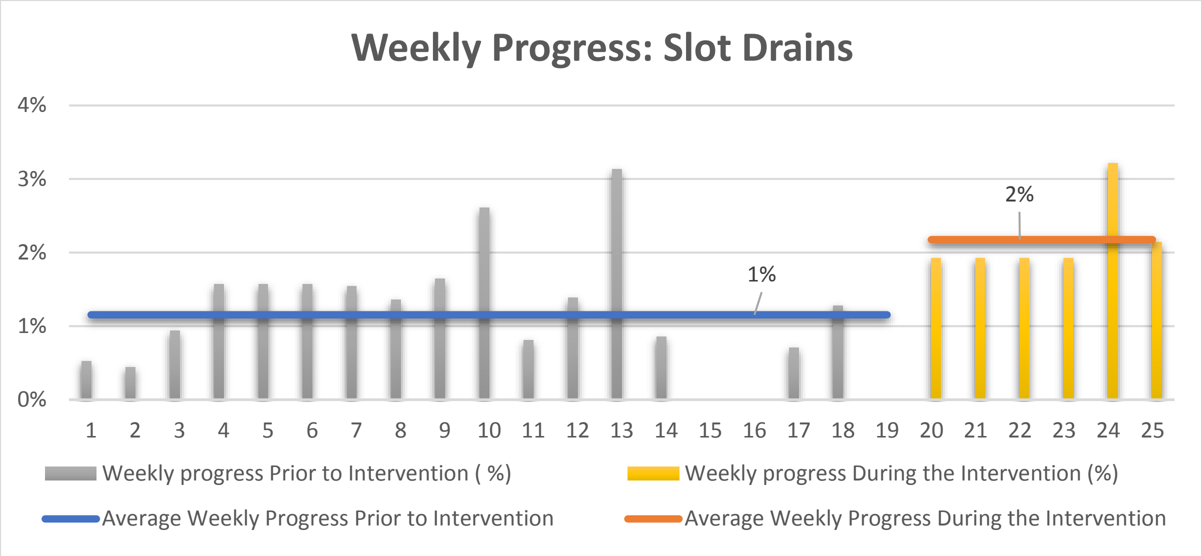


Figure 40. Weekly Progress Slot Drains

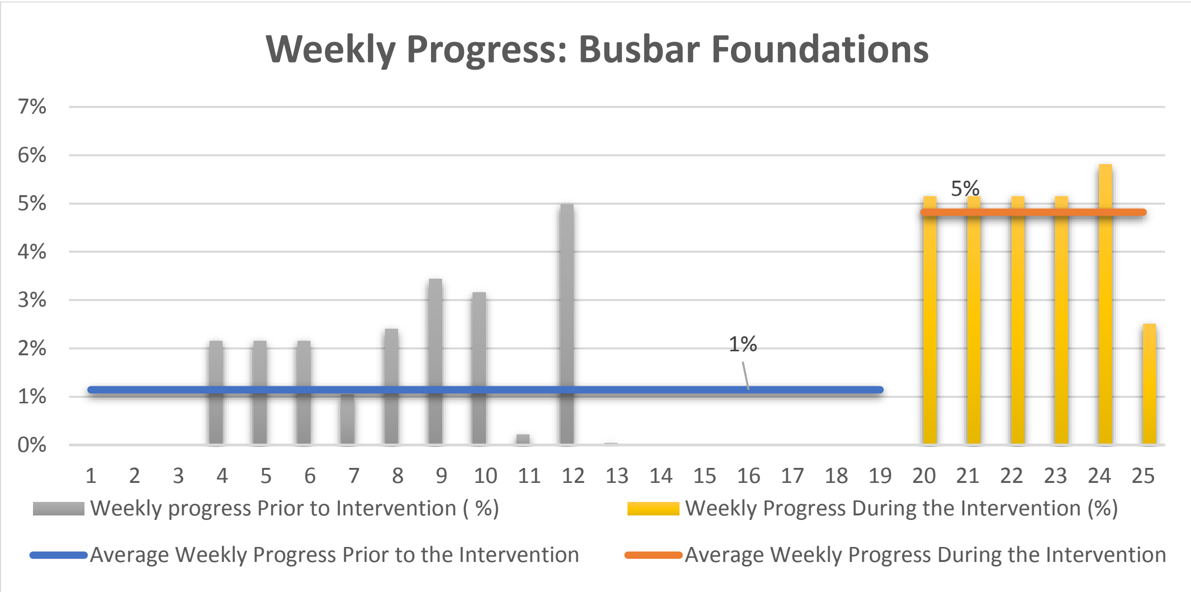


Figure 41. Weekly Progress Busbar Foundations

With regards to the slot drains and the busbar foundations, the main concern was that these sub work packages did not have any work spaces available for efficiently entering and completing the tasks. Therefore, during the interface meetings, the plan was to enable work spaces for the slot drains and busbar foundations through a close out campaign of certain utilities that had been completed. The construction manager stated that S-Curves hide information such as an element that is complete up to 95 to 99%. With this, it is not always possible to open up workspaces for the successor activities. Through the 4D model, the incomplete predecessor items were signalled according to the colour code and the crews proceeded to tackle these items as a first priority. Teams on site are quantity driven in their progress since they are asked to do quantities, not specific items.

5.2.3.2. Schedule Performance Index (SPI)

Schedule Performance Index values for the Slot Drains prior to the implementation fluctuated each week and achieved an average SPI per week of 68%. During the implementation, the production met the targets required every week for an average SPI of 100% as seen on Figure 42. According to the staff on site, the Slot drains met the targets every week during the implementation since there was a work space coordination that enabled the crews to enter these on a regular basis. Prior to the implementation, teams encountered the planned work spaces had conflicts with other work packages or the access roads. In the case of the Busbar Foundations, on Figure 43, the same behaviour is shown as in Slot Drains. The tasks are driven by workspace availability. This is aligned with research that states that increased reliability on a workflow in which they could maintain a steady pace is more efficient than carrying out sprints on workspaces when these are available (Winch, 2006).

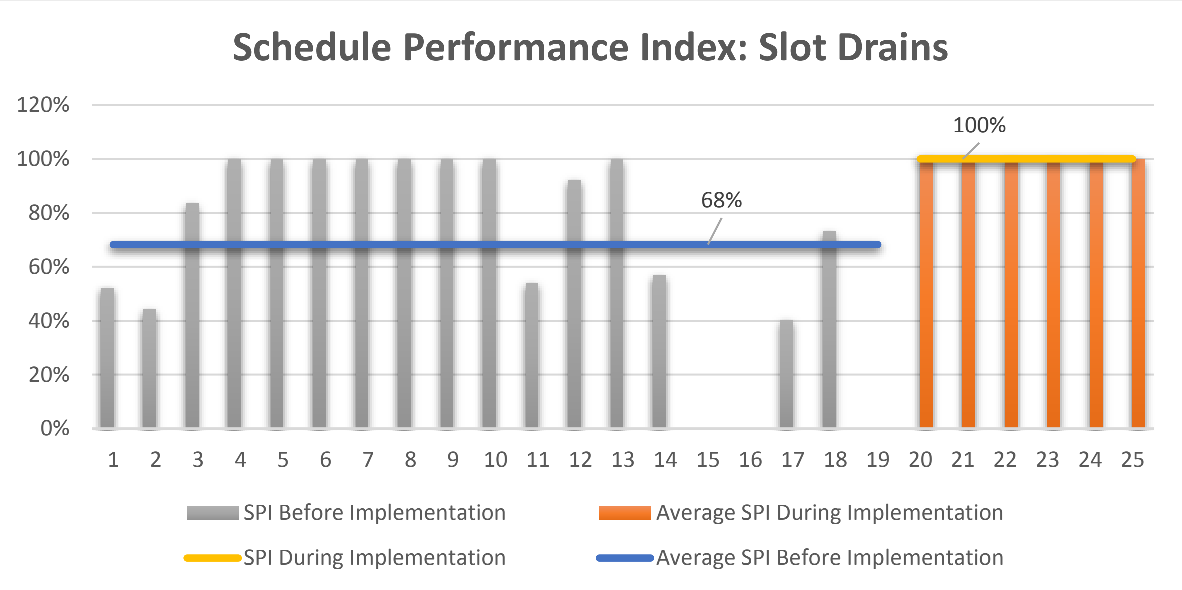


Figure 42. Schedule Performance Index Slot Drains

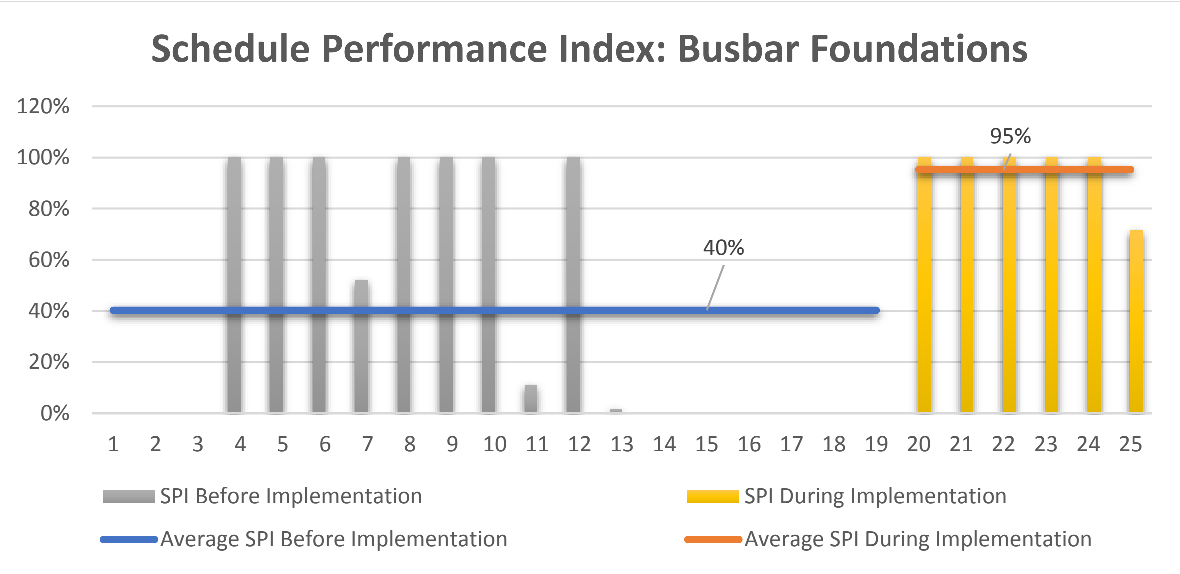


Figure 43. Schedule Performance Index Busbar Foundations

5.2.4. Pavements

5.2.4.1. Earned Value

The Pavements are the last activity in the sequence of works in the project. Also, it is highly dependent on work space availability. Resources then need to be allocated according to the work spaces that the predecessor activities can supply. It is not efficient to complete the tasks as soon as the crews can with a large amount of machinery, if this is going to stay idle for longer periods of time. Therefore, it is desirable to maintain a limited fleet that can tackle the workspaces available in a manner that does not increase the rental costs. This is aligned with the theory of continuous flow of Lean Management

(Al-Sudairi, 2007). It is therefore not efficient to have production peaks if resources will remain idle and increase the operational costs.

Given the conditions mentioned above, the weekly progress decreased its maximum weekly peak values considerably, since on average, the weekly values achieved were of 0.99%. prior to the implementation. During the implementation, the production was stabilised at a 1.02% average production which in fact is higher than the previous average as seen on Figure 44. The difference is insignificant. However, the important aspect in this section is the work space visualization one may see in the near future. This is not possible just by looking at the performance rates of the available resources. One needs to visualize what is actually possible to complete in the coming future, given the availability of work spaces. Perhaps this is one of the most important aspects that can be derived from all the results analysed in this research. Interviewees state that during the planning, those involved tend to be overly optimistic and neglect the actual spatial condition, as well as interface coordination.

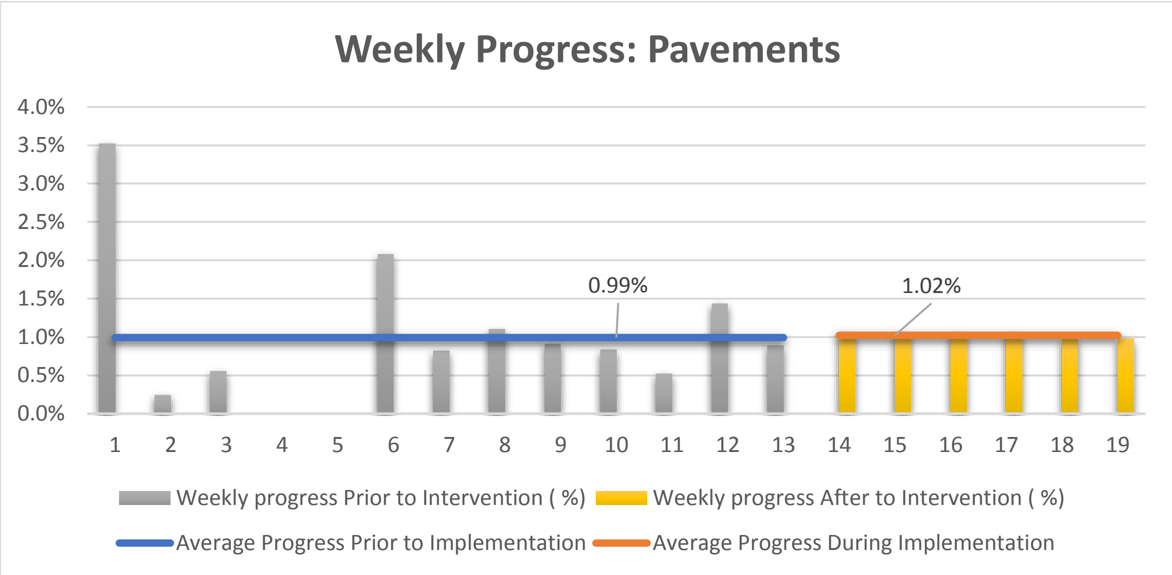


Figure 44. Weekly Progress Pavements

5.2.4.2. Schedule Performance Index (SPI)

Given the temporarily reduced fleet for the Pavements, yet remaining with the same baseline scheduled plan, there is a decrease in the SPI between the period prior to the implementation (67%) and during the implementation (51%). The targets should have been adjusted, yet since it is a baseline, these are fixed. However, during the implementation, the strategy shifted in the predecessor activities as to focus on handing over their lagging work spaces to the pavements teams. Nevertheless, the effect on the focus on these workspaces is not translated into an immediate result, but one that has a certain lag, since the Utilities open workspaces for the Busbars and Slot Drains which later on open up a work space for the Pavements. Therefore, as stated by the operations management on the project, it is expected that the availability of workspaces would increase with the aforementioned lag.

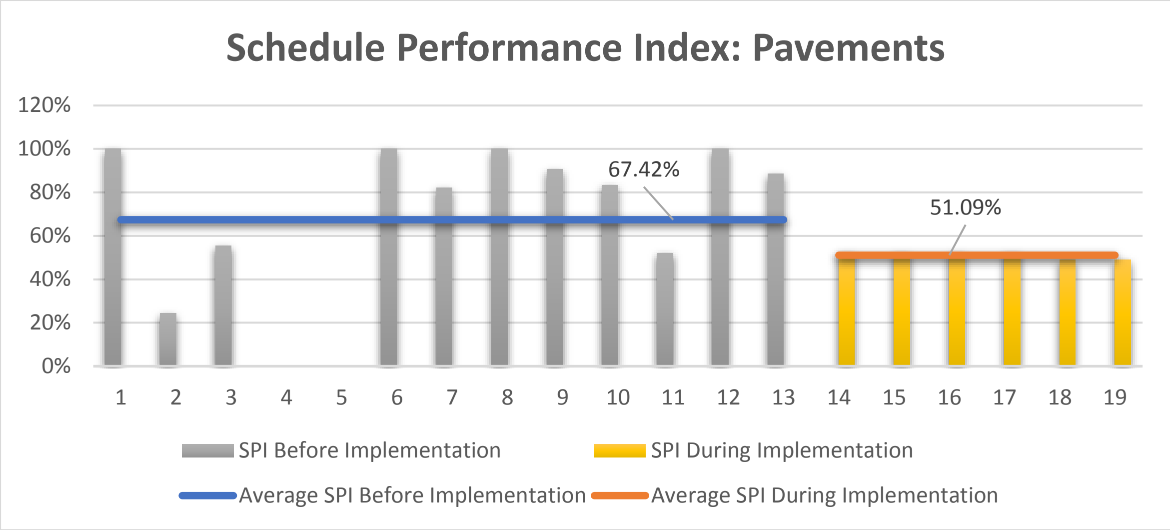


Figure 45. Schedule Performance Index Pavements

5.2.5. Reefer Racks

Due to the fact that Reefer Racks have achieved a finishing touches stage and therefore its progress curve has reached the upper plateau of the S Curves (lower weekly progress values), the analysis of results in terms of earned value and SPI would not be suitable. However, a qualitative analysis is carried out in terms of the interfaces with other work packages.

To be able to start the works, it was necessary to have the workspaces handed over from the crews that were in charge of building the pedestals upon which, the reefer rack structures were erected. The model was used to identify those lagging activities that were preventing the installation of the reefer racks and these were tackled. However, these were not completed by the end of the implementation period, yet these were advanced in the process. The implementation permitted to accelerate the recovery from the deviation.

In terms of the crawler crane used for hoisting the metallic structures, since there was a significant deviation in the predecessors of the installation of the reefer racks, a recalculation and resequencing of activities had to be carried out since the crawler crane would clash with the civil works and utilities. This is a clear example of the derived clashes from a significant deviation in the predecessor.

5.2.6. Administration Building

Similar to the Reefer Racks, the Administration Building has reached the finishing works during the implementation, which are not comparable to the steel structure erection and concrete works. However, it is possible to analyse the interface management between subcontractors in a qualitative manner.

The workspace distribution was carried out in a 4D Model analysis and these were controlled this way to see their alignment with the baseline. In terms of performance control, this was improved since a time location distribution was required to coordinate and control all the subcontractors. However, special attention was required in the setup of the model since floors, walls and ceilings have different layers of works. Therefore, it is necessary to make use of the white transparency in the scope to be able to pin point which layer the model is making reference to.

Also, at an exterior point of view, it is possible to analyse the interface between the temporary perimetrical scaffolding from the building, the utilities connecting to the building and the window subcontractor, in a qualitative way. Initially, the plans had the installation of the underground utilities prior to the placement of the scaffolding. However, given a negative deviation of the utilities, the scaffolding had to be placed in the perimeter of the building without the completion of the utilities. Given the need of energizing the building, a resequencing of the window installation had to be done to allow for the works to be done on time. Interviewees state that in the event of deviations in a project, the remainder of activities are then planned in an accelerated manner which means that are closer together and in some cases overlapped. According to them, this increases the need for improved visual coordination of remainder of activities.

5.3. Qualitative Results

5.3.1. Conceptual Model Performance During the Implementation

In the previous sections a quantitative analysis of results has been carried out on the impact the model had on the progress, as well as the schedule performance index. In the present section, an evaluation is carried out on the performance of the conceptual model during the implementation in terms of the qualitative results. From this assessment, the author can determine the points of improvement in the tool in terms of the visualisation of the construction sequence, two and six week look aheads, interface and workspace coordination, deviation control, colour coding, critical path visualisation and the coordination of the remaining works with the aim of formulating the recommendations and conclusions. One of the aims has been to bridge the knowledge gap in 4D BIM (which has been used mostly for preconstruction planning) and propose a model to show the possibilities of its implementation during the site execution.

5.3.1.1. Visualisation of Construction Sequence: Coordination of Remaining Works

Prior to the implementation, the 4D model was used only for preconstruction analysis of the sequence of works. During the implementation, the model was updated and revised on a biweekly basis and the remainder of works of the project were recalculated and visualized. Initially the coordination of the remainder of the works in the project was carried out in detail during the implementation, yet the 4D modeler and engineers stated that the detailed plan should be done for a reduced time window and the remainder of works in a less frequent basis since it is a time-consuming practice and the stakeholders can only plan ahead in detail (at execution planning level) for a reduced time frontier such as six weeks. However, they stated that it is of high benefit to carry out simulations of the remainder of works in the project to check the interfaces and their assumptions periodically.

Since knowledge increases as the project progresses, interviewees stated that it was highly profitable to introduce the lessons learned into the model and correct initial assumptions with the additional information available. Staff on site specified that since the sequence was made clear in the 4D Model during the implementation, it was simple to understand the logical arrangement of tasks, and therefore discuss further to agree on the appropriate array of works. They also stated that it gave the staff a better understanding of the scope of works ahead to be able to position themselves on the site in a strategically efficient manner without the need of double handling of props and materials.

5.3.1.2. Two and Six Week Look Ahead

Since the two and six week look aheads were carried out in a joint effort between the planning department, 4D Modeler, engineering department and site staff, six week look ahead plans aligned the execution plans with the master plan and as a result, out of sequence works decreased considerably.

During the implementation in the biweekly meetings, the two week plan was contrasted to what was actually constructed as seen on the right frame on Figure 46. According to staff on site, this generated a greater level of accountability in the foremen on site, since the two week plan was seen as a visually binding target (on the left of Figure 46) that could be easily contrasted to what was in fact constructed (on the right of Figure 46). As stated by the staff on site, this made clear that the site management was well aware of what each work front had to deliver and what they actually did. Therefore, it increased the commitment on the site staff to completing what was targeted for the two weeks.

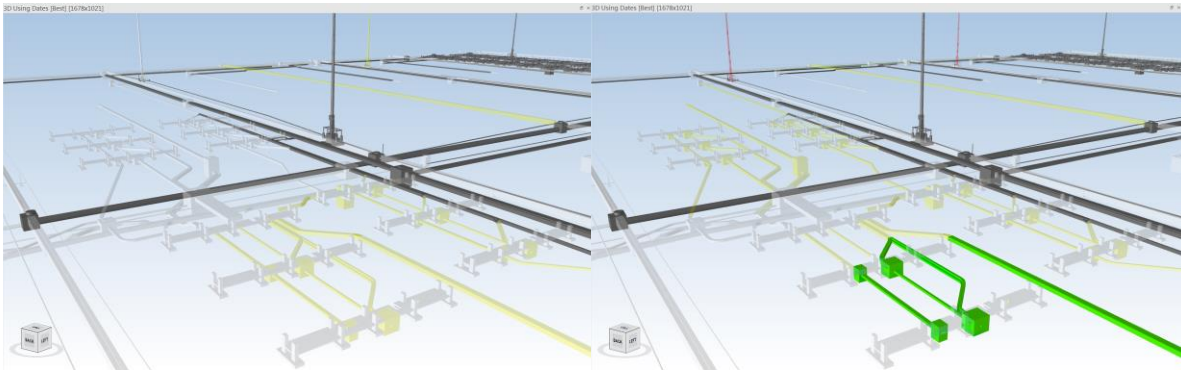


Figure 46. Contrasting what should have been completed in yellow (left), to what was actually completed in green (right)

5.3.1.3. Interface and Workspace Coordination

Interviewees stated that the quality of the comparison between the as built and the baseline plan relies highly on the quality of the latter. If this benchmark sequence does not offer a feasible plan, then the situation on site may deviate significantly from the as planned sequence. As a consequence of significant deviations between the baseline and the as built, the analysis would not offer comparable performance results and would require for an adjusted forecast to be issued. Interviewees also stated that if interfaces are not properly coordinated, then the forecasts are flawed and would need to be adjusted at a later stage to reflect an updated forecast.

During the implementation, the separate 4D Models from each work package were combined in one sole project model to detect clashes between disciplines with the aim of coordinating the workspaces in advance and improve the estimates of completion of the remainder of works of the project. By introducing the intersection volumes proposed in the research by (Kassem, Dawood, & Chavada, 2015), an evaluation of the workspace was carried out, including the manoeuvres from machinery and their positioning. According to the interviewees, during the implementation a more realistic assessment was carried out since the initial coordination of activities during the preconstruction phase considered the objects to be built isolated from the rest of the work packages without the aid of the intersection volumes. This analysis enabled to adjust the baseline for the remainder of the project that yielded improved results. This can be visualized in the increase in the schedule performance indices in the evaluated cases. The increase in progress values is aligned with the findings in the research carried out by (Mallasi, 2006), in which links a reduction of productivity with poor workspace planning. In terms of the process of setting up the intersection volumes, the interviewees stated that whole array of possibilities in which the moving machinery may interfere with other parts of the project, make it highly time consuming and state that it would be ideal to simplify the analysis.

By including temporary structures such as scaffoldings, containers and site offices in the coordination, an increase in the success rate of plans was achieved as seen on Figure 36, Figure 38, Figure 40 and Figure 41. Interviewees stated that by including these elements, the quality of the six week lookaheads improved significantly, and these became a realistic run through simulation of the following six weeks of the construction sequence and interface coordination, rather than the prior practice of highlighting on a drone picture those areas to be tackled by the site crews.

According to the staff on site, the forward look up to the completion of the project aids in understanding which are the ideal locations to mobilize their props, offices and materials, so that they would not waste time in double handling of these. According to them, this forward look created an awareness of the works carried out by other work packages, which they did not have prior to the implementation and permitted them to make decisions without harming the progress of others involuntarily, such as mobilisation of offices and materials around the island. This is a clear shift towards a project oriented view, rather than a project island view. Interviewees stated that it is not their intention to create project islands, however, due to the lack of information on the works to be carried out by others, it is not possible for them to identify the potential interface clashes.

The planning of the pavements as well as the subcontractor coordination in the buildings evidenced one major shortcoming of traditional methods of planning and controlling performance, which relates to the availability of space to start the works. Prior to the implementation, this was carried out by looking at the tracking Gantt Chart. However, this did not offer a physical representation of pending items. During the implementation with the 4D Model it was possible to visualise the up to date status of works and those tasks that were pending signalled in a red appearance. By representing on the 4D model the availability of work spaces through time, subcontractors and managers could estimate their optimum levels of resources. Instead of maximising their resources and therefore, experiencing resource peaks, the approach was to estimate the targeted production and the resources based on the available work spaces. According to the planners interviewed, this reduces the idle hours of resources, since these would not have a continuous operation under the previous approach, but a start and stop condition.

By understanding the actual estimate of available workspace, decision makers can act on the bottle necks and increase the resources accordingly on predecessor activities to make the targeted workspaces readily available or focus the available resources on those specific points that are lagging.

5.3.1.4. Traffic Management

All projects require access for resources to reach the workspaces, regardless of the size. These accesses inevitably interrupt works temporarily from being completed, until these accesses are shifted elsewhere. Therefore, the works need to be coordinated in a smart way to prevent the access from further affecting the performance of a project. Traffic management is not part of the theory of performance, however, to be able to deliver a sound baseline, aspects as this one need to be looked after in the process of the baseline set up. This aspect relates closely with the previous section on workspace coordination.

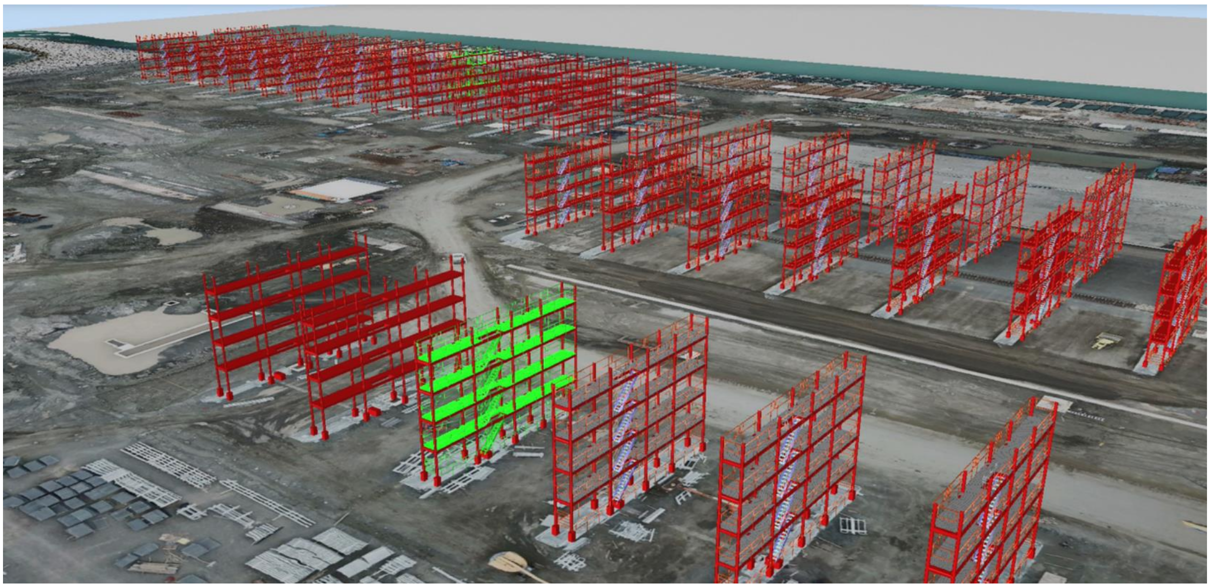


Figure 47. Traffic Management Around Reefer Racks

Prior to the implementation, the traffic was managed according to the preconstruction plans. However, given the deviations, an updated long term version was needed, since the temporary roads required for constant shifts in location and reworks. By doing an integrated plan between the work packages in the 4D Model and placing the top view drone picture (as seen on Figure 47) into the model and coordinating the traffic as well as the workspaces, the availability of workspaces increased considerably and the cascading effect allowed for higher progress values at project level. At performance control level, the feasibility of plans increased considerably and therefore, the as built was comparable to the baseline since prior to the intervention, the traffic management was a reason given when failing to accomplish the targets, because there were constant shifts of roads and therefore, interruptions. The idea has been to reduce the negative effects of external controllable factors to focus on the actual performance of the crews when evaluating them.

5.3.1.5. Visualisation of Deviations

By overlapping the as built 4D model on top of the baseline 4D model, the model automatically signalled clearly the points where the site crews were lagging behind compared to the baseline plan. According to the interviewees, this made the detection of deviations to be immediate, simple and clear. Interviewees stated that this was a good practice, as long as the baseline plan was a feasible one. If it was not the case, the baseline would need updating to be a comparable parameter.

According to the management, this simplified their decision making, since normally they do not possess in depth knowledge of the whole scope of works in a mega project, and even less do they know what is the exact state in terms of progress of each element in that scope. Therefore, by signalling those lagging elements, it is straight forward for them to visualize the status and act upon this diagnosis of the works on site. This suits the purpose of the research.

During the implementation it was possible to see those items that had negative deviations (lagging behind the baseline). However, those elements that had a positive deviation were not signalled out. There are different opinions on this subject since some stakeholders stated that the positive deviations should be rewarded for the surplus in progress, however, others stated that it would promote a quantity oriented mindset with out of sequence works.

5.3.1.6. Performance Colour Coding

Initially, the proposed colour coding for as built elements (green for on time elements and yellow for delayed works) was not overlapped on top of the grey elements. Therefore, interviewees stated that the model was overwhelming and it was difficult to focus on the deviations, which were the most important aspect for the decision makers. Therefore, the model was corrected, and the completed objects were colour coded overlapped on top of the same elements in grey (as the proposed conceptual model). This way, the audience can focus on the deviations easily, as well as they can evaluate element per element by paying attention at this overlapped colour coding. Also, the grey appearance that makes the performance colour coding milder, aided in focusing on the items under construction and those with deviations. Given this information, it is clear that the interviewees are not interested all the time on seeing what is on the left of the data date in an S Curve, but actually on the data date and to the right of it. Nevertheless, interviewees stated that it is important to have this performance rating in mind to the left of the data date, but from the data date onwards is what they can impact so there is where their focus is. Also, it is important to have this colour coding to assess the recent progress from each crew compared to the two week look ahead. According to the statements from the interviews, the green, yellow and red colour coding is simple since these colours already have a generally accepted connotation and are associated with ideas of appropriate, intermediate and undesirable (Chen & Chen, 2013), and therefore, are easy to visualize as heat maps and topographic maps do.

5.3.1.7. Critical Path Visualization

The critical path visualization is done with the aim of focusing on their completion in order to help prevent project delays. According to the interviewees, by representing those elements that are in the critical path in a purple appearance, they could more easily prioritise their works for the week. With this prioritisation, it was possible to focus the resources on these activities. Moreover, the visualization of the critical path aided in solving and prioritising in workspace conflicts and interface clashes.

The critical path did not offer a major distraction in the visualization of key aspects in the model, according to the interviewees. Also, they stated that the critical path visualization is vital in bridging the gaps of knowledge that cannot be visualized in an S Curve and to introduce one of the most important qualities of Gantt Charts.

5.3.2. Implementation Soft Results: Phase 2

On the previous sections, the impact of the implemented conceptual model as a tool were presented. In the present subsection, the soft aspects of the implementation process are addressed with the aid of the interviews held with the actors. The results of this sections are taken into account to refurbish the conceptual model will be added to the implementation recommendations.

5.3.2.1. Information Flow: A BIM Approach

Over the duration of the intervention, the two week look aheads were shared on site with the site crews as 4D sequence movies to observe the logical sequence of works to carry out. This way, the visual targets for every crew were established in what the crews referred to as a straight forward guideline of what is expected of them. At the end of the two weeks an evaluation was carried out by comparing what was planned, to what was completed. The staff on site considers that when the sequence and targets are clear, then there is no room for them to deviate.

During the implementation the site tracking was carried out with the tablet application Synchro Site which is compatible with the Synchro PRO software. The 4D Model was uploaded into the tablet application and the site engineers could track the progress by tapping into the objects in a 3D Geometric model and updating the status of each element. The model is loaded with the object properties, and hence reduces the need for additional blueprints or specifications on paper. When updating the model the site engineers stated that the process reduced their workload since the previous practice was to track on site through photographs and then translating these on the site office. During the implementation, the work was reduced to go on the site and update the status of new works and immediately this was recorded and available as the daily progress. Furthermore, the progress is uploaded back through the 4D Modeler to the planning department. The planning department then uploaded the 4D model data into the P6 Schedule for testing the functionality of the method and updating the status of elements in a semi-automated way. The site engineers and planners considered highly useful to carry out the tracking process in this manner since it reduced significantly the amount of time discussing the progress reported on an inventory in a spreadsheet, since the data generated through the Synchro Site application was linked to the objects and these objects are also linked to the activities on the schedule on Primavera P6. However, there was a logical reluctance to automate this process of uploading the data to the schedule, since it had not been used before by the planning staff and they feared that the inputs would not be uploaded correctly. This is a clear reflect of previous research that states that organizations will remain sceptical about changing established work practice in response to new information systems (Guha, Thakur, Konar, & Chakrabarty, 2011). However, in the trial runs carried out, the information matched correctly to the one handed over from the site on the daily report spread sheets. Therefore, this process can be deemed satisfactory, yet it needs for careful implementation. Interviewees stated that since their workload was reduced, they could pay more attention and revise their own work to give more reliable results and focus more time on engineering than on reporting.

Having updated the input data for the schedule, the Modeler could upload the revised schedule and assess the weekly performance on site from the crews and send the screenshots for the crew performance reports. After this had been completed, the 4D Modeler gathered with the package engineers to hold the biweekly interface meeting to discuss the clashes and the workspace coordination. Following this biweekly meeting, the progress evaluation was presented to the management with the deviation control signalling to act upon these. After this was finished, the two-week cycle started again. The interviewees mentioned that these interface meetings were more dynamic than the ones carried out before, since the 4D model enabled to quickly view the sequence of all the works instead of looking at the 2D drawings or the static 3D Geometric Model. Also, the package engineers mentioned that the plans were readily available and aligned with the master plan, so there was no need to carry out major re planning and checking the alignment with the planning department. However, during this meeting, the model was adjusted in detailed with the aid of the package engineers and site supervisors, introducing the site know how into the plan.

5.3.2.2. Critical Success Factors

The main aspects evaluated during this research in terms of the critical success factors on the implementation of BIM in an organization, were the awareness on BIM, coordination between parties in the project, the company policy of implementation as well as the managerial and institutional sponsorship, the experience using this integration methodology, the suitability of the model and the quality of the baseline plan, as established on section 4.2. These aid in evaluating the intervention and answer the sub-research question:

"Which are the factors that hinder the implementation of 4D BIM for planners and managers?"

With regards to the awareness level and experience of project staff in 4D BIM, in general terms the knowledge on the subject was high. Nevertheless, a portion of interviewees had the misconception that BIM is merely a 3D geometric model and not an integration methodology through an object based 3D geometric model. However, the 4D modeler, the BIM department and the project manager ranked the highest in awareness of the subject and demonstrated to be highly knowledgeable in the field of BIM.

The relative lack of awareness on the topic, in combination with a project island condition in the case study were deemed as the factors that made the previous implementation of BIM in execution to not be as successful, according to the interviewees. Since each work package was isolated from the rest, the interfaces did not have an optimum coordination and there was a lack of awareness on the scope of other work packages which led to clashes in the workspaces and double handling of materials. During the implementation studied in this research, actors considered that the process was carried out in a more integrated manner and therefore, managed to stand the challenges of the intervention. Project management sponsorship on the implementation made this integration possible.

Prior to the intervention, the progress was updated on Blue Prints on a wall by highlighting the completed items. However, the project manager showed discomfort with this practice and stated that the company is making a big effort to shift towards a digital control and it has not yet occurred in the organization since there are several parallel efforts of portraying progress but are not aligned on another. The project manager sponsored the implementation fully and gave the necessary directions and resources for the intervention to be carried out as planned. According to the 4D modeler and the BIM Department, the sponsorship from the project manager was key for the implementation, since work packages had to shift towards this approach. As a result, the progress control and deviations were carried out on 4D Model workspace screenshots that showed the progress carried out compared to the baseline.

On the management point of view, there are organizational issues that need to be addressed in the recommendations section. However, the previous aspects referred to the organization and the process. Now it is important to address the content in terms of the suitability of the model. An overwhelming majority of those interviewed considered the top aspect that determines the success or failure of the implementation is the quality of the model but most importantly, the baseline plan linked to the 3D Geometric Model. The main reason given for this affirmation is that the 4D visualization is flawed if it represents a faulty plan, since the model follows the baseline plan and it is merely a translation of it. Interviewees stated that if the rates are not properly estimated and the risks are not considered in the planning, then the model may show a proper and detailed sequence with a poor duration assignment. Therefore, the model would fail to represent the reality on the site with an acceptable accuracy.

In the case study, the 3D geometric model was considered of very high quality since it was on the vicinity of an LOD 400 as seen on Figure 48, in which the coordination and clash detection of the underground utilities could be carried out between the different systems and sequenced in a layer by layer manner going from the deeper utilities first, to the most superficial last. The colour coding in Figure 48 refers to each separate system (drainage, sewage, firewater, electrical duct banks). However, stakeholders considered that the baseline plan was not at the same level, due to the fact that during the project there was a high level of uncertainty in the actual handover of areas to the main civil contractor which generated a great deal of delays in the actual condition. Therefore, the baseline had to be adjusted to represent a more accurate version of the works on site. During the implementation the corrected baseline represented a feasible plan according to site supervisors, which differs from the prior practice in which there were considerable deviations between the as built and the baseline that were therefore, not comparable.

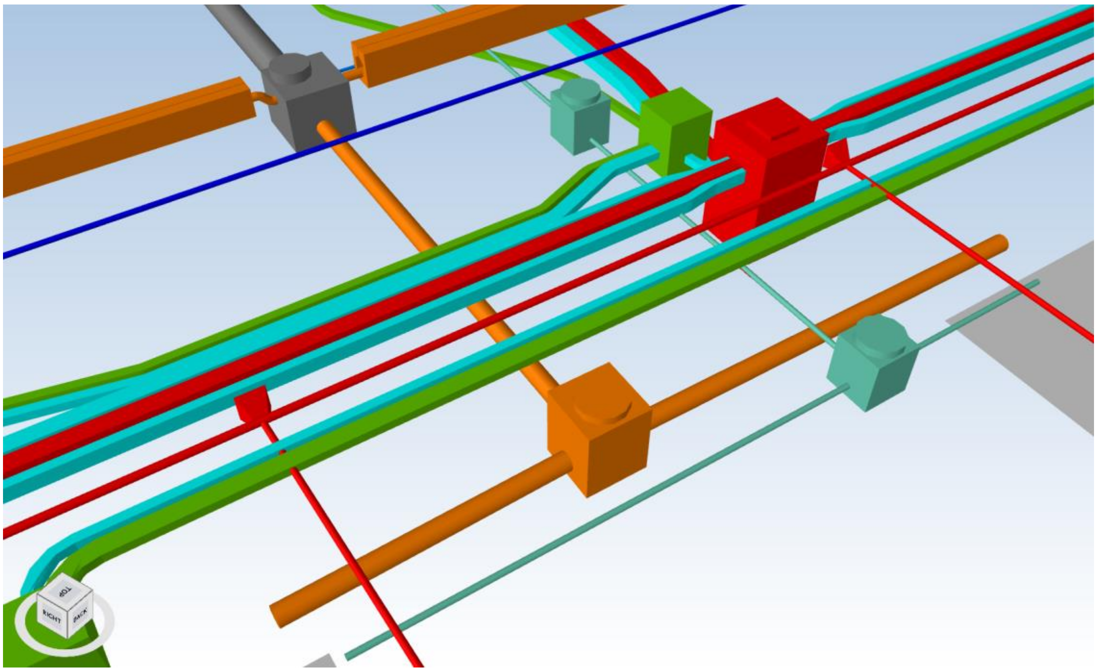


Figure 48. Detail of Underground Utilities in the Case Study

The critical success factors from the theory enumerated in section 4.2, are confirmed in the case study interviews. However, there is an additional aspect which will be addressed in the following section which is the management of the blend between senior management and junior members of an organization when dealing with an implementation of a new approach in a project.

5.3.2.3. Senior Management and Junior Staff

From the implementation, it was clear that there is a generational gap when it comes down to the use of new approaches and technologies. Through interviews with senior management (ages 50 and up) and junior staff (ages 30 and under), it was possible to detect a series of patterns in both generations as to what each one regards on the other, as well as on their own generation and the implementation of new techniques. The aforementioned patterns are what the interviewees consider the fear of obsolescence, the traditional way of performing works, underrated knowledge and capabilities, underestimation of field experience and the "techno-centrism". These will be described in the following paragraphs. This section tackles the sub research question:

"What are the perceptions of construction managers, project managers and planners about 4D BIM and the introduction of new technologies in construction site execution for deviation control?"

Young engineers consider that there is reluctance from senior management to adapt to new approaches and technology in the construction industry and that these new approaches are regarded by older generations as unnecessary and are thus, seldom sponsored for implementation. On the other hand, senior staff acknowledge a lack of preparation in new techniques and approaches, due to a generational gap in their education and the older construction managers have not been trained in the manipulation of technologies such as the software for this implementation. Therefore, it is troublesome for older staff to adapt to changing technologies. However, younger interviewees have gone further in their description of the problem and consider that senior management are a conservative group that evidence a fear of becoming obsolete in a market which is rapidly shifting to the application of new tools and technologies and therefore, orient the protocols into a field which is more familiar and favourable to them. Since the majority of the older construction managers lack the knowledge in new technologies, they fear they would enter a ground in which young and unexperienced engineers would have to take the lead. Interviewees state that the mindset of performing tasks only in the traditional way also extends to other practices that do not involve software operation, such as alternative methods of building an element in which older staff refuse to yield to changes.

Middle aged staff (ages between 31 and 49) consider that the main feature that more seasoned staff has is their track experience on the site and therefore, are not endangered of being replaced. However, these group of interviewees considers that senior staff needs to adapt to the industry through training on how to manage younger staff in a technological environment. This group considers that the senior staff does not need to necessarily receive training on the specifics, however, that they should be given an overview of the possibilities and capabilities of new approaches to manage younger personnel into applying new technologies in the workplace to exploit the benefits of these.

In the case study and in the interviews, it was evident that senior staff prefer to maintain traditional practices and methods. When asked why they should not adopt new approaches and technologies, senior staff have stated that they have been doing their work the same way for over thirty years or more and they do not plan to change their proven methods. Without the sponsorship and instruction from the project manager, the implementation would not have had an active participation from the more seasoned construction managers. However, the project BIM manager considered that the generational gap needs to be bridged through the project manager's sponsorship by involving the teams and collaborating since the aforementioned fear of becoming obsolete and replaced by technology can be dealt with through participation and becoming habituated with the implementation.

It is important to analyse how these two generations regard each other to understand how these see each other's capabilities and limitations. From the interviews it is clear that junior staff feel that their capabilities are underestimated by senior staff and therefore, opportunities are not being given as expected. On the other hand, construction managers consider that young staff must go through a maturing process on the site as they did once in the past without skipping steps. Construction managers also mentioned that there is a tendency on young engineers to give a higher importance to software packages, in a sort of techno-centric manner, than to the civil engineering content. Construction managers stressed on the fact that site expertise should not be replaced with software packages, since this approach would become highly detrimental to the thinking and engineering process.

More seasoned staff considered that the proclaimed benefits of 4D BIM might be inflated by promoters of the technology and that the success in a construction projects lies in the experience in the engineering field. Intermediate aged staff consider that one must not be caught up in the propaganda of the BIM movement, just for the sake of implementing BIM, but to explore its capabilities. This group considers that the shift to BIM applications are what once was the change from handmade blue prints to computer aided drawings. They stated that if these techniques are not learnt, they will become obsolete. However, they also considered that regardless of the direction in which the construction industry moves to, the most important aspect is the engineering content, since they consider that the right blend of experience aided with improved techniques will lead to a higher success and a better flow of knowledge in organizations. In terms of 4D planning, more seasoned managers consider that the site has a greater complexity that in their opinion, cannot be modelled and prefer to allow for manoeuvring, rather than to aim at controlling every single detail. Intermediate aged staff and planners in general consider that it is important to visualize the site logistics and interfaces to provide better estimates. However, they consider that the key ingredient is the underlying schedule and the right estimation of performance rates. They stated that a 4D model depends on the planning and *"if the inputs are garbage, the outputs will be garbage as well*".

In the present case study, the aimed approach has been to make the data more visible in an object-based model on the 3D geometric model. It is not an automated process to replace the thinking process, but a visualization tool. In the recommendations chapter, the aspects portrayed above will be addressed to formulate an implementation plan that suits these.

5.4. Analysis of Results

With regards to the research question *"To what extent can an implementation of 4D BIM improve construction project performance control and reduce delays?",* it has been made clear that the implementation can help to communicate both the sequence to the crews on site, as well as the information on the status of objects on site can be visualized by decision makers to act upon this feedback. From the intervention it was clear that progress values can increase as well as schedule performance indices. However, the extent to which an implementation of 4D BIM on site can impact the progress and schedule performance index depends highly on the matureness of the project. The intervention aids in increasing the level of knowledge on the project and speeding up the level of matureness in the learning curve, by creating awareness on works on the work package, as well as interfaces with other work packages. This helps in providing a better understanding on work space coordination and availability. The less mature the project is, the higher opportunity of impacting the learning curve there is. For more mature projects, the impact would be lower, since understandably, the crews would have already learned how to do their tasks in a more efficient manner.

The data collected has been processed to show the quantitative results in the form of Earned Value comparative values in terms of Progress Completed as well as Schedule Performance Indices. The results that are derived from the implementation show a positive outcome in general terms with higher maximum values and higher minimum values of progress. The qualitative data explains the soft aspects surrounding the implementation and the reasoning behind the variations experienced during the intervention. With the results obtained, conclusions can be drawn an extrapolated to other types of projects, which is the purpose of conducting this research.

In general terms, there are two types of works studied in the case study, those with hard logic in the sequence of their works, and those with soft logic in their sequencing. Those with a hard logic are those structures which follow a logical sequence determined by the physical predecessors which enable the following activities as stated in the theory in section 2.1.4. The second type of work are those with a soft logic within their own work package, which in appearance, their sequence is not determined by any physical clashes that govern the predecessor activities, but by availability of resources. However, given that in the case study, the different work packages are stacked one on top of the other, then the former soft logic activities turn into hard logic in the form of interfaces. According to the research, the main reason for these interfaces being overlooked, is the lack of information and visualization in a work package about the other surrounding work packages as well as lack of initial detailing by design from the engineer. Through the implementation it was possible to create awareness of these interfaces that if solved, could enable work spaces for subsequent activities. This increased the production in the project as a whole significantly, by spotting out the lagging elements through the colour coded model.

The difference between the period of the implementation and prior to it shows that hard logic activities experience an increase in production in general terms due to a better understanding of the optimum sequence through visualization of the model. Formerly considered soft logic works (yet deemed interface clashes) also experienced an increase since these were detected as bottlenecks in the model and deemed as hard logic works. The linking process between work packages improved significantly according to interviewees, since the model enabled the decision makers to physically visualize the sequence and determine the priority of works. Workspace coordination was a fundamental aspect in the present research since decision makers could visualize the status of the project and what needs to be adjusted to enable workspaces, or what are the possibilities in the project for the available crews. This can be extrapolated to any workspace coordination ranging from buildings in the coordination of finishing works, as well as mechanical, electrical and plumbing (MEP) works since the conceptual model enables a visualization of pending items to be completed in an area. In any type of project, interviewees consider that the conceptual model would bridge the project islands mindset into a whole project mindset since the methodology promotes interface coordination in advance to foresee clashes and address workspace coordination.

For all the work packages, the interviewees stated that the conceptual model highlighted those deviations clearly and were easily spotted by decision makers to establish an action plan which satisfies the main research goals during the implementation. Deviations were made clear and therefore, increased the accountability of the crews since the results are tangible with the conceptual model. With this deviation control tool, decision makers expected that the remainder of the project would be lees troublesome to foresee and dynamic interfaces can be tackled in a timely manner.

According to interviewees, this methodology could enable planners to produce estimates with an increased reliability and more accurate estimates for project completion since stakeholders are generally overly optimistic and neglect spatial coordination and interface management.

Chapter 6
Validation

6. Validation

To be able to validate the current research and determine its reliability, the author conducted interviews with key staff in the head office and compared the intervention, the project and the methodology of implementation with other projects from the same company. This validation process aids in establishing the degree of replicability of the research to extrapolate recommendations and conclusions to other implementations. This chapter aims verifying if the interviewed experts consider that the proposed solutions result in unravelling the main problem described in this research both by assessing the framework as well as the deviation control and forward-looking tool.

6.1. Validation Interviews

The interviews in the previous sections were conducted with the site staff, planners, construction and project managers, young engineers, BIM experts and the 4D planner on the site of the case study to gain more insight on their experience with both the project under study, as well as previous experiences, With those interviews it was possible to explain the problem first, evaluate the proposed conceptual model and explain the results during the intervention. For validation purposes, it was necessary to interview key staff at the head office (personnel isolated from the project) in order to determine the specificity and replicability of the conceptual model proposed on this research and verify the research and further evaluation to establish recommendations and conclusions. Staff at the headquarters have been interviewed and give insight as to how they observed the implementation unfold with an outsider view compared to other ongoing projects since they offer a less biased point of view.

6.2. Case Evaluation

6.2.1. The Conceptual Model

6.2.1.1. The Framework

For validation purposes, the framework needs to be evaluated in terms of its applicability to other cases and the factors that would make the model vary from one case to another. With the latter it is possible to make recommendations to adapt the model to other circumstances. According to interviewees, the conceptual model is well adapted to the circumstances of the case study and in general to other cases since it encompasses different disciplines as in the project under study, however, they mentioned three factors that would require for adapting in the model, such as the type of contract the parties engage in and the project setup, the level of implementation of BIM in a company or a project and the stage of the project.

Depending on the type of contract (or delivery method) the parties in a project decide to engage in, the conceptual model would require modifications since the case study was setup in a design-bid-build delivery method (often referred to as Traditional Contracts). For this kind of delivery method, the nature of the relationship between client, design engineer and contractor is fragmented (CSI. Construction Specifications Institute, 2011). The implementation of BIM is said to be more effective under Design Build delivery methods (also referred to as Integrated Contracts) in which the design engineer and the contractor collaborate under one sole organization (Hardin, 2009). Therefore, in the recommendations, a variation will be presented for integrated contracts. The interviewees stated that the variations should be carried out in the transition from IFC drawings to the BIM department on Figure 35 to integrate the designer in the process. For traditional contracts, based on their previous experience, the interviewees stated that the proposed framework adheres properly to the delivery method and given that the case study includes different types of works, it was determined that the functionality of the framework is not affected by the type of work carried out since the flow of information was identical for different work packages during the implementation. Therefore, the interviewees concluded that the framework is suitable and can be used for traditional contracts. Given that in parallel to the implementation, traditional communication flows (not integrated through BIM) were maintained, it was possible for the interviewees to compare and determine that the flow of information is as reliable as traditional flows of information and more efficient with the aid of BIM, since applications and tools aid in communicating information to several parties in a clear manner. Based on interviews conducted with staff at the headquarters, the framework was deemed suitable when compared to other ongoing projects with a similar delivery method.

Another aspect that interviewees stated as one that would require for the framework to be modified, was the level of implementation of BIM in a company or a project. As seen on Figure 35, the framework setup is comprehensive for the whole project, however, most organizations have implemented BIM only at drafts, design, planning and engineering. In other cases, such as the one in the case study, the use of BIM is barely reaching the site execution control (in addition to the drafts, design, planning and engineering). In most cases, the implementation does not reach other areas such as finance and management of the project. Therefore, it is important to carry out the implementation in future cases in a segmented manner according to the reach of BIM in the organization which can be extended if the organization is capable of doing so. According to project managers interviewed, the proposed framework would be suitable for a mega project such as in the case study, which is worthwhile implementing BIM since the setup of a BIM framework does not represent a large investment compared to the project. However, for smaller scale projects, the implementation in the whole organization may become too costly (as a proportion of the total cost of the project) according to interviewees. In terms of company implementation of BIM, one of the interviewees stated that in previous companies he has worked before, there is a high pressure for the use of BIM and portraying it to the construction industry for public relations purposes, which in his opinion leads to deceitful representation of the real state of the use of BIM. Therefore, it is important to carry out the research on the site of the case study to verify the actual state of the art in these implementations. In his opinion, the steps taken forward in the implementation of BIM and 4D BIM site execution control need to be done in a firm but gradual manner and reach the goals in a middle to long term period, instead of over representing the real state of the use of 4D BIM due to construction industry pressures, which results in a failed attempt at implementing the frameworks. This confirms previous findings on research that state that moving from traditional practices to novel 4D BIM practices will be a gradual and difficult process due to current organizational structures, culture and routines present in the construction industry (Nordahl-Rolfsen & Merschbrock, 2016). The latter is according to the interviewee, due to the fact that when this occurs, BIM representations are seen as a public relations tool and is then not implemented for project purposes. He states that the pull for the implementation of BIM should be done by design and engineering and not commercial purposes.

The implementation was carried out in an ongoing project and therefore the framework was generated to suit the requirements of the ongoing project and other projects in general. However, the framework needs to be segmented in such a way that the framework is suitable for other stages of the project life cycle according to interviewees in such a way that when the project begins, the site execution control segment (which was previously inactive) starts functioning as stated in the framework.

The framework was considered suitable for current projects, as well as taking the next leap forward in terms of the implementation of 4D BIM in site execution. One of the aspects that the interviewees stated was the importance of not only looking at how the organization works in an integrated way as seen on Figure 35, but also the way in which this organization carries out these two week sprints as seen on Figure 33, Figure 34, since the framework in their opinion, needs a dynamic approach to tackle the project and have the parties integrated and aligned. Overall, interviewees saw the framework as an efficient communication and flow of information in a project which encompasses the different axis of a project and integrates them with the aid of BIM. Interviewees stated that the current status of communication flow in international projects is more traditional (information flows from one department to another by handover of information) and fragmented between parties involved (Hasan, Baroudi, Elmualim, & Rameezdeen, 2017). Most international projects lack BIM integration (Boton, Kubicki, & Halin, 2015) and therefore, the process of implementing needs to be carried out in a phased manner. Project managers stated that the framework has proven to behave well in the trial carried out, yet they state that for mega projects it is very sensible to use proven tools, therefore they need to implement it in smaller projects to confirm the track record of the framework in order to carry it out continuously and implement it in mega projects then in a seamless manner. However, the engineering manager considered that it is plausible to have the setup ready for the following project from the beginning, given the results in the present implementation and apply it in the following mega project. The interviewees agreed that the setup of the framework took longer than desirable, since it was done on an ongoing project and it required for adjustments. However, they consider that the geometric model and conceptual model setup from the beginning of the project would aid in setting up the framework in an acceptable period of time.

Project managers saw an increase in the efficiency of the handover of information, specially from the site reporting to the office, yet they consider that the main problem is solved primarily by the tool that shows deviations between the as built and the baseline, yet the framework enables fast communication of these deviations to be able to tackle them in a timely manner. Project managers state that they have an issue with the flow of information in mega projects as it is traditionally, in which all the project progress is loaded into the planning software and by the time the information is ready, the data date is already one or two weeks behind. Therefore, they consider that the framework allows them to have real time and up to date information on the project to be able to make decisions that would affect the project they are seeing and not a lagging visualization of a project that is no longer an actual view. Therefore, the framework has been deemed satisfactory and fit for purpose. However, the alterations based on the observations will be carried out on the recommendations chapter.

6.2.1.2. The Tool

On chapter 5 the results showed a very positive impact and partially validated the deviation control and forward looking tool. However, it is necessary to validate these results fully with the aid of interviews to confirm the impact of this tool and to discard any other possible sources that would distort the results. On chapter 5, the validation and results analysis were carried out through interviews with staff in the project. For this section, it has been carried out through interviews with the staff at the head office. Also, in this section the aim is to pin point the key aspects that interviewees considered that aided in the tool's functionality.

Interviewees stated from the beginning that the researcher should not focus on the solution, but the problem itself, since the former would lead to a reactive deviation control tool which represents what is occurring on the site but would not offer any solutions in the remainder of the project. The latter made the tool a preventive and comprehensive one that offered a visualization of the status as well as the action plan for the rest of the project. The regional operations manager valued the fact that the tool had a past, present and future approach to resemble an S Curve, and considered essential that the forecast showed the way in which the remainder of works were going to be carried out, considering the dynamic interfaces. In his opinion, there is an industry flaw in which even though the past and present performance in the project is below expectations, yet engineers and planners forecast an increase in the production, which as a result, unrealistically make the curves achieve the completion of the project on time, without any explanation as to how the project will accomplish it. The interviewee calls this phenomenon, the "hockey stick", given the flat line for past progress followed by a steep slope for the forecast of the remainder of the project. However, as he mentions, the 4D model is highly dependent on the quality of the planning since the model represents the activities from the schedule. Therefore, it is important to plan realistically, and increase the accuracy of the planning by assigning the activities to the 3D geometric model and foresee bottlenecks and interfaces issues. The interviewee also mentioned that it is highly important to increase the accuracy of the model by including the different work packages in one sole combined model, as well as including the resources and temporary structures and works. However, he considered that the required accuracy of the model can only be achieved on a short term (maximum six weeks), therefore, the planning of the remainder of activities should be proven for interfaces and clashes, yet the planning should be flexible and left more open from the end of the six week period onwards. The interviewee also mentioned that by doing so, more focus on specific details can be put into the near future (two week look ahead) and generate a high quality action plan for site execution.

Given that the 4D model may become overwhelming to understand if the colour coding is not appropriate or if the focus is placed on several locations, there was scepticism from planners at the head office about carrying out the deviation visualization on an overlapped model as proposed in this research and not on a "side by side" analysis as it has been done previously. However, after evaluating the implementation, the planners have determined that the model contributes in improving sufficiently the detection of deviations and stated that the tool tells the audience in a very clear manner where these are located. Therefore, it has been determined that the visualization problem of the "side by side" analysis has been bridged with the proposed conceptual model. The planner interviewed at the head office stated that the model succeeds in resembling an S Curve by doing the overlapping of models and showing the whole scope of works in a transparency, the deviations between the baseline and the as built plan on one sole model which had not been done on previous research. Nevertheless, interviewees stated that such leaps forward should be carried out in parallel to traditional practices to make a soft transition from traditional to 4D BIM oriented approaches to verify and validate the data shown on both methods to later convince those used to traditional tools, about the functionality and benefits of using 4D tools. Also, traditional tools such as S Curves need to remain in use and be complemented by visualization tools, earned value components are linked to the models, since organizations require quantifiable information on the project for cash flow purposes.

This helps in complementing the answer to the sub research question: *"How can 4D Models bridge the existing gaps of traditional performance control methods?",* since the present research builds upon traditional control tools such as S Curves to replicate the functions of these (to make a soft transition from traditional tools to 4D BIM approaches) and through the functionalities of the proposed tool (colour coded deviation signalling, interface coordination and workspace availability visualization) the research bridges the visualization gaps as presented in the previous chapters.

6.3. Other Project Experiences at Royal Dutch BAM

It is now important to determine how this intervention is regarded and compared with other Royal Dutch BAM's branch's projects. This is essential to understand the applicability of the conceptual model into the other projects studied which contain in each one at least one of the structures studied in the previous case study.

6.3.1.1. London City Airport

The project is a deck on pile extension to the current airport runway in the city of London along the river Thames, similar to the wharf built in Moín Container Terminal project and therefore comparable for the purpose of this research. The project is currently ongoing and has made use of 4D planning with Synchro PRO software since the tender phase to present the sequence of works. The transfer of information from the site to the site office in this project is carried out with the aid of BIM 360 field from Autodesk and not on Synchro Site as in the intervention in Moín Container Terminal.

During the execution phase, 4D technologies and methods have not been fully exploited and therefore, deviation control is not performed with the aid of 4D models on a regular basis. When carried out (seldom), the deviation control is done on a side by side approach, and not overlapped, as in this research. This is aligned with previous findings of current practice of using the 4D model merely for preconstruction purposes and not during the execution phase. This causes the 4D model to not be up to date with the current status of the project and constrains the user from performing deviation control as the one proposed in the current research. However, according to the planning staff, the project progresses at a pace that does not require for a reissue of the baseline, since possible deviations are within the acceptable parameters of the staff and client. Nevertheless, the 4D models when updated, present the same shortcomings mentioned on previous sections, since the side by side analysis relies heavily on the audience to spot out the deviations.

The interviewees stated that the deviation control tool would be of great use in their project since the delays are not identified clearly in a spatial manner with the side by side analysis and therefore, the aftermath of the deviations is not yet fully dimensioned, if it involves an interface clash later in the project. However, even though interviewees stated that the deviation control and forward-looking tool would be of great benefit for the control of the process, they initially considered that the framework would not be their biggest point of attention, since there is an acceptable level of integration in the flow of information. Nevertheless, the lack of use of BIM technologies that integrate the planning with the control (such as Synchro Site) rather than BIM 360 Field (which is more oriented towards quality control and assurance, rather than progress control), hamper the flow of information on the status of the project. When briefed about the functionality of the framework with the tablet application (Synchro Site) to facilitate the flow of information to the site and from the site, interviewees stated that the framework would be helpful to reduce the amount of work carried out in reporting and would in fact expedite the process of transferring knowledge on the status of the project yet also they stated that it was also profitable to use Primavera mobile applications.

Interviewees considered that the present research is of great use for their project, even if the project would have consisted of a different discipline, since they consider three points that will be applicable for any other project independent of the discipline to be executed, which are deviation control, interface management and workspace coordination. The staff considered that regardless of the type of project to be executed, all projects share the same struggle which is identifying where the deviations are physically, rather than to see deviations as lagging bar charts on a Gantt Chart, since these do not offer a dimension of the complexity of the problem and the entailing consequences. However, they stated that it is always important to visualize the Gantt Chart as well, since it is easy for them to see the time delay on it. Also, interviewees stated that the main case study selected is representative of international mega projects and it supports the research in terms of understanding the importance of interface coordination. Therefore, they consider that the findings on this research on the fact that deviations between the baseline and the as built impact the interfaces and workspaces further down the road in the project, would have been seen on any other complex project. They considered that it is important to address it and evaluate it in every type of project. Interviewees stated that the research is valid and applicable to other projects in a generic way since the three aspects mentioned (deviation control, interface and workspace coordination) are an everyday struggle for most projects.

6.4. Other Industries

6.4.1. Aircraft Industry

The validation process requires a study of other industries to gain insight on the methods of planning and production control of the assembly procedure, to evaluate if these are applicable to the construction industry as well as to compare where the construction industry practices are standing with regards to other industries. The construction industry is unique, yet for research purposes, a large scale comparable production line such as the aircraft assembly was reviewed since it is somewhat similar to a construction project in terms of costs and part fittings. This differs from an assembly line for the automotive industry which resembles more an ongoing operation than a project. The research was carried out on digital tools and methods used for planning and controlling the process, equivalent to a 4D model.

The aircraft industry is characterized for its customization which requires for strict approval in terms of quality assurance and certification (Becker, Schmidt, & Calis, 2014), which is carried out with the aid of a digital mock-up, which dictates the exact array of parts to be assembled ranging from large parts such as cockpit assembly, to the wiring of the aircraft. This digital mock-up serves as a manufacture planning as well and it is compared to the real model, which is basically the contrast between the baseline and the as built. These digital prototypes are often used for alternative configuration assessment (as in construction project in value engineering), yet these require further calibration between the real model and the virtual model (Becker, Schmidt, & Calis, 2014). The virtual model is used for sequencing purposes and it resembles a construction project which consists of modular parts being assembled together.

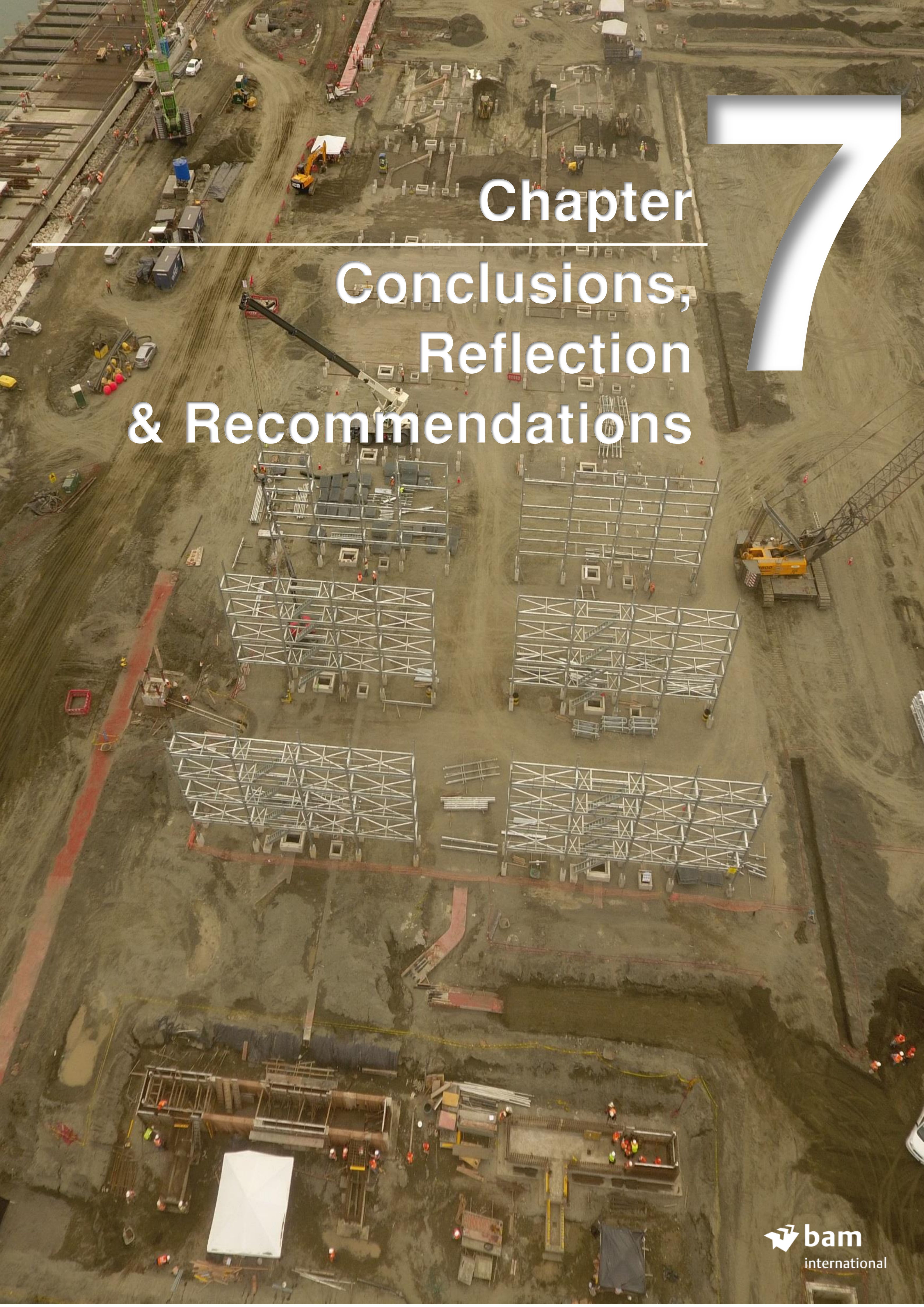
The comparison between the planned and actual performance is carried out on an overlaid imagery of the actual situation, on top of the virtual 3D geometric model with the aid of augmented reality tools as well. The process of assembling the parts of an aircraft are monitored with the aforementioned comparison, similar to the baseline and as built comparison studied in this research, however, in the aircraft industry, the variations are recorded on a georeferenced manner, processed and modelled virtually to assess the impact of these variations for certification purposes. This recording of information is similar to that proposed by Golparvar-Fard et al, for the construction industry. Nevertheless, like the construction industry, the aircraft industry does not present a solution to deviation signalling in the models and thus relies heavily on the user to visualize these. Virtual models in aircraft construction are mainly oriented towards quality control and assurance of the as built condition for validation in the certification process, as well as verification of part interaction to ensure proper functionality of the end product. This gives an idea of the priorities in the aircraft industry, since the main driver is the quality, in order to prevent any failure from happening.

The state of the art in production control in the aircraft industry is oriented primarily towards quality control for certification of functionality purposes, yet it also plays a sequencing role for the assembly of parts. In the construction industry, each project differs greatly one from another and so does the workspace (construction site) and therefore, requires for a greater deal of planning of these different circumstances for each project with the aid of 4D technologies and methods. The aircraft industry does use the geometric model intensively during the execution to compare the virtual model to the real one, yet in terms of quality and not primarily on a scheduling and planning basis. This due to one of the main drivers that can be detected in this industry as preventing hazardous situations, rather than a fitness for purpose orientation in the construction industry (van Gusteren, 2011). The construction industry has fallen behind in the implementation of 4D control tools during the execution process (Boton, Kubicki, & Halin, 2015), however, it leads in terms of implementing for sequencing and deviation control in terms of planning. It can be concluded that the practice in the aircraft industry does not offer yet a more advanced and replicable methodology in terms of deviation control to apply in the construction industry (as those proposed on previous research) and current practices are not inferior than those in the aircraft industry. The practices in the aircraft industry may well be of profitable use in modular buildings. The state of the art in 4D planning in the construction industry, as well as this research may be determined to be aligned and up to date with current practices in other industries. Therefore, the present research can be validated in terms of contributing with an up to date solution.

6.5. Validation Conclusions

Given the evaluation of the tool and the framework it can be concluded that the research offers a leap forward in the deviation control between the baseline plan and the as built production in construction projects. The results have been validated through the results, as well as the interviews and comparison with other projects and industries. The case study offers a wide array of different disciplines that as seen on the London City Airport case, portions of the Moín Container Terminal project may be used for applications for other cases (in this second case, the deck on piles are applicable). However, the aspects dealt with in this research (deviation control, workspace and interface coordination) are everyday struggles in most projects. Therefore, it can be determined that the case study is rich in content since there are different types of projects in one sole mega project (Moín Container Terminal project) and the tool and framework can be extended to other cases.

The conceptual model proposed in the first phase (the tool) alone, could be seen as a considerable scope, yet it is important to understand that the tool proposed does not solve the problem of communicating deviations, if these are communicated with a lag. Therefore, in the validation process it is clear that the right information has to arrive at the right time in order for decision makers to have an impact on the project, which means that the first phase alone fails to solve the problem if it is not implemented along with the second phase of the conceptual model (the framework) which enables this information to flow faster and in an efficient manner.



Chapter 7

Conclusions, Reflection & Recommendations

bam international

7. Conclusions, Reflection and Recommendations

7.1. Conclusions

The main objective of the present research was to improve project controls by providing a tool that enables decision makers to be better informed on the project status and a framework to implement the tool in the execution phase of a project. This was achieved by bridging the visualization gaps from traditional tools, with the aid of 4D models. However, having improved information does not solve the problems stated in this research, if the information is handed over with a lag, product of inefficient traditional practices. Therefore, it is important to complement the proposed tool with the framework to enable the information to flow faster. The main issue in this flow of communication is located between the planning departments and site execution teams where there seems to be a general broken link. With the implementation of 4D BIM during the execution phase, it was possible to bridge a communication gap between these two parts, by aiding with visualization of a 4D plan for two and six weeks look ahead in the direction from the engineering and planning to the site execution crews and in the opposite direction, through the framework it was possible to extract the information on project progress in a timely manner.

The research showed a general symptom in the construction industry in which engineers and planners are excessively optimistic when estimating the remainder of activities in a project, as seen on the pronounced slopes on S Curves between the data date and completion date. However, they also tend to neglect spatial coordination and interface management, which leads to a failure to accomplish the plans, since the lack of consideration of the interfaces and workspaces may lead to a delay in the starting day of an activity. The planning increases its reliability by visualizing these interfaces and workspaces. Nevertheless, since the 4D model is a product of the 3D geometric model linked to the planning, it will only be as accurate as the level of detail and precision of both the 3D geometric model and the planning. Therefore, the site needs to provide feedback both on the feasibility of the plans, as well as the performance rates achieved on the site. If these are communicated and updated, then the plans will gain in precision. If this is not the case, then the 4D model is just a sequence movie that offers no precise information on the time component.

Even though the implementation of the tool and framework in the case study can be considered successful, it is necessary to state that the limitations of S Curves and Gantt Charts do not make these tools impractical. These tools are very useful for planning and controlling, yet the present research aims at bridging the visualization gaps in these, through the capabilities and opportunities in 4D models. Therefore, it is not a recommendation of this research to replace these, but to complement these with 4D tools to obtain improved results. Traditional tools are most useful for producing schedules that feed the 4D model as well as to generate numerical values for calculating the critical path, delays and estimating the cash flow of a project.

The research (and the research questions) followed the logic of first determining what is the current practice in construction project controls and the shortcomings of it, to then explore the alternatives to bridge the current gaps of knowledge and propose solutions that would be implemented in a case study, which then would be measured with the aid of key performance indicators and interviews.

Having answered these aspects, a recommendation can be provided to answer the main research question as to what measures need to be taken in an implementation of 4D BIM to improve performance control. Following this research logical line, the first sub research question makes a diagnostic of the current situation below.

"What is the current common practice of controlling progress in projects and what are the possible alternatives in 4D BIM?"

The construction industry has been oriented traditionally towards a set of tools that are based on measurable numerical values, such as S Curves, Gantt Charts, Time Location Charts and Key Performance Indicators such as Schedule Performance Index and Cost Performance Index, which enable decision makers to quickly understand the general performance status of a project and easily calculate parameters (performance, delays, deviations, completion dates and others). However, these tools are a collection of clustered information that in many cases are not explicit nor fully representative of a project, since projects are multidimensional bodies that require a deep understanding in order to make an educated decision. The main drawbacks of traditional control tools are the lack of visual representation of physical elements which the industry has attempted to bridge through Building Information Modelling and 4D Models. However, 4D Models fail to provide a numerical value representation. Therefore, through 4D Capabilities it is possible to complement the current traditional tools through workspace and interface visualization, as well as pin pointing where the deviations are present and obtain numerical values from current graphical representations. 4D models and the implementation of these techniques are still undeveloped, which is evident since the industry has seldom applied 4D BIM during the execution phase and it has remained as a preconstruction tool for planning and clash detection. The latter leads to the following sub research question:

"How can 4D Models bridge the existing gaps of traditional performance control methods?"

The visualization gaps detected in traditional control tools such as S Curves and Gantt Charts were successfully bridged through the innovative capabilities of the proposed tool for deviation control, workspace coordination and interface management. Guidelines were provided on these three aspects to allow a close control by signalling where there are deviations physically in the project through the overlap of the Baseline 4D Model and the As Built 4D Model, as well as to coordinate workspaces and interfaces to increase the feasibility of the plans which increase the reliability of estimates. The approach was to take first a traditional tool such as an S Curve and replicate its capabilities through 4D models, in order to take a first step into the direction of a 4D BIM environment. The following step was to incorporate those aspects that are lacking in the S Curves to spot out not only where the deviations are physically (not possible on S Curves) but also to answer the question of how the plans for the remainder of the project are going to be fulfilled by coordinating the interfaces and visualizing the workspaces. Interfaces are not static and therefore need to be reviewed periodically, since deviations in the production may alter conditions on the site and initial assumptions on the interfaces may vary. Having stated this, it is necessary to provide a framework to implement these 4D capabilities in a 4D BIM environment, which leads to the following sub research question.

"What stepwise coordination is required between planners, managers and site engineers?"

As stated in section 4.7, the detailed planning of works on site needs to be aligned with the master plan and satisfy its milestones and requirements. With the aid of 4D models, site execution teams can sequence the works and coordinate the interfaces to achieve the goals within the 2 week and 6 week control points set out on the corresponding look ahead plans. With the actual performance on site, the tracking data is then feed to the planning and estimates are recalculated in the Master Plan, as well as the Internal Planning. The outcomes of the execution during the 2 week periods are contrasted with the baseline plans, and the adjusted targets are presented during the biweekly progress meetings. After this, a new iteration begins in the following biweek as seen on Figure 33 and Figure 34. With these Figures, it is possible to see how the organizations attempt at satisfying the Master Plan in 2 week cycles and how the planning is done in an iterative manner. With the aid of Figure 49, it is possible to understand how the information flows within a project organization in the case of traditional contracts. The framework set out on this figure integrates the teams in a BIM environment and facilitates the communication of plans towards the site execution teams, as well as to obtain the up to date information on progress in an expedite and compatible manner for each department. Variations to the initial framework are mentioned below, and the corresponding figures are in Appendix A.

The proposed framework on Figure 49, is adjusted for integrated contracts as seen on Figure 50 in the appendices. The main variation is that IFC drawings in this case are now incorporated in the internal organization. The main framework for traditional contracts as stated by the interviewees, is satisfactory and remains unchanged. The stepwise process is stated in section 4.7.1.

The adjusted framework with regards to the level of implementation of BIM in an organization is shown on Figure 51. In orange one may visualize the essential aspects that need to be taken into account at the most basic level. At a higher level of implementation, it may be even possible to integrate into the framework the financial and resources (5D), procurement and project controls aspects (in green) which would allow the information to flow through the whole organization in a more efficient and comprehensive way. However, this is a stage that has not been traditionally reached in the construction industry. The proposed framework in orange allows for the information to flow from the client, into the organization and establishing the connection with site execution team in which information flows in both directions. In case the organization is capable of integrating those aspects in green, it would be recommended to link traditional tools to the framework for automatic updating that would enable project controls as well as to integrate the status of elements to be procured to establish an improved communication flow with the suppliers to state when one needs the elements and the supplier updates the status of these. The higher level of implementation, the more capabilities there are of integrating information.

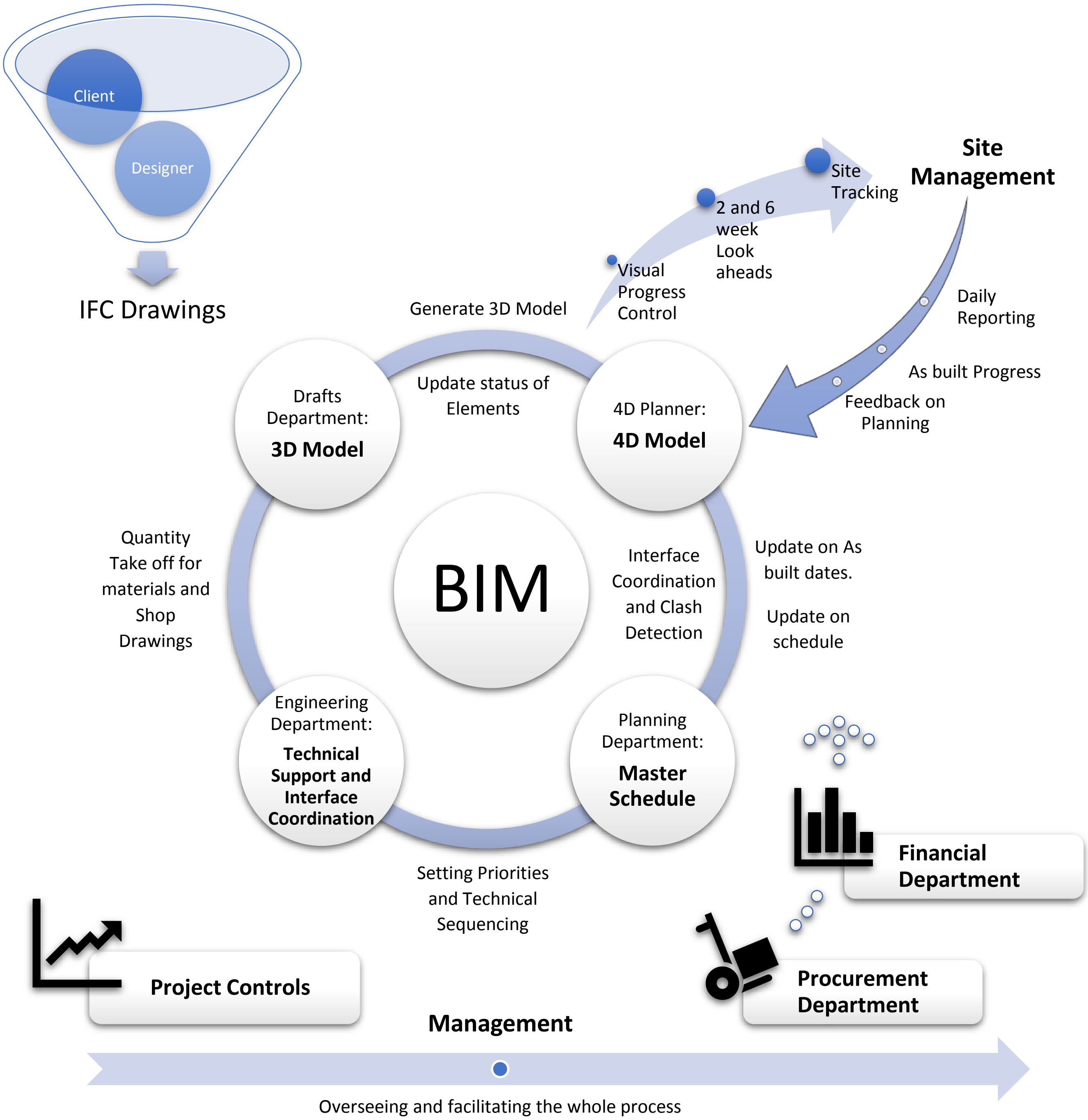


Figure 49. BIM Framework Setup for Traditional Contracts

Figure 52 shows the implementation of the framework according to the stage of the project. At preconstruction stage, the only aspects that would be active would be the flow of IFC drawings into the project organization to the 3D Modelling, 4D Planning, Engineering and Planning (those items in green in Figure 52) to allow for the flow of information from the client in the form of IFC drawings and specifications into the organization to be processed and generate plans and models. Once the project starts on the site execution stage, the flow of information to the site and from the site towards the other actors in the project will begin to be active (those elements in orange in Figure 52). However, these need to be prepared allowing for sufficient time so that the models do not lag in the delivery. These stay active until the end of the site execution. Depending on the level of implementation of the organization or project, the flow of information in a BIM environment towards and from Project Controls, Financial and Procurement aspects (those elements in blue and yellow in Figure 52) is activated during the preconstruction stage and stays active until project commissioning and documentation closeout. As stated in the previous framework case, the degree to which these aspects can be integrated, increases the opportunities of integrating the organization in a BIM environment and enabling communication to flow in a more efficient manner. However, the phases of a project need to be factored into this stepwise coordination to understand the level of development into which the models should go according to the stage of the project. With regards to the stages, it is useful to detect also the LOD's that would be recommended as stated in section 2.4.3 and necessary to answer the following sub research question.

"What are the most suitable levels of detail for each work package at each stage?"

From the research it was possible to determine that the information on the project increases as the project progresses. However, it is also important to understand that for example, in tender phases, the level of detailing may vary significantly, and this may range from being given a rough estimate of quantities and therefore the tender is based on rates, up to having a well-defined model that can be used for planning and bidding. Projects vary significantly from the tender stage, up to the site execution and therefore, for a tender phase, therefore, the most practical LOD would be in the neighbourhood of LOD 200-300. For preconstruction purposes, in the research and in the interviews, it was determined that an LOD 350 would be most practical. As seen on Figure 3, Figure 4, the knowledge on the project increases as time passes by and the uncertainty logically decreases. The phased planning approach depicted on Figure 4 is the selected one for the development of the model by detailing those elements and plans up to an LOD 400 for short term plans (two to six week look aheads) and to leave the remainder of works to be planned in an LOD 350 for interface clash detection and workspace coordination. To achieve this, it is highly recommended that the contractor generates a model that suits their construction planning requirements. Having established intervention to be carried out with its corresponding implementation plan in each stage of the project, it was necessary to measure the effects of it during the case study to answer the following sub research question.

"To what extent can an implementation of 4D BIM improve construction project performance control and reduce delays?"

The results of the intervention showed on general terms that by implementing 4D models during site execution there is an acceleration of the maturing process in the learning curve, demonstrated by the increase in production, as well as a stabilization of the production at a higher level (higher maximums and higher minimum values). The implementation of the tool can be deemed successful and valid for other disciplines and cases, since the aspects upon which the tool is oriented (deviation signalling as well as workspace and interface coordination) are generic, applicable and present in every project as seen on the different disciplines in the case study. The research shows that by addressing these aspects with the aid of 4D models, the production increases significantly and the feasibility of the planning increases since there is an increased awareness on the works to be performed and how to perform these (clear and tangible goals) which lead to a higher level of visual accountability, as well as the scope of works to be performed by other work packages, which helps in mitigating the project island approach and shifts to a holistic approach.

In terms of the tool, the overlapping of baseline and as built 4D models on Synchro proved to yield improved results than former side by side practices and bridged the gap of detecting deviations in a simplified manner. The tool enabled a higher level of understanding of what specific elements need to be completed, which aided in decreasing the quantity-oriented mindset and helped in focusing the site crews on critical path activities, as well as completing bottleneck activities that enabled workspaces for successor activities. This is specially the case in quantity intensive disciplines such as pipelines, roads, tunnels and railroads to mention a few. However, there are several aspects that prevent the implementation from fully exploiting the potential of an intervention.

"Which are the factors that hinder the implementation of 4D BIM for planners and managers?"

From the research on site and from the literature review, it is clear that actors in the construction industry tend to be conservative when faced with innovation and therefore, are reluctant to shift practices to new information systems. Also, BIM and 4D technologies are relatively new concepts in the construction industry and the majority of the staff is not fully aware of the capabilities and benefits of applying these aspects in practice. To counter this, the implementation needs from strategic sponsorship from the company executing as well as staff which is knowledgeable in these techniques to be able to jumpstart these in the construction industry. The success or failure of an implementation relies heavily on organizational issues such as the level of commitment of the organization, as well as the level of implementation and its sponsorship on this. The setup of the project also determines the outcome of the implementation since it requires mechanisms in the organizational structure that prevent from creating project islands and in the contrary, promote the integration of actors in a project.

The success or failure is also highly dependent on the level of development of the inputs for the 4D model. Both the 3D model and the planning to be detailed and accurate enough to suit the requirements of the project. In case the 3D model does not satisfy the required level of development, then it is possible that interfaces are not detected and the sequencing is flawed. However, the most important aspect is that the planning fed to the 4D model is of high quality, since if it does not satisfy the accuracy requirements, then the 4D model will not represent accurately the reality on the site, resulting in a sequence movie that does not have value in terms of tracking, since it is not a comparable baseline for the project. If the inputs are not up to par with the requirements of a project, it serves of no benefit to the execution and is merely considered as a public relations tool to portray sequences to other audiences.

Since it is essential to have the sponsorship from organization leaders, it is necessary to understand what the perceptions of these are on the techniques under study, which leads to the following sub research question.

"What are the perceptions of construction managers, project managers and planners about 4D BIM and the introduction of new technologies in construction site execution for deviation control?"

Construction managers demonstrated to be reluctant to the implementation of these techniques and this conservative behaviour is explained by younger actors as a reflex to the lack of preparation in use of software packages and lack of awareness. Construction managers also considered that the benefits of these 4D BIM capabilities are over estimated by the construction industry and the focus should be put on the engineering behind the construction process and not on the technology. In the case of younger actors, there was a considerably higher acceptance and knowledge on these new technologies and there was a high will to implement these on the site and amongst these, are project managers willing to sponsor these initiatives.

Having answered the sub research questions, it is possible to tackle the main research question:

"What measures need to be taken in an implementation of 4D BIM to improve performance control in the execution of construction projects to reduce the amount of delays?"

To improve performance control in the execution of construction projects it is necessary to implement the 4D Model deviation control, workspace and interface coordination tool, in parallel with the framework proposed above since the information not only needs to be accurate, but communicated to decision makers in a visually clear and timely fashion.

To fully perceive the benefits, it is necessary to implement the tool and framework during the whole project lifecycle by building upon the tender 4D Models and adapting them to the levels of development required for preconstruction planning and during the execution process, updating the model on a regular basis (preferably biweekly) to control performance by comparing the baseline against the as built plans and tackling the deviations signalled on the 4D Model and continually testing and coordinating workspaces and interfaces until project completion by re estimating the remainder of the project in an iterative fashion.

However, the process needs for constant evaluation of the inputs and outputs, since the 4D Model is highly dependent of the quality of the inputs (feasibility of the planning and the level of development of the 3D geometric model). Flawed inputs will result in a faulty representation of the conditions on site and will therefore, not provide a comparable baseline for benchmarking with the as built 4D model. The resulting 4D Model from each iteration will serve as an input for the master planning for recalculation and evaluation of previous assumptions. It is expected that the accuracy and feasibility of the estimates in the planning to increase through this process as the knowledge on the project increases and the uncertainty decreases as the project progresses, by adjusting the estimates to the actual performance on site.

The implementation needs for organizational aspects to be coordinated to increase the probabilities of its success. An organization which pursues implementing 4D BIM during the execution phase must sponsor these initiatives with a clear strategy, as well as creating awareness on the topic through the spread of the benefits of an implementation, as well as training the actors on how to perform tasks and how to manage under a BIM environment. This way, the proposed framework can be applied in line with the theoretical critical success factors stated in section 4.2. The implementation needs for both the technical features mentioned above, as well as soft skills aspects, to allow for technological development to bridge current gaps.

7.2. Reflection

The present section serves as a reflection on the research carried out, both of the process and the outcomes of it, to evaluate the methodology and the content to determine areas of improvement. The reflection includes the reasoning behind certain decisions taken during the research.

7.2.1. Methodology

The methodology set out on Figure 1 was the logical line of reasoning that the research followed to tackle the set of sub research questions that enabled answering the main research question. In retrospective, the methodology and the sequence of research question lead the research and the report into a smooth transition from one aspect, to the next. Therefore, it is necessary to highlight the importance of planning out thoroughly the investigation through the research questions and the intention of each one, since these stirred the research. If the author were to carry out more research, he would spend more time planning out the research questions.

Through a literature research a problem was detected and within this literature review, the technical background was built. After knowing the problem and having an initial idea of how to solve it, the approach was to present a solution and test it in a case study through an intervention. The motivation for this is to propose a solution and test it to provide evidence that could create awareness of the benefits and setbacks of an implementation of 4D BIM. The backing evidence of the benefits of this implementation stimulate additional efforts to implement further these techniques on the site and the evidence of the setbacks aid in detecting the gaps that need to be addressed in further research.

7.2.2. Theoretical Background and Interviews (Sources of Knowledge)

Even though the research was intervention oriented, and therefore presumably slanted more to the practical environment than the theoretical one, it was a personal goal to make use of the research experience to understand the theory and contrast how it holds in the practical world and how experts regard it. Therefore, the two sources of knowledge were the literature and the interviews with experts. The theoretical background was wide-ranging, yet necessary to substantiate each of the aspects covered and this may have not been clear for the audience at the beginning, but these were the tools the audience needed to follow the research. Perhaps the theory could have been stated prior to each section in which it would be used, yet the author considered it would give it a more scattered feel in case some topics would be covered partially in different sections.

The approach of obtaining knowledge was to build upon the existing theory on research and textbooks and complement it with interviews from experts on the site. It is a personal belief of the author that the construction industry is heavily oriented towards lessons learned mainly on the experience on the field whilst at the same time, academic knowledge sharing is underestimated. The author considers that this learn-by-experiencing mindset contributes to the inefficient practice of the industry. Therefore, it was important to capture as much knowledge from experts through interviews and share their experience in the present research to make these lessons learned available to the academia. This apparent broken link between the industry and the lecture halls is somehow evident in the research, since the topics covered on performance control using 4D BIM focused mainly on the technologies used to capture progress with specific cameras and gear, rather than to focus on the problem from a construction practice point of view. In other words, the previous research on this topic lacked a civil engineering background and how to use this information in construction but was more oriented towards information technologies. To counter this, the author attempted at bringing the performance itself and the reasons for unproductive practices to the discussion and how this were visualized with the aid of 4D BIM.

7.2.3. Case Study

The case study approach was aimed at bridging the theoretical and practical fields to provide and test solutions that could provide evidence that can create more awareness in the topic. In terms of breadth, the case study was rich in information on civil engineering projects as well as buildings that can be translated to other cases. In terms of depth, since the research was based on a mega project, it would have not been feasible to pursue further depth in all work packages. Moreover, initially the idea was to study two cases, yet the Moín Container Terminal project proved to be comprehensive and highly time consuming. The two-case study approach was deemed not feasible.

The intervention aided in generating data and insight (quantitative and qualitative) which helped in understanding and explaining the quantitative data. This approach supports the quantitative results, since the intervention cannot be reduced merely to the numbers. However, the numerical values are highly important in the research since these are hard evidence that is measurable and unbiased. The latter is important since the facts are presented, and not only perceptions which can be more easily disputed. Therefore, it is of great value to have both the quantitative and qualitative data in the present research.

With regards to the work packages, it would have been profitable to have a high rise building, which would have been useful to visualize the deviation signalling for a larger scale building. Nevertheless, the case study had sufficient disciplines that satisfy the objectives of the research and these can be extrapolated to other scales of projects.

7.2.4. Conceptual Model Creation (the Tool and the Framework)

The conceptual model aimed at solving a portion of the problem, whilst at the same time, the objective was to give the tool and the framework a technical background related entirely with the construction performance and the information flow to distance the research from previous investigations on similar topics. Even though the tool can be considered a leap forward in the theory, it was also a risk that the author took, since it is probable for the implementation to not be successful given that the data prior to and during the intervention could have easily not offered comparable initial conditions, with those during the implementation. For this reason, the preparation work prior to the intervention was extended for several months since the author feared not having representative data and not having a fair comparison in case the conditions prior to and during the implementation would differ significantly.

7.3. Recommendations

7.3.1. Academic Research

The present research focuses on how to visualize performance in order to control it, as well as the reasoning behind inefficiencies in the construction industry to act upon these. However, most of the research is focused on detecting and visualizing performance, yet seldom is the case in which the research focuses on how to solve these practical inefficiencies. Therefore, the author recommends that more research focuses on the practical solutions of these inefficiencies and how to make the construction practice more efficient. For this, it is necessary to establish strong interconnection between the construction industry and the academia. It is understood that most of this innovation is part of the secrets companies in the industry keep in confidentiality, yet it is recommended that more research and development is carried out, even if it is within a company.

With regards to further research branching from the present research, the author built upon the three dimensions of the geometric model and the fourth dimension of time and aimed at visualizing performance in this research (which can perhaps be understood as another dimension), however, there are other unofficial dimensions such as risk that need to be understood in models to make the models more insightful and reflect conditions from the site so that decision makers can make better informed decisions. Similar to this subject, it would be recommended to carry out research in linking Monte Carlo Simulation with a 4D Model to truly perform construction project simulation. Another recommendation is to carry out research in the field of tendering and the way the industry carries out this process, in order to impact the link between the conception and tender phase into the preconstruction planning and execution, since there seems to be a broken link and information flow can be deemed inefficient. In terms of performance visualization, there is still area for research for further innovation since the key performance indicators could be integrated into the visualization, yet it is necessary to maintain a simple model that does not overwhelm the audience and is rather a recommendation to keep as modes that can be switched on and off when the audience decides to focus on each of these aspects. The author also recommends performing research in the performance visualization and deviation signalling for high rise buildings to establish the opportunities that arise in this type of construction projects.

7.3.2. The Company

The author highly recommends the company to extend the use of 4D Models into the site execution phase to control performance. However, it is necessary to implement alongside with BIM integration to allow for information to flow to and from the site in a more efficient manner. However, in order to implement it is first necessary to create awareness through knowledge sharing of this pilot experience, and the benefits of the intervention. Moreover, this awareness should be coupled with training of staff on how to manipulate software packages, as well as to how to integrate organizations under a BIM approach. It is essential that companies train all their relevant staff since if it is not carried out, the handover of information is carried out in a traditional manner in which one sole knowledgeable staffer (or a small portion of personnel) knows how to manipulate the models and therefore, the information flow is channelled and dependent only through this small portion of the project organization. It is also recommended to carry out further pilots of implementation in other projects to introduce the techniques into projects in a gradual manner to shift practices towards a more digital construction-oriented approach. It is highly recommended to seek for those sponsors in projects (main project leaders) who can enable the required change towards an integrated approach and motivate them to pursue an implementation. The shift towards a BIM approach relies on knowledge and involvement of all the relevant parties and it cannot be carried out without the awareness, training and sponsorship.

The author recommends the company to start by implementing 4D BIM fully on tender phases to allow further stages of the project to have an initial model to build upon. It would be recommended to apply these guidelines from the initial phase of the project to enable the setup to be ready for site execution to keep a close control and detect deviations in a timely manner. The model needs to be updated periodically based on the information collected from the site to keep the model as an accurate representation of the site execution. In case significant deviations occur and the baseline plans are no longer feasible, it is recommended that to adjust and reissue the baseline plan. It is also recommended to implement the model during the whole project life cycle and exploit the capabilities during site execution to improve visualization of current status, deviations and future coordination required. The implementation must include the communication directed towards the site (two and six week look aheads) as well as the feedback provided by the site execution staff to update the planning (through mobile applications such as Synchro Site) and increase the accuracy in the subsequent plans by collecting data on start and end dates of activities to recalculate performance rates.

The implementation needs to be inclusive of all the project staff, since these can benefit greatly from integration and knowledge sharing. To enable older staff, it is important to train them on how to manage these technologies and give them an overview of the breadth, and train younger staff on the depth to exploit BIM capabilities. Also, it is important to train intermediate aged staff on BIM tools since these may be the key players in the process since these possess a blend of knowledge on techniques as well as a track record of useful experience.

The author considers highly profitable for the construction practice to establish an ongoing operation of research and development in house or to sponsor research alongside with the academia to investigate on the possibilities to bridge traditional gaps of the industry and solve for inefficiencies in construction practice. Carrying out research is essential for the companies to understand which technologies are suitable for their business and to explore how to exploit them.

Chapter 8
Limitations

8. Limitations

8.1. Introduction

The implementation is subject to external factors that influence the outcomes. However, it is not possible to accurately quantify the individual impact of these factors on the results obtained. The limitations are mainly related to the single in-depth case study, effects of weather, learning curve effects, the size of the project, the period of evaluation and the unequal circumstances that the crews faced prior to and during the implementation. Replicating this research would not lead to the exact same outcomes due to the fact that there are environmental, human and technological limitations that are not affecting each implementation in a uniform manner.

8.2. Singular Case Study: Inferring from a Statistical Sample

Due to the fact that the present research studies and measures one case study in detail and refers to other case studies in a qualitative manner through interviews, the statistical sample is not sufficient to be able to draw up conclusions that can be further generalized to the rest of the cases. However, the results and conclusions obtained from this research are validated though case study comparisons and expert judgement.

8.3. Weather Conditions

Performance is the main aspect studied in this research and it is directly affected by the weather which enables or prevents the crews from progressing in a project. Weather conditions during the evaluation period were not uniform, and therefore, required for data manipulation to match the conditions prior to and during the implementation. During the implementation period, average rainfall conditions were present and therefore, the extreme rainfall events have been extracted from the analysis as well as extreme dry conditions to be able to have a comparable set of results. It is not feasible to obtain the exact same precipitations, humidity and temperature readings at the same time of the day and therefore, the quality of the data is deemed satisfactory.

8.4. Learning Curve Effects

The only available measurable parameters in this research to determine the performance on site were the progress achieved on a weekly basis as well as the duration per activity. From these, one could observe if there was an improvement or not during the implementation. The point of comparison in terms of progress is taken as an average number since the production fluctuated prior to and during the implementation. It would be preferable to state a starting reference point in the learning curve, yet during the evaluation period prior to the implementation there was the aforementioned fluctuation of production, and not a clear trend from which one could derive the starting condition in the learning curve.

For learning curve purposes, it would be preferable to establish the relationship between the amount of manhours put into each individual works and the outputs, but this data was not available. Nevertheless, the working hours and amount of personnel remained relatively unchanged during the whole evaluation period.

8.5. Scope of Works: Mega Project

The results obtained will vary from one case study to another, since each project is quite specific. The results must be understood in terms of the reasoning behind each of the improvements, since these will be the aspects that could repeat themselves in other cases. Also, tracking the large scope of works on site in a mega project is quite time consuming, therefore, the largest portion of the data collection on site is destined for the numbers. However, in a smaller project, it would be less of a burden and hence, there would be more time available for further visualization and analysis of the site conditions.

8.6. Resources

Fortunately, in the case study, the resources were quite stable which enable a fair comparison of the progress values, as well as the schedule performance index prior to and during the implementation. Logically there are small discrepancies from one week to the next since there is a logical fluctuation of personnel, yet it did not represent even a 1% change at any time. Logically, this is not the common practice, and therefore, the recommendation for research reproduction purposes, would be to divide the progress into the amount of manhours to obtain a fair comparison.

8.7. Concurrent Factors

Given the multidimensional nature of a construction project in which a series of aspects affect simultaneously the outcomes on the site, it is not feasible in this research to quantify the effect of each individual factor on the performance. To make up for this shortcoming, the research includes in its data analysis only those results for the periods in which no additional factors are included such as bonuses, additional resources (if it were the case), night shifts as well as extreme weather conditions.

8.8. Unequal Circumstances

The construction industry is not perfect; therefore, it is necessary to understand that conditions will variate from one project to another, and within the same project, variations will be experienced over time. Therefore, if one were to replicate this study, the results would yield different results. The second aspect makes the comparison in this research complicated, yet the circumstances were recorded prior to and during the implementation for a fair comparison.

8.9. Evaluation Period

The implementation period had a duration of six weeks. Fortunately, the research showed variations in the results. However, it would be understandable if the period were not considered extensive for two reasons: first, the research could yield increased numbers in progress over a longer period of implementation and second, one could argue that the effects of the implementation could perhaps not be sustained over a longer period of time. However, the results show a clear improvement and therefore, these could be deemed as satisfactory. The reasoning behind the extended duration of the period of evaluation prior to the implementation, and a six week period during the implementation is a twofold, first the setup of a proper model in the execution process was time consuming and second, since the conditions in the future are unpredictable, the author gathered data prior to the implementation over an extended duration to ensure that there would be data that would match the conditions present during the implementation.

8.10. Conclusions

Even though this research had the aforementioned limitations, the actions taken to mitigate the effects can be considered satisfactory, since the construction process does not take place in an isolated environment, and every case will have varying conditions. It would not be practical to quantify the individual impact of each of the aspects to state the individual contribution since the aim is to provide a functional method of controlling performance.

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Appendix A. The Adjusted Framework

Framework for Integrated Contracts

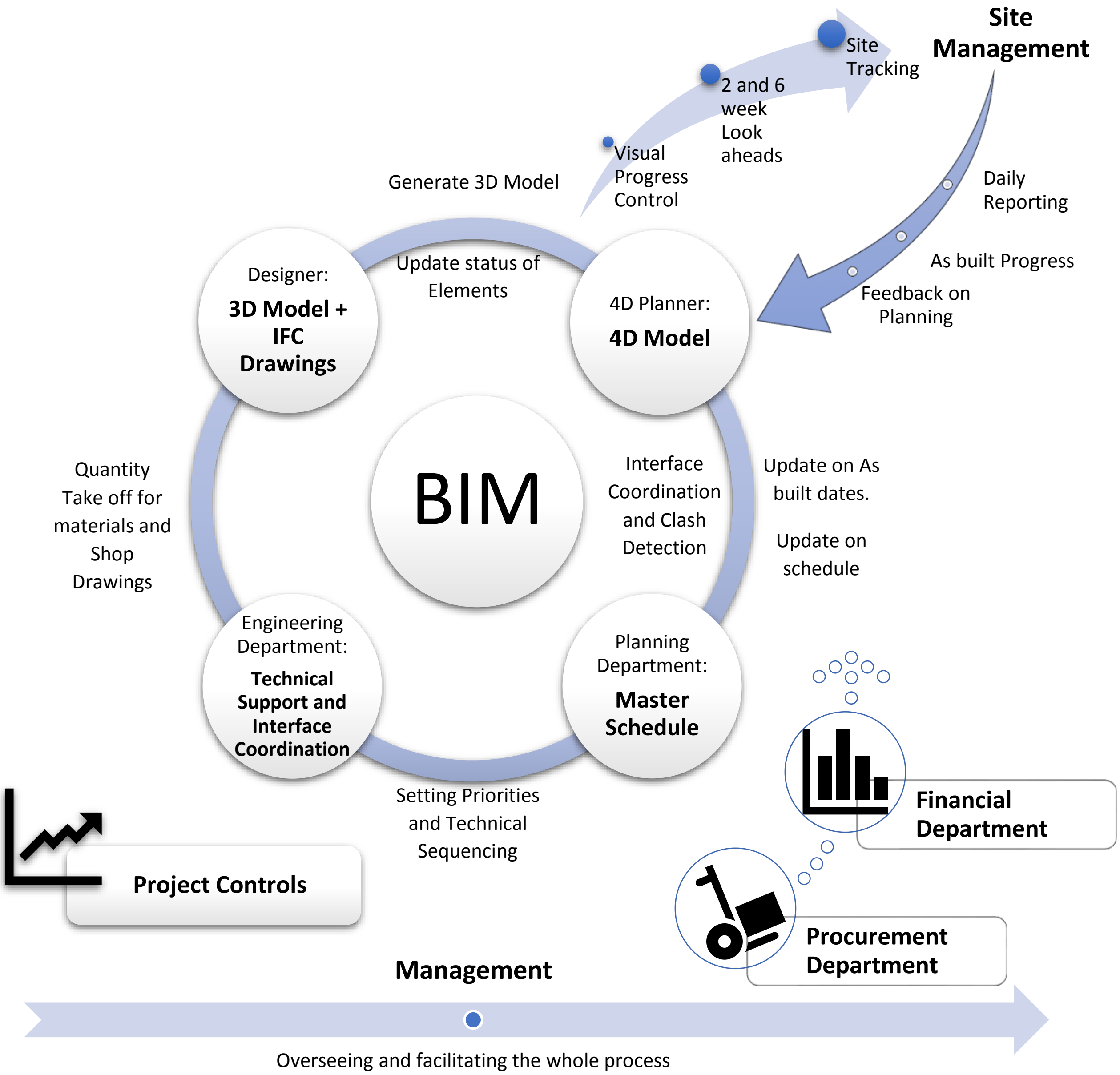


Figure 50. Adjusted Framework for Integrated Contracts

Framework depending on the Level of Implementation of BIM

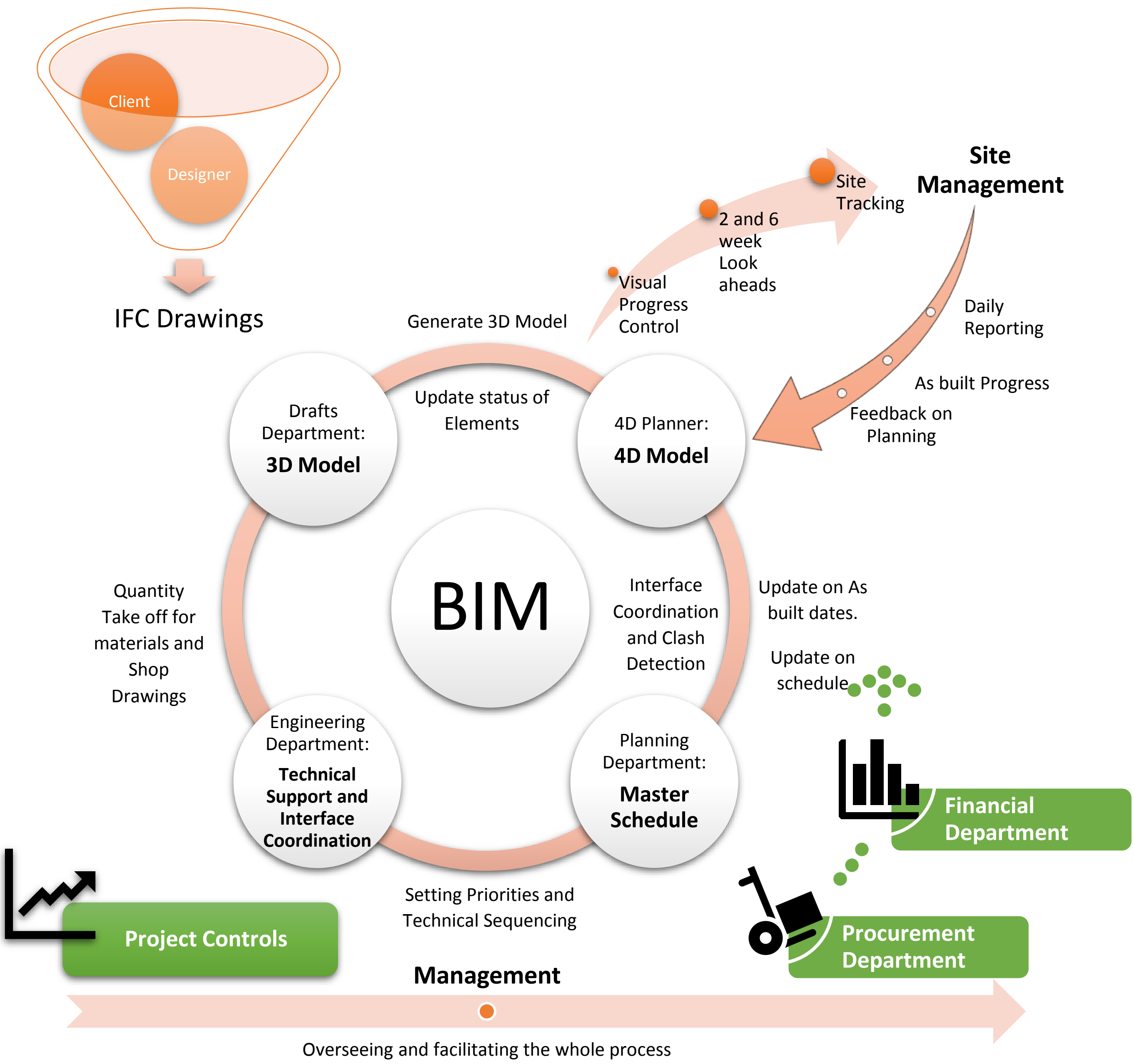


Figure 51. Adjusted Framework depending on the Level of Implementation of BIM

Framework depending on the Stage of the Project

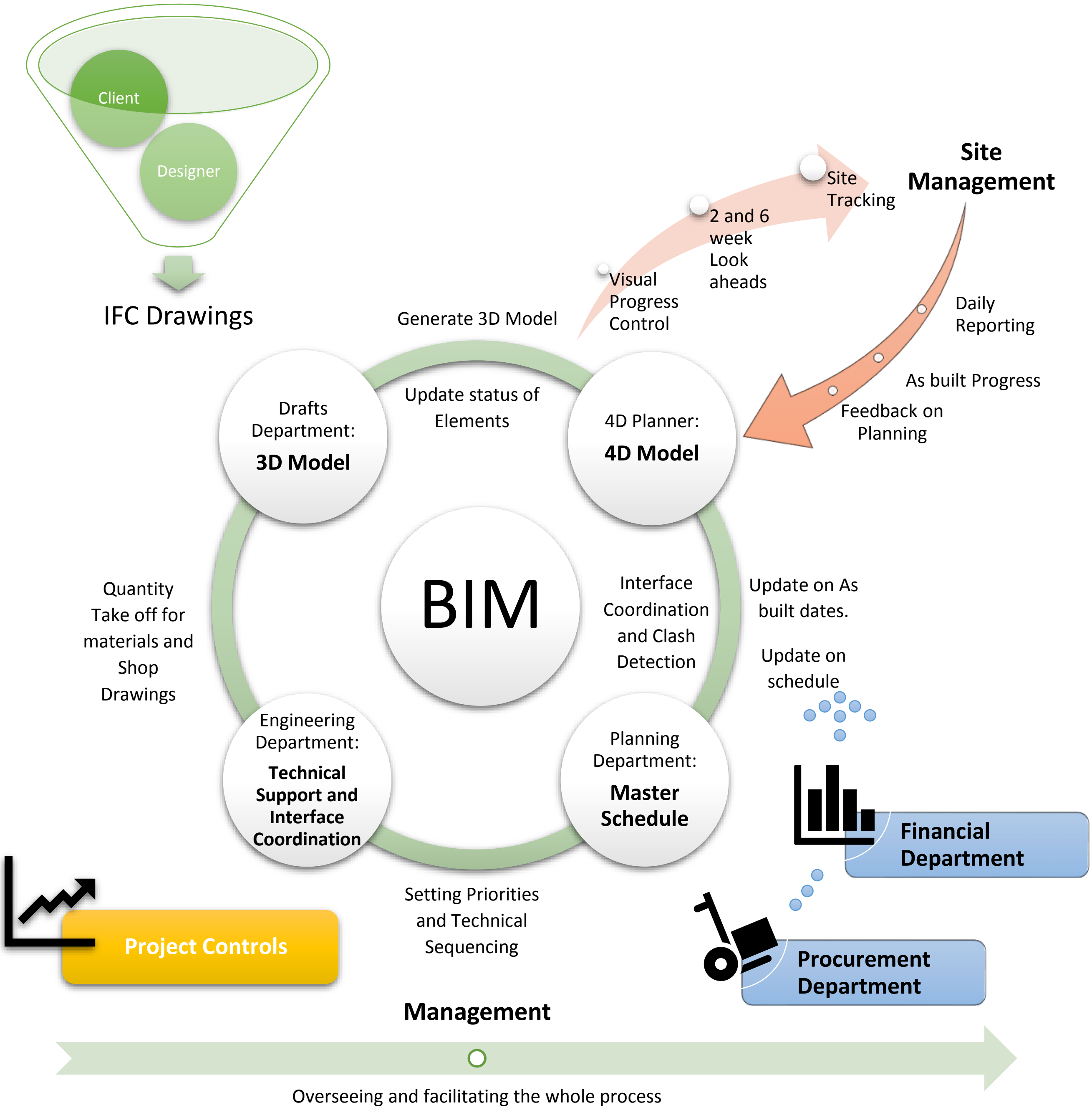


Figure 52. Adjusted Framework depending on the Stage of the Project

Appendix B. The Setup Guide

Level of Development According to Project Phase

- Setup for the Tender Phase

The contractor should generate a tender 4D model with a Level of Development between 200-300 (depending on the amount of details given on the drawings and specifications from the engineer). The model should be partitioned and detailed as per the needs of the contractor to visualize construction sequence and interfaces. 3D drawings are normally done on Sketchup or other rapid portrayal programs.

- Setup for the Preconstruction Planning Phase

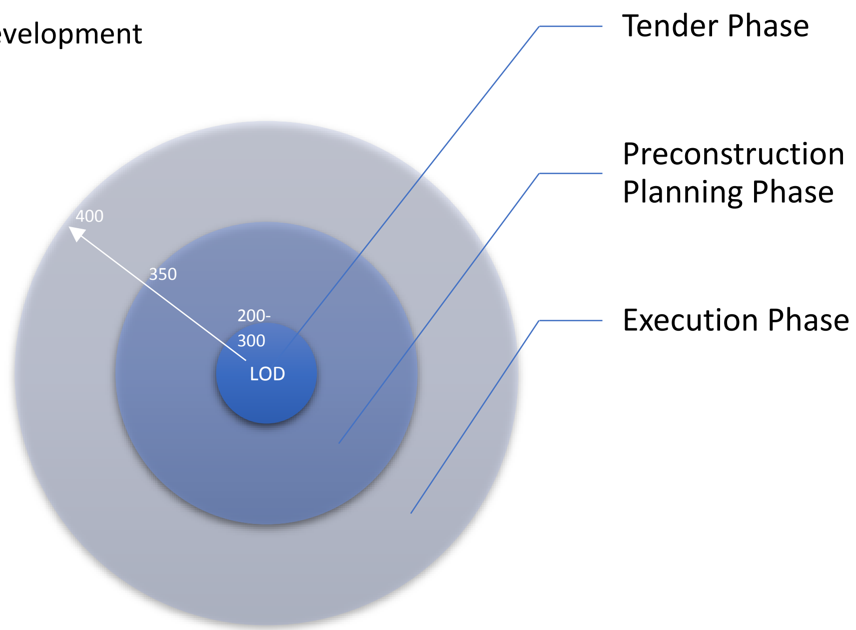
The contractor should further detail the 3D model in more elaborated software according to the drawings and specifications from the design engineer. The level of development should be in the neighbourhood of 350. Interfaces and workspaces should be coordinated to allow for the planning to be recalculated in case of clashes or other opportunities visualized in the 4D model.

- Setup for the Execution Phase

The model should be further developed to an LOD 400 during the execution for the following 6 weeks to allow for detailed visualization of daily installation procedures and sequences that the site teams must execute. The sequence of the remainder of works must be coordinated for interface clash checks.

The planning must be carried out in a multilevel approach, allowing for the Master Plan to have sufficient detail yet remaining on a manageable level for the whole project scope. At work package level, the planning must be further detailed to establish the work preparation that the site execution teams must carry for each day over the course of the following 2 to 6 weeks.

Level of Development



4D Model Baseline and As Built Setup

- The Baseline Model

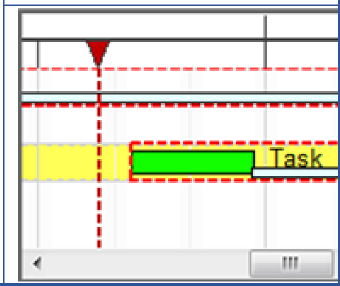
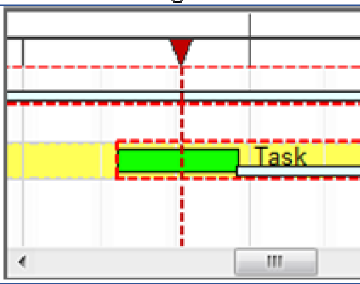
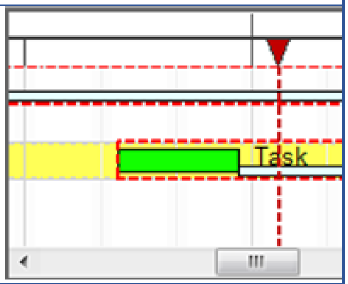
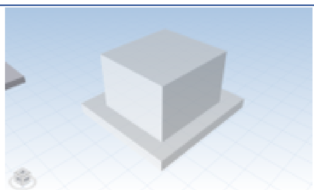
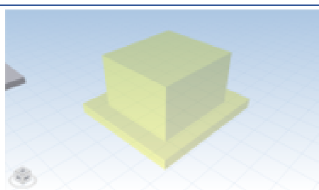
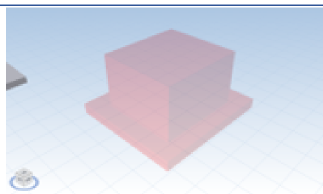
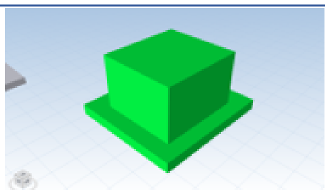
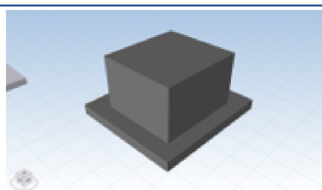
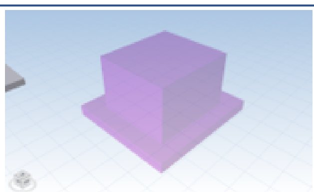
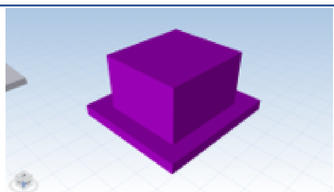
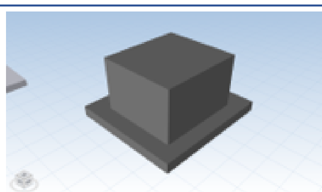
The Baseline Model 4D Model is the product of the 3D geometric model, and the baseline schedule of the project. The objects are linked to the internal planning of the work package to ensure sufficient level of detail. This baseline must not be modified or updated unless the baseline and the as built 4D models are no longer comparable and plans are no longer feasible. This must be done on a separate file.

- The As Built Model

The status of built elements (start date, progress and end date if completed) must be updated daily (or as regularly as requested by project) through mobile 4D BIM based applications (in this case Synchro SITE is suitable). The start date, progress and end date must be assigned to each element to produce the As Built 4D Model to record the actual sequence of works on a separate file.

- Colour Coding

The baseline and the as built 4D model should be generated on separate files. In each one, it is necessary to set the appearance profiles of the elements according to the schematic shown below depending on the focus time and the model referred to (baseline, as built or critical path).

	Focus Time		
	Before Task	During Task	After Task
Profile			
Baseline	 White Transparency 60%	 Yellow Transparency 70%	 Red Transparency 80%
As Built	 Transparency 100%	 Solid Green	 Solid Grey
Critical Path	 Purple Transparency 70%	 Solid Purple	 Solid Grey

- Overlapping

At the end of every week or two, the Baseline and As Built 4D Models must be integrated into a sole file to be able to make the comparisons in an overlapped approach between the two models.

Deviation Control

From the overlap of the two models, it is possible to visualize the crews that are lagging and the elements that are deviating. From this visualization, it is up to the decision makers to establish the action plan, to make up for the deviations through increase in resources, extended shifts (not recommended) or other approaches.

The data must be fed to the Master Plan to update the planning and the performance rates must be recalculated to correct the forecasts.

2 Week and 6 Week Look Aheads

Each work package must create their internal detailed plan that satisfies the master plan and one that provides enough detail on the daily sequence for the following 2 weeks and 6 weeks. Also, each work package must create a rough sequence of works for the remainder of the project (after the following 6 weeks from the data date). In case it is not feasible, this must be red flagged for revision and recalculation. Each work package must do their 2 week and 6 week look ahead plan on a 4D Model of each work package on an isolated file.

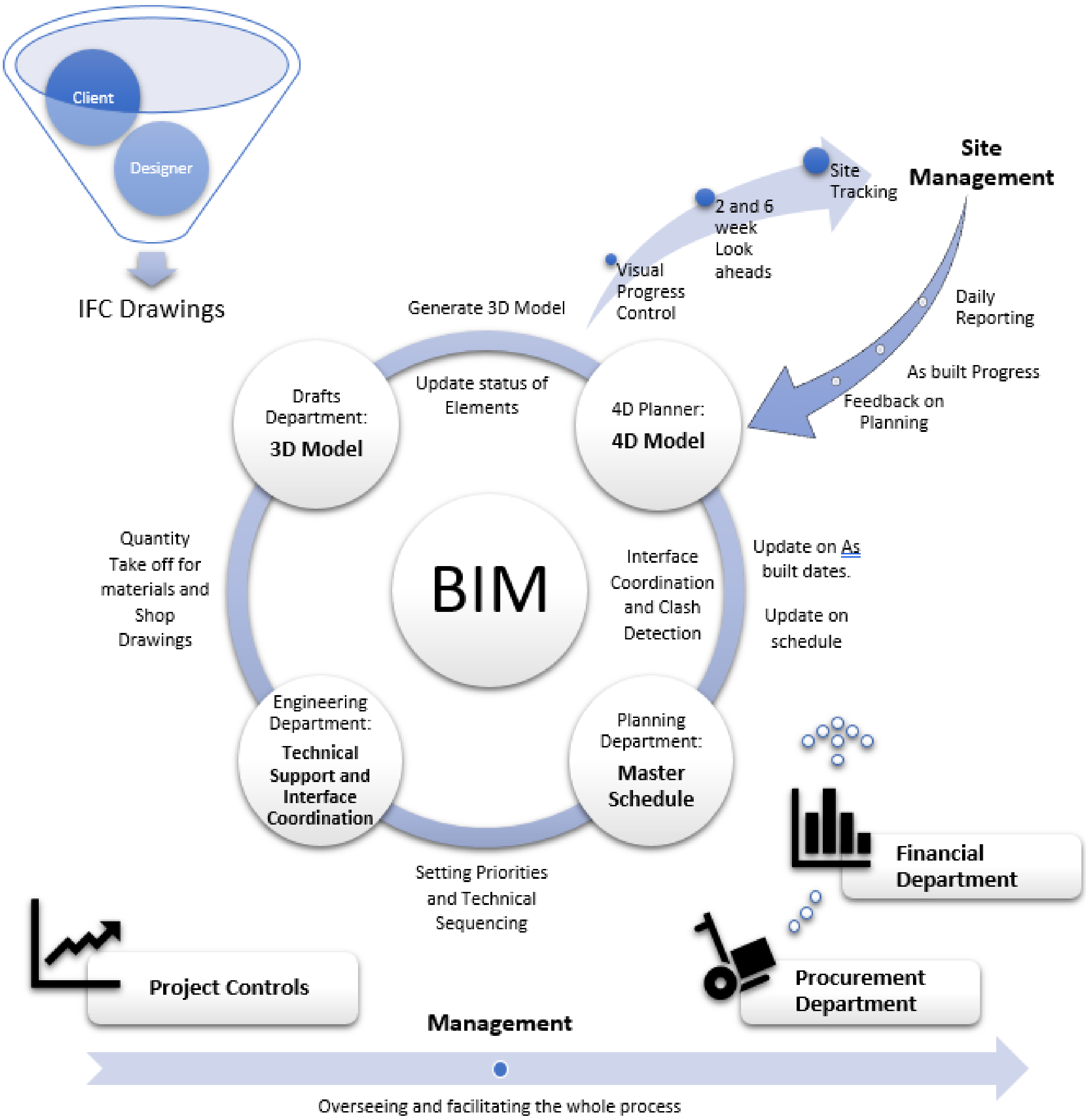
Interface and Workspace Coordination

Each work package model must be then integrated into a sole project model with all the scope of works by a 4D Modeler, who should detect the clashes and assign a priority to each clash based on the criticality of the works. Furthermore, the work package leader should meet periodically (every two weeks) prior to progress meetings, to discuss interface clashes, resource allocation, workspace coordination and traffic coordination for the following 6 weeks.

This process must be carried out iteratively from the beginning of the execution phase, up to the completion date of the project.

Flow of Information

The information flow should follow the figure shown below in which the flow is initiated with the issuing of drawings and specifications by the design engineer. This information is interpreted and processed by relevant work package engineers and draftsmen. Following this, an object based 3D Model should be generated. Given the quantity take-off, specification review, performance rate estimation and visualization of the scope of works, the planning department must create a schedule for the works to be carried out. At work package level, a detailed sequence of works should be carried out to provide substantiated schedules for the crews on site to perform. Having the 3D geometric model available and the planning ready, these two are linked together and the interfaces as well as the workspaces are coordinated to detect clashes. A 2 and 6 week lookahead is issued for project execution teams to accomplish. On a periodical basis, the progress data is updated on mobile applications if present, and the feedback of site execution is fed back to the planning department, to recalculate and reforecast the remainder of activities of the project. This process is iterative and the flow of information keeps on going up to the end of the project.


Client
Designer
IFC Drawings
Generate 3D Model
Visual Progress Control
2 and 6 week Look aheads
Site Tracking
Site Management
Daily Reporting
As built Progress
Feedback on Planning
Drafts Department:
3D Model
Update status of Elements
4D Planner:
4D Model
Quantity Take off for materials and Shop Drawings
BIM
Interface Coordination and Clash Detection
Update on As built dates.
Update on schedule
Engineering Department:
Technical Support and Interface Coordination
Planning Department:
Master Schedule
Financial Department
Setting Priorities and Technical Sequencing
Project Controls
Procurement Department
Management
Overseeing and facilitating the whole process

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