CHALMERS

A quantitative methodology for measuring 4D performance in design and construction phases of construction projects

Master of Science Thesis in the Master's Programme Design and Construction Project Management

VO THANH CONG

Department of Civil and Environmental Engineering
Division of Construction Management
CHALMERS UNIVERSITY OF TECHNOLOGY
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Department of Civil and Environmental Engineering
Division of Construction Management
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

Cover:
A 4D model of the housing project of the case study in this thesis

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ABSTRACT

Although research pertaining to 4D CAD has presented various benefits of 4D models in construction projects, these benefits has been still questioned whether they can compensate the initial cost and effort to create those models. Thus, this thesis aims to develop a methodology for assisting construction actors to quantify 4D benefits. The methodology for measuring the 4D performance is built upon literature review and case study. Through literature review, 4D benefits and their corresponding Key Performance Indicators (KPIs) are identified and combined into a framework. The indicators are categorized into the design and construction phases and then tested in a case study. The case study is a housing project in Gothenburg, Sweden. The data collected from the design phase and the construction phase of the case study reflect a high level of design quality but a low level of project plan's reliability. These findings are analyzed and discussed in order to evaluate the content, the use and the practicality of the integrated framework. Due to three limitations of the case study such as time constraints, improper planning procedure and insufficient standardized performance documented, the methodology has not been fully verified yet. Therefore, it needs to be tested in further case studies.

Key words: key performance indicator, literature review, case study

Contents

Preface

"If I have seen a little further, it is by standing on shoulders of Giants" (Isaac Newton). It would have been impossible for me to complete this Master Thesis without help, guidance, and support from my supervisors, friends and beloved family.

I would like to take this opportunity to express my gratitude to my supervisor, Börje Westerdahl. Without him, I would never have had a chance to learn new things, make new friends, be exposed to new working environments and enjoy the study.

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Confucius said "A journey of thousand miles begins with a single step", and it is Tobias Boström, my senior, who has helped me to take my first steps. I am very thankful for his kindness and enthusiasm in helping me when I initially knew nothing about the project.

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Last but not least, I want to thank my parents, little sister, and my sambo – those who have sacrificed a lot for me. I would never have gone this far if they had not loved, cared for and supported me all the time. I am happy to dedicate this paper with my love and gratitude to my family.

Thank you all for everything.

Göteborg May 2012

Vo Thanh Cong

1 BACKGROUND AND OBJECTIVES OF THE STUDY

"*Certainly in most of the world we now see that creating a 3D model and spinning it around on the screen to impress the owner is no longer sufficient*."

Mark Sawyer – CEO and President of VICO Software.

Since the 1990s, the popularity of 3D CAD has abated, gradually giving up the market to a higher technology, 4D CAD. This new method is perceived to augment effective design and planning by means of integrating the fourth dimension, time, into 3D models (Hijazi, Alkass, & Zayed, 2009). Several construction projects implementing 4D CAD have been documented up to now. For example, Gao et al. (2005) listed twenty-one cases studied across the world vis-à-vis the different usages of 4D CAD. A few notable examples are Terminal 5 of London's Heathrow Airport, London, England (2003-2007), Hong Kong Disneyland, Hong Kong (2001-2005), and The Pilestredet Park, Oslo, Norway (1998-2003). In Sweden, 4D CAD has been employed in different types of construction projects encompassing a wide range from small residential buildings in Stockholm (Gao, Fischer, Tollefsen, & Haugen, 2005) to a giant pelletizing plant in Malmberget (Woksepp, Jongeling, & Olofsson, 2005). Notwithstanding, the promising results of 4D-CAD applications in the aforementioned projects, the effectiveness of 4D CAD and its potential in respect of the construction industry have not been fully comprehended as yet (Gambatese, Dunston, & Pocock, 2007).

The preponderance of previous research has concentrated upon three areas of 4D application thus far: i) product modeling and visualization, ii) process modeling and analysis, iii) collaboration and communication (Heesom & Mahdjoubi, 2004). The first research area has managed to overcome the technical impediments of constructing a 4D model and appraising the resulting benefits regarding visualization. Diffuse images and the arduous 2D→3D→4D converting process epitomize the technical problems that currently inhibit 3D/4D models from simulating the real world (Roupe & Johansson, 2009; Woksepp, Jongeling, & Olofsson, 2005). Scholars and software developers have endeavored relentlessly to solve those problems and their unremitting effort has paid off, especially regarding visualization of project process. According to an evaluation of the applicability of 4D CAD on construction projects (Mahalingam, Kashyap, & Mahajan, 2010), the usefulness of 4D CAD for clients to visualize the construction process and to review constructability are very high. The study presented 4 construction projects in India where 4D models were employed to overcome their unique problems. For example, one of the projects was mostly constructed underwater, and 4D was used to simulate the construction sequences. In addition to the case studies, these researchers also reported results of a survey they conducted regarding usefulness of 4D applications. Out of maximum 5 (indicating a high degree of usefulness) visualizing construction process and reviewing constructability score averagely 4.74 and 4.26 respectively. This qualitative result infers that construction actors consider 4D models to be immensely helpful. Resulting in significant advantages of visualization, 4D CAD is expected to reduce rework, increase accuracy and, thus, to save cost and time.

The second research area, process modeling and analysis, constitutes a holistic approach, wherein construction activities, their attributes and interrelations are scrutinized through the project life-cycle. 4D CAD, availing itself of the fourth dimension (time), is primarily considered a fruitful tool to facilitate the scheduling process. Research has ascertained that project stakeholders seemed to be able to understand a construction schedule delineated by 4D CAD better than by traditional tools such as Gantt chart and 2D drawings (Songer, Diekmann, & Karet, 2001; Yerrapathruni, Messner, Baratta, & Horman, 2003). Ergo, 4D models can attain a greater approval rating than other planning methods (Allen & Smallwood, 2008). Additionally, a case study by Luleå University of Technology (Sweden) revealed the benefits of 4D CAD in the scheduling process of a huge project (Woksepp, Jongeling, & Olofsson, 2005). Unlike a Gantt chart that encumbers the process with a formidable number of activities and interrelations, 4D CAD accommodates a high degree of spatial understanding and better comprehension of how and when the construction is going to be executed. However, 4D CAD might not be a one-best-way solution for all problems pertaining to process modeling and analysis. Mahalingam et al. (2010) found that construction actors doubt that 4D CAD will play a preponderant role in contractual dispute resolution. Analyzing contractual disputes by 4D models consumes a lot of time and effort, but probably yields small benefits due to possible disagreements over the assumptions made by involved parties in 4D models and unnecessary presence of details about shape and geometry.

The third research area has addressed the feasibility of utilizing 4D CAD to improve communication and collaboration. To measure the efficacy of the 4D CAD method, Professor Dawood from University of Teesside (England) and his team conducted an experiment in which two groups of participants were provided with 2D drawings and a 4D model respectively, in order to build a small and simple "LEGO" house model (Dawood & Sikka, 2008). The results were clearly in favor of the 4D group. Overall, they surpassed the 2D group by using 22% less time to extract information, 7% less time to construct the model, and 77% less rework. In conclusion, the research argued that 4D CAD facilitated collaboration fruitfully, and enhanced mutual understanding, expedited the process and reduced rework. Not being limited to only small-scale and simple projects, these benefits are deemed to be amplified in the context of the construction industry where 4D users have to deal with multifarious stakeholders, spatial constraints, and hostile environments such as submarine or underground conditions (Mahalingam, Kashyap, & Mahajan, 2010).

In spite of numerous intensive studies, current research on 4D CAD pertinent to the construction context is still at its infancy and deficient in two respects. First, most of the previous studies have barely delved into the requisite costs and efforts for building up and implementing 4D models. Although the research on this issue is still only rudimentary, scholars have asserted that the tremendous costs and efforts have so far been the heaviest burdens (Gao, Fischer, Tollefsen, & Haugen, 2005; Webb, Smallwood, & Haupt, 2004). For example, in the case of The Pilestredet Park (Norway), the 4D package including a model and managing software cost 160,000 Euro and 1.5 years to complete (Gao, Fischer, Tollefsen, & Haugen, 2005). Another example is the giant pelletizing plant in Malmberget (Sweden). In spite of the availability 2D drawings, 4D designers spent several months converting 26,000 2D-objects to 4D and assigning properties for 50,000 objects. These figures raise a crucial question and lead to the second aspect: do the benefits of 4D suffice to compensate for the costs and efforts? So far, researchers have reiterated their praise for 4D CAD in order to answer the question, but the majority of them have inferred their results from their qualitative research results. That is to say, those praises are not absolutely convincing. Answering the question convincingly entails quantitative research.

Previously, 4D CAD has been known to offer higher degree of spatial understanding, better construction management (Woksepp, Jongeling, & Olofsson, 2005), but now it is paramount to determine how much money and time those advantages can actually save. In fact, Professor Dawood's experiment (2008) mentioned above, did present quantitative results; however, his experiment with the simple LEGO models is incapable of representing a full-scale construction project. Ergo, a need for evaluating the benefits of 4D CAD quantitatively in a real-life construction project has arisen. Unfortunately, no appropriate method for such evaluation has yet been established.

In pursuance of a quantitative methodology used to measure the benefits of 4D CAD in the design and construction phase of construction projects, this paper proposes a research project, the scope of which consists of two primary objectives: i) constructing a methodology and ii) verifying it. The former aims to specify the benefits of 4D CAD, identify their corresponding key performance indicators, and establish a framework together with an instruction on how to use the framework to collect data properly. The latter objective is to target the reliability and limitation of the methodology when it is implemented in a real construction project. In this step, a case study is conducted to test the methodology. The case study aims to explore stakeholders' perspectives on identified 4D benefits and the methodology's feasibility of obtaining quantitative data from a construction site. With better understanding of 4D CAD, it helps a company to accrue its sustainable competencies and direct its future strategic development.

This thesis comprises six chapters. Chapter 1 introduces the contemporary development of research on 4D CAD first, and then states the objectives of this study. Chapter 2 summarizes related literature, identifies the benefits of 4D CAD and their measures. Chapter 3 elaborates the methods used to establish the framework for measuring 4D models, collect data from the pilot case, and test the established framework. Chapter 4 and Chapter 5 summarize the findings of the study; the fourth chapter presents the resulting framework with some discussion, while the fifth chapter reports the real-life case in which the framework was used. Finally, chapter 6 discusses the constraints of the study, draws the research conclusions and provides recommendations for further studies.

2 RELATED LITERATURE

"The 4D model saved Heathrow's Terminal 5 project £2.5m in the first 9 months of use"

Marcus Kapps - Senior Strategy Manager, BAA Heathrow

Since construction actors have started availing themselves of 4D CAD modelling (4D) to manage the construction process, the method has resulted in advantageous outcomes in many projects, and has thereby attracted enormous attention from both academia and industry. The benefits that 4D contributes to the success of construction projects have been scrutinized by several scholars and practitioners. Independent studies such as those carried out by Yerrapathruni et al. (2003), Heesom & Mahdjoubi (2004), Webb et al. (2004), Worksepp et al. (2005), Gao et al. (2005), Allen & Smallwood (2008), Dawood & Sikka (2008) and Mahalingam et al. (2010), were conducted to elicit and evaluate the benefits from implementing 4D in construction projects. These studies are presented in the following section.

Among the first endeavors to compile and categorize the benefits systematically were published in 2004. In their study, Heesom & Mahdjoubi (2004) presented three areas of 4D application (product modeling and visualization, process modeling and analysis, collaboration and communication) and the usefulness of 4D in each area. Although the study provided researchers with a panorama of 4D applications, the compiled list of benefits was not exhaustive and was lacking in detail. Ergo, in pursuance of quantifying 4D's benefits a need for an exhaustive list arose. Shortly after Heesom & Mahdjoubi (2004), Webb et al.(2004) established a new list, wherein the benefits of 4D with the construction process were outlined. The study categorized the process into the preconstruction phase and construction phase. The preconstruction phase encompassed four primary tasks: conceptualization, engineering & design, presentation and planning, while the construction phase comprised actual construction, communication, and training. This classification is logical since it concurs with the four orthodox phases of the construction project life-cycle (conceptualization, planning, execution and termination). The study by Webb and his colleagues heralded an exhaustive framework which depicts how 4D benefits a construction project. The list of 4D's benefits was, however, mainly based on the research team's experience and only one project, thus further research was necessary to verify its reliability.

In 2008, Hartmann, Gao and Fischer (2008) managed to establish a new list based upon the aforementioned studies and 26 different projects documented from 1997 to 2005 by the Center for Integrated Facility Engineering (CIFE) at Stanford University (US), a key protagonist in 4D implementation. In the new list, the findings of Heesom & Mahdjoubi and Webb et al. coalesced. Yet two modifications emerged. In the first modification, the construction phases and activities proposed by Web et al. (2004) were winnowed down to three main phases: conceptualization, design, and construction. This classification adheres to the widely-accepted project life-cycle's phases, thus avoiding unnecessary confusion. In the second modification, Hartmann, Gao and Fischer augmented the areas of 4D applications and the list of identified benefits. Instead of three areas, the list of 4D applications was now extended to six, namely, i) photorealistic renderings/presentations, ii) virtual design review, iii) cost estimation, iv) analyzing design options, v) analyzing construction operation, vi) construction document production and finally vii) bid package preparation. Table 1 illustrates the list of 4D benefits compiled from both Web et al. (2004) and Hartmann et al. (2008).

Table 1: The areas of 4D application and the 4D benefits according to Hartmann et al. (2008)

Project Phases	Areas of 4D application	The 4D benefits
Conceptualization	Photorealistic renderings/presentations	- Serving marketing purposes to seek for financial supports or public involvement
	Virtual design review	- Checking or revising specifications to satisfy building codes/standards
Design	Photorealistic renderings/presentations	- Virtually presenting building models, construction methods to multifarious stakeholders
	Virtual design review	- Communicating complex geometry clearly in meetings
		- Creating a communal medium for joint discussion among different parties
	Cost estimating	- Establishing a direct link between 3D and bills of quantities
		- Facilitating changing and updating cost estimation by reducing estimating time and cost, and increasing accuracy
	Analyzing design options	- Providing more reliable evaluation of design alternatives by taking all temporal constraints into account
		- Comparing design options with cost constraints to find optimal design solutions
	Analyzing construction operation/process	- Establishing a link between 3D and schedules, which allows visualization and analysis of the construction sequences
		- Planning for site layout and required working spaces such as delivery, transportation and storage
	Construction document production	- Standardizing building components to reduce assembly time, cost, errors, and to increase accuracy
		- Reducing material orders' lead time
	Bid package preparation	- Defining the scope of work clearly for subcontractors to provide better understanding and avoid future conflicts
Construction	Analyzing construction operation	- Detecting conflicts in schedules such as time and sequence conflicts
		- Detecting spatial conflicts
		- Detecting design and on-site conflicts

		- Detecting conflicts between subcontractors and among different parties
		- Developing resolutions/alternatives when disruptions occur due to unexpected incidents/changes
		- Maintaining cost control during construction
	Virtual design review	- Instructing and training construction teams before engaging in intricate, challenging, or hazardous activities
		- Overcoming language barriers, especially in the context of international projects

The 22 benefits identified in Table 1 are reliable since they were tested in 26 full-scale construction projects spreading over seven countries. In the next step of my study, these benefits were correlated with key performance indicators (KPIs) in order to quantify the enumerated benefits.

About two years after Hartmann, Gao and Fischer (2008) established the categorization framework for the benefits of 4D, Professor Nashwan Dawood from University of Teesside (Middlesbrough, UK) managed to compile KPIs for measuring the performance of 4D in construction projects. His study (Dawood, 2010) is a compilation of various previous studies including Kaplan & Norton (1992), Li et al. (2000), Chan et al. (2002), Robert et al. (2002), Cox et al. (2003), Bassioni et al.(2004), and Chan & Chan (2004). As a result, nine KPIs that are correlated to 4D's performance were identified: time, safety, client satisfaction, planning efficiency, communication efficiency, rework efficiency, cost, team performance, and productivity performance. Table 2 below elucidates the definition of those performance indicators.

Table 2: Definition of the identified KPIs (Dawood, 2010, p. 213)

KPIs	Definition	Specific measures
Time	Percentage number of times projects are delivered on or ahead of schedule	Schedule performance (Earned-value analysis)
Safety	Effectiveness of safety policy and training of the personnel engaged in activities carried out on site	Time lost in accidents per 1000 man hrs worked Number of accidents per 1000 man hrs worked
Client satisfaction	How much the clients are satisfied with the product/facility	Number of client change orders Satisfaction questionnaire Number of claims (time/cost)
Planning efficiency	Hit rate percentage	Percentage of activities started and completed on time (hit rate %)
Communication efficiency	How well information is exchanged between members using the prescribed manner	Number of meetings per week Time spent on meetings per week
Rework efficiency	The activities that have to be done more than once in a project or activities which remove work previously done as a part of a project	Number of design errors Number of design corrections Number of schedule sequencing clashes Number of request for information
Cost	Percentage number of times projects are delivered on/under budget	Cost performance (Earned value analysis)
Team performance	How well team members' activities are coordinated in terms of performance, motivation, working environment	N.A
Productivity performance	The number of completed units put in place per individual man-hour of work	(for example) number of piles driven per day, number of pile caps fixed per day

To the best of my knowledge, Dawood's study (2010) is the most recent literature review of 4D performance measures as yet. The study, however, did not associate the identified KPIs with the benefits of 4D and therefore did not clearly delineate the approach in which those benefits are quantified. In other words, Dawood did not match up the listed KPIs with 4D benefits, and thus the methodology for measuring a certain specific 4D benefit still remains vague.

3 METHOD

Previously in chapter 2, the 4D benefits were reviewed mainly from the studies of Heesom & Mahdjoubi (2004), Web et al. (2004), and Hartmann, Gao and Fischer (2008). These three studies provided a comprehensive perspective on the 4D implementation because their findings cover an extensive range of 4D benefits. Furthermore, the benefits identified by Hartmann, Gao and Fischer (2008) are also tested in 26 full-scale construction projects, thereby increasing the identified benefits' veracity. After presenting the 4D benefits, their corresponding key performance indicators were summarized based on the study by Dawood (2010). His study was conducted in 2010 and deemed to be the latest regarding the 4D performance measurement.

Based on the literature review in chapter 2, a new framework that includes 4D benefits and their corresponding key performance indicators is constructed in chapter 4. In that chapter, the listed 4D benefits are matched up with the measures indentified by Dawood (2010). Those 4D benefits and indicators are categorized under the design and construction phases together with detailed instructions on how to use the indicators.

After the framework was completed, it was then verified in a case study, which is described in chapter 5. This case study is a housing project, constructing two tower blocks (respectively called L-house and P-house) with 81 apartments in Gothenburg, Sweden. The project started from August 2011 and planned to finish by September 2013. Its budget was estimated around 114 million Swedish kronor and its work has been executed by a prestigious contractor among Nordic countries. In attempts to test the resulting framework presented in chapter 3, this housing project was recommended by that contractor. The contractor reasoned that this project is suitable with my study because its duration fits the study period, which took place from August 2011 to April 2012. And more importantly, the project was planned to employ 4D CAD. The 4D model in this case study was created by combining 3D models and the project schedule. The 3D models were created separately by using graphical software, ArchiCAD, while the project schedule was produced by using planning software, PlanCon. After the models and the schedule were available, the contractor used linking software, iLink, to connect 3D models with Swedish building components' recipes. Then those connected models and the project schedule were put together by Naviswork to form 4D models. In this housing project, these models have served as a tool for workers to visualize the construction sequences on site, as a common model for related actors to discuss about errors and conflicts in project meetings and as a simulation of the project schedule.

Through the design and construction phases of the project, the data were gathered from 18 observed activities. In the design phase, the data were obtained from two collision tests and 15 project meeting reports. In the construction phase, the data were found in weekly schedule tracking and 5 project meeting reports. The project schedule was tracked continuously for 73 working days. Unfortunately due to the time constraint of the thesis, the collected data are only able to reflect the design phase and the beginning of the construction phase. After collecting data by using the KPIs listed in the framework, these results were analyzed to evaluate the reliability and validity of the proposed framework. In order to examine if the results presented by the framework are reasonable and reliable, the discussion addresses three aspects of the framework: i) the content of the framework, ii) the use of the framework, and iii) the practicality of the framework. These sections aim to answer respectively the questions concerning whether the content of the framework is instructive and understandable, if the data attained by using the framework reflect the actual situation, and if the framework is a suitable for measuring 4D models' performance. The discussion is augmented by regular interviews with 4D users in the company, available standards in the construction industry and a study by Bourne et al. (2002) regarding seven factors blocking a measurement initiative. Details of the discussion are presented in section 5.2. Through the implementation of the framework in practice, the difficulties and limitations of the framework were also explored.

4 THE RESULTING FRAMEWORK FOR MEASURING THE PERFORMANCE OF 4D CAD

In order to connect the benefits to their according measures, Table 3 presents an integration of the research done by both Hartmann et al. (2008) and Dawood (2010).

Table 3: The benefits of 4D and their corresponding KPIs

Project phases	The benefits of 4D	KPIs
Conceptualization	- Serving marketing purposes to seek financial support or public involvement	Not available (N.A.)
	- Checking or revising specifications to satisfy building codes/standards	N.A.
Design	- *Virtually presenting building models, construction methods to multifarious stakeholders* *Communicating complex geometry clearly in meetings* *Creating a communal medium for joint discussion among different parties*	*Communication efficiency* *Rework efficiency* *Client satisfaction*
	- Facilitating changing and updating cost estimation by reducing estimation time, and increasing accuracy	N.A.
	- Providing more reliable evaluation of design alternatives by taking all temporal constraints into account	*Rework efficiency*
	- Comparing design alternatives with cost constraints to find optimal design solutions	N.A.
	- *Establishing a link between 3D and schedules, which allows to visualization and analysis of the construction sequences*	*Time* *Rework efficiency* *Planning efficiency*
	- Planning for site layout and required working spaces such as delivery, transportation and storage	N.A.
	- *Standardizing building components to reduce assembly time, cost, and errors*	*Productivity*
	- Reducing material order's lead time	N.A.
	- *Defining the scope of work clearly for subcontractors to provide better understanding and avoid future conflicts*	*Communication efficiency* *Rework efficiency* *Client satisfaction*
Construction	- *Anticipating and detecting conflicts in schedules such as time and sequence*	*Rework efficiency*

	conflicts	
	- *Anticipating and detecting spatial conflicts*	*Rework efficiency*
	- *Anticipating and detecting design and on-site conflicts*	*Rework efficiency*
	- *Anticipating and detecting conflicts between subcontractors and among different parties*	*Rework efficiency* *Communication efficiency*
	- Developing resolutions/alternatives when disruptions occur due to unexpected incidents/changes	N.A.
	- **Controlling progress, planned activities, and construction methods**	**Time, and** **planning efficiency**
	- Facilitating changing and updating cost control by reducing estimating time and effort, and increasing accuracy	N.A.
	- *Instructing and training construction teams before engaging in an intricate, challenging, or hazardous activities*	*Safety* *Productivity*
	- *Overcoming language barriers, especially in the context of international projects*	*Communication efficiency*

Legend:

Normal letters: No suitable KPI and measure

Italic letters: No appropriate specific measure despite having suitable KPIs

Bold letters: KPI and measures are available

The attempt to align the identified 4D benefits with the listed KPIs did not result in a complete framework, but revealed 3 problems regarding the quantification process.

8 out of 22 benefits have no suitable KPI and consequently no specific measure. This problem arises due to the limitation of the KPIs' definitions presented by Dawood (2010). For example, the reduced amount of material orders' lead time failed to have an indicator because the KPI-time, according to Dawood, was defined as percentage of number of times that projects are delivered on or ahead of schedule. To surmount the problem, measuring these nine benefits requires the definitions to be broadened; additional measures are also necessary.

13 out of 22 benefits can be measured by at least one of the KPIs listed by Dawood (2010), but have no appropriate specific measure. For example, the advantage of communicating complex geometry can be appraised by the KPI-communication efficiency since it correlates with the information flow among stakeholders. However, the specific measures such as the number of meetings per week and the amount of time spent on meetings per week do not directly reflect better understanding of complex geometry. Modifying the existing measures or selecting other measures is thus a requisite for evaluating such benefits.

The measures of team performance were not mentioned in Dawood's study (2010), although it was a significant indicator. Hence, supplementary literature must be reviewed to determine team performance's measure metrics.

Table 3 shows that only 1 out of 22 benefits can be quantified properly so far. That is to say, the usefulness of 4D in terms of controlling and monitoring the construction process can be evaluated by using scheduling performance (time indicator), cost performance (cost indicator), and hit rate percentage (planning efficiency).

In order to make Table 3 succinct, those benefits serving similar purposes are allocated in one group with the same indicators. For example, virtually presenting models, construction methods, or complex geometry to multifarious stakeholders and creating a communal medium for joint discussion can have the same indicators because they serve the same purposes of creating common understanding among construction actors and reducing time to extract information. Likewise, the others are also categorized in groups. As a result, 22 identified benefits are allocated in 14 groups. Table 4 summarizes the identified groups of benefits.

Table 4: 4D groups of benefits

Project phases	4D groups of benefits
Conceptualization	Serving marketing purposes to seek for financial supports or public involvement
	Checking or revising specifications to satisfy building codes/standards
Design	Virtually presenting models, construction methods, or complex geometry to multifarious stakeholders and creating a communal medium for joint discussion
	Facilitating changing and updating cost estimation
	Improving the reliability of design alternatives
	Visualizing and analyzing the construction sequences
	Better planning site layout and working spaces
	Standardizing building components
	Defining scope of work for subcontractors clearly
Construction	Anticipating and resolving different types of conflicts/errors (schedule conflicts, time-space conflicts, design conflicts, design-onsite conflicts, and conflicts among actors)
	Developing alternatives in case of disruption
	Controlling and monitoring the building process
	Facilitating cost control
	Instructing and training construction teams prior to engaging in intricate, challenging or hazardous activities

The benefits highlighted in grey in the table are perceived to be inappropriate for the scope of this project. Therefore, they can be ignored. There are three reasons for omitting these benefits in my study; they are explained below.

First, 4D is deemed to be a combination of 3D and "time" (also known as "schedule" in the construction context). Consequently, this study concentrates only on those benefits that are brought directly from that combination. Hartmann, Gao and Fischer, in their study that integrates studied 4D business benefits (2008), advocate using 4D to estimate and control the project cost. However, since Hartmann, Gao and Fischer (2008) argued that this benefit is a corollary of a combination between 3D model and cost-estimating software, "facilitating changing and updating cost estimation" and "facilitating cost control" becomes irrelevant.

Second, the reviewed studies used to build up the framework do not show a clear division between the benefits of 3D and 4D or between 4D and Building Information Modeling (BIM). As 4D equals 3D plus time, it is reasonable to assume that 4D models possess all the benefits of 3D models. However, this assumption is not valid in the case of 4D and BIM because they are two different methods. While 4D models add the fourth dimension, time, into 3D models to improve construction projects, BIM models combine separate information into a common database in order to standardize building components. Hence, investigating the benefits that pertain to BIM such as "standardizing building components" is left for BIM-specialized studies.

Third, since this research focuses on the design and construction phase, the two groups of benefits in the conceptualization phase are also omitted.

The initial 14 groups of benefits are now reduced to 9 groups. The next step is to match up these groups and their respective specific measures. Selecting specific measures may vary from project to project. This paper, however, attempts to recapitulate and present the specific measures which have been previously documented in literature. The specific measures for five benefits in the design phase and four benefits in the construction phase are elaborated respectively.

Table 3, where the benefits from the study by Hartmann et al. (2008) and the KPIs from the study by Dawood (2010) are compared, pointed out that virtually presenting models, construction methods, and complex geometries to multifarious stakeholders as well as creating a communal medium for joint discussion is appraised by communication efficiency, rework efficiency and client satisfaction. Communication in the design phase of construction projects that involved 4D models are mainly observed in project meetings. Hence, communication efficiency should represent how well the participants in the meetings understand the information presented by 4D. Dawood and Sikka (2008) suggested two communication efficiency measures: "the number of times information accessed" and "total time spent on understanding information". In this context, information is considered virtual presentation of an activity by a 4D model. The first measure counts the number of requests to access the information and the latter measure indicates how long the information is explained and discussed during a meeting. Even though these specific measures are able to directly indicate communication efficiency, they are only appropriate to address a single specific activity. For a normal discussion that includes a mix of activities, the same information can be accessed many times for different activities, thus the measures cannot clearly reflect the effectiveness of 4D model. Because of that, in real-life project meetings, the measures necessitate additional efforts to categorize the collected information. Recently, Dawood (2010) suggested using two simpler measures such as "the number of meetings per week" and "time spent on meetings per week" to evaluate the communication efficiency. However, the measures are too generic and fail to connect directly with 4D performance.

Rework efficiency is a very handy indicator which embodies both effectiveness and efficiency of 4D CAD. To put it simply, the indicator is capable of warning construction actors if they are not doing things right or not doing a right thing. The specific measures of this indicator are flexible and customized according to each situation. In the case of using 4D models for design presentation, the specific measures should be “the number of design errors and conflicts” as Dawood (2010) recommended. A design error constitutes a wrong design that causes re-design, while a design conflict can be a conflict between designs from same actor or different actors.

Client satisfaction is one of the earliest KPIs in the industry. This indicator has been used in several benchmarking documents, for instance, Construction Best Practice Program KPIs, Mechanical and Electrical Contractor KPIs, Construction Products Association KPIs, and so on (Beatham, Anumba, Thorpe, & Hedges, 2004). Since the indicator has been well studied, it is most convenient to use the listed specific measures, namely, “number of client change orders” and “satisfaction questionnaire”. By using these conventional measures, it will be easier to compare the effectiveness of 4D model with the standard performance. To update customers and maintain high satisfaction level, the measures should be conducted regularly through all project phases.

The second group of benefits brought by 4D is to produce a more reliable design alternative. Hartmann et al. (2008) explained the meaning of “reliability of a design option” in terms of “ensuring to meet all requirements and specifications” and “optimizing the operating cost”. As argued above, the focus is not on cost-related benefits, the specific measures for this group of benefits reflect only the first term. In order to ensure that requirements and specifications are met, inspection check lists are usually used. Besides inspection check lists, rework efficiency’s measures, for example, number of design errors and conflicts after choosing an alternative, are the most suitable to ascertain whether a design option satisfies required specifications.

The next group of benefits resulted from integrating the fourth dimension, time, into 3D models. The integration enables the models to analyze and visualize the construction sequences, also known as construction schedules or construction plans. Like the specific measures in the second group, this group’s measures also serve to test the reliability of plan. Thus, rework efficiency measure, “the number of schedule conflicts between activities”, is a requisite indicator. These conflicts can arise from the same actor or different actors. As the time dimension is involved here, rework efficiency is not sufficient on its own. Dawood (2010) added an indicator, called Planning efficiency, to evaluate the reliability of a schedule. The proposed specific measure is hit rate percentage, which will be used in the construction phase. The objective of the measure is to find the percentage of activities having zero start and finish variance over the total number of activities in a package. An additional measure to appraise the reliability of a plan is percent plan completed (PPC). Ballard and Howell (1998) defined PPC as the percentage of completed assignments and the total number of planned assignments each week. Unlike Hit Rate Percentage which strictly requires activities to be conducted exactly according to the decided dates, PPC allows planned activities or parts of an activity to be done in a period of time. Although Hit Rate Percentage and PPC are calculated differently, their concepts are very similar since both of them aim to evaluate reliability of a plan. Ballard and Howell (1998) observed that if overall PPC is above 50%, the project performance will be increased.

Therefore, an above-50% hit rate percentage is also expected to indicate a good performance as Hit Rate Percentage is described as a stricter measure.

Improving site layout and required working spaces by 4D is the fourth group of benefits. Site layout and working space management deal with a very special kind of resource: space. Unlike other common resources, such as labor, equipment and material – which vary only through time – required spaces for a construction activity change in all four dimensions (Akinci, Fischer, & Kunz, 2002). Insufficient management regarding this issue possibly leads to time-space conflicts at construction sites (Riley & Sanvido, 1997). Both aforementioned studies imply that the number of time-space conflicts is an important measure to judge site layout and working space management. That is to say, time-space conflicts should be the specific measure for this group.

The last group of benefits in the design phase concern assisting the preparation of the bidding package. 4D users, especially construction contractors, want to employ 4D to compete with other contractors in tendering and defining the scope of work clearly in the case of assigning work to subcontractors. According to Hartmann et al. (2008), the research on this aspect is very new and still developing. Moreover, 4D implementation in the tender phase is beyond the scope of this study because cost-related factors are often the most critical criteria in tendering documents. As a consequence, the measures concentrate on evaluating how clear the scope of work is defined to communicate with subcontractors. Since 4D is used as a communication tool to subcontractors, it is reasonable to use communication efficiency measures. Also, the rework efficiency measures should be added in the construction phase to check the quality of the work executed by subcontractors. The specific measures reflecting communication efficiency, rework efficiency, and client satisfaction are allocated in five groups of benefits in the design phase. In the next section, specific measures, together with planning efficiency's measures conducted in the construction phase, are assigned to the three remaining groups.

The first benefit of 4D in the construction phase is to anticipate and resolve different types of errors and conflicts occurring during the building process. The categories encompass the errors and conflicts mentioned before in the design phase such as design errors and conflicts, schedule errors and conflicts, time-space errors and conflicts and a new type of conflict, design and onsite conflicts. The new kind of conflict represents a clash between initial designs and in-situ constraints. Recording the number of times these listed conflicts occur allows the 4D users to know how well the 4D models can prevent and resolve such incidents.

The next two groups of benefits, "developing alternatives due to disruption" and "controlling and monitoring the building process" have measures that are very similar to the above-mentioned groups "analyzing design alternatives" and "visualizing and analyzing construction sequences". While the first group inherits all the measures from its counterpart in the design phase, the second group is recommended to include an additional indicator, schedule performance (SP). One of the most popular techniques to monitor and control the schedule progress is earned value analysis (Vargas, 2003). A survey conducted by Thamhain (1998) with 400 professionals working with 180 distinct projects shows that 41% of them are using the technique. The objective of this technique is to track whether the project is behind schedule by means of schedule performance (SP). The formula is shown as below

SPI = Budgeted Cost of Work Performed(BCWP) / Budgeted Cost of Work Scheduled(BCWS)

If SPI>1, a project is ahead of schedule. If SPI=1, a project is on schedule. Otherwise a project is delayed.

The last benefit of 4D models is instructing and training construction teams prior to engaging in intricate, challenging or hazardous activities. Obviously, rework efficiency, productivity and safety are the applicable indicators. Rework efficiency is easily measured by an inspection check list, and safety measures are standardized, so the only indicator that ought to be discussed further in this section is productivity. In fact, measuring productivity in construction projects has posed tremendous challenges to researchers (Crawford & Vogl, 2006). In one of the first attempts, Edkins and Winch (1999) proposed three approaches to measure productivity in the industry: pricing studies, case studies, and macroeconomic studies. For a specific activity, the "case studies" method is the best fit as it estimates the performance case by case. It can measure an individual or a group of individuals in a specific task or a package of tasks. A specific measure draws information from day-to-day observation by an independent activity on site. An example of specific measures for productivity can be "the number of piles driven per unit time".

Table 5: The final framework

4D benefits	Specific measures	Project phase	
		Design phase	Construct phase
Virtually presenting models, construction methods, or complex geometry to multifarious stakeholders and creating a communal medium for joint discussion	- Number of time information accessed - Total time spent on understanding information - Number of design errors and conflicts - Number of client change order - Questionnaire	X X X X X	 X
Improving the reliability of design alternatives	- Number of design and errors conflicts - Inspection check lists	X X	
Visualizing and analyzing the construction sequences	- Number of schedule conflicts - Hit rate percentage	X	X X
Better planning site layout and working spaces	- Number of time-space conflicts	X	X

Defining scope of work for subcontractors clearly	- Number of time information accessed - Total time spent on understanding information - Inspection check lists	X X	 X
Anticipating and resolving different types of conflicts/errors (schedule conflicts, time-space conflicts, design conflicts, design-onsite conflicts, and conflicts among actors)	- Number of design errors and conflicts - Number of schedule errors and conflicts - Number of time-space conflicts - Number of design and onsite conflicts		X X X X
Developing alternatives because of disruption	- Number of design and errors conflicts - Inspection check lists		X X
Controlling and monitoring the building process	- Number of schedule conflicts - Hit rate percentage - Schedule performance		X X X
Instructing and training construction teams prior to engaging in an intricate, challenging or hazardous activities	- Inspection check lists - Number of accidents per 1000 working man-hour - Productivity		X X X

Table 5 constitutes the framework for evaluating the performance of 4D models in construction projects. In order to verify the framework, it must be tested in real-life projects. As explained above, such measures as "number of time information accessed", "total time spent on understanding information", "questionnaire", "inspection check list" and "productivity" are only applicable to specifically selected activities. Consequently, those measures do not reflect the performance of 4D from a thorough perspective. They are more appropriate to be used in a detailed study where distinct selected activities are monitored continuously. The remaining measures are considered "weekly measurement" and their data are collected from all project activities on a weekly basis.

5 IMPLEMENTATION OF THE FRAMEWORK IN A REAL-LIFE PROJECT – A CASE STUDY

5.1 DATA OBTAINED BY THE FRAMEWORK

Due to time constraints on the thesis, the data for the study were obtained from August 2011 to February 2012. During these six months, the "weekly measurement" appraised the performance of 4D through the design and construction phase. In the design phase, the used specific measures were "number of design errors and conflicts", "number of client change order", "number of schedule conflicts", and "number of time-space conflicts". In the construction phase, while "number of design errors and conflicts", "number of schedule conflicts", "number of time space conflicts" continued to be used, three additional measures, "number of design-onsite conflicts", "hit rate percentage", and "schedule performance" were added.

The number of design errors and conflicts is attained from 2 collision tests and 20 project meeting reports. The collision tests require participating sub-contractors in charge of different tasks, such as ventilation and electricity, to put their 3D models together and then identify errors and conflicts. Although the collision tests evaluate mainly the benefits of 3D models in virtually presenting building geometry, they can still reflect the performance of 4D models because we assumed that 4D models possess all the benefits of 3D models. After two collision tests, 17 errors and conflicts were found. The first test identified 11 errors and conflicts while the second test found 6. Details of the tests are listed in Appendix A. The project meeting reports listed 10 major errors and conflicts, see Table 6. Half of them resulted from design missing or insufficient specifications. The remaining half was caused by conflicts in designs among the actors.

Table 6: Design errors and conflicts

Report	Code	Description
6	4.6.1	Designs were missing
6	4.6.2	Design conflicts between A and K regarding Balconies and façade of the P-house
7	3.5.1	Drawings missing regarding garbage vacuum system in 3D
7	13.6.2	Failure to consider the temperature of ducts in main documents
7	13.6.3	Design conflicts between elevator and fan room in L-house
9	4.9.1	Main documents have wrong information about layout of entrance in L-house
9	11.8.1	Missing drawing from architecture about garbage room
11	4.11.2	Uncertainty in document about hoods
14	4.14.2	Drawing conflicts between architect and kitchen supplier (because the drawing from the kitchen supplier came after architect's drawing)[1]
14	13.14.1	Failed coordination between VVS and K about base plate. Drawings must be revised

Schedule errors are reported in the project meeting reports and summarized in Table 7.

Table 7: Schedule errors

Report	Code	Description
5	10.3.1	Procurement document of prefabrication frame delayed and end date changed
6	10.3.1[2]	Procurement document delayed and its end date changed one more time
7	10.3.1	Continued to be delayed without an anticipated end
8	4.1.8	Problem with when and how to install the insulation
8	10.8.1	Adjust delivery time for facade in L-house

[1] It indicates no cooperation between A and the kitchen supplier (Myresjökök)

[2] Report 6: 10.6.1: said that the project was not delayed because they moved all activities forward 1 week

9	10.8.1	Adjust the time again (refer to report 8)
11	10.8.1	Adjust the delivery time again (refer to report 9)

The results of schedule errors and conflicts indicate a serious problem in the planning process. The tasks mentioned in Table 7 were delayed several times and the planners were still unable to identify the end date. As a result, those activities were not planned by any means. The reasons why such incidents occurred have not been confirmed. However, the reason might be that 4D CAD does not support planning such activities or the planners did not make the schedule properly. This discussion will be elaborated further in the next sections.

Only one “client’s request to change” and no “time-space conflicts” were reported. According to the project meeting report number 2, the client wanted to add a customized system which allows them to number completed apartments as they want. Because this study ends by June 2012, it restricts making further approaches to the client and evaluating client satisfaction regarding the customized system. However, with only one request made, it is reasonable to assume that the client is satisfied with the proposed designs.

The construction phase has been under execution since 9th November 2011 and was monitored day by day until 14th February 2012. Besides measurement of errors and conflicts, the construction phase entails schedule performance and planning reliability evaluation. The measurement of errors and conflicts is obtained by the number of design errors and conflicts, time-space conflicts, and design-onsite conflicts, while schedule performance and planning reliability evaluation are reflected respectively from Earn Value Analysis (Schedule Performance) and Hit Rate Percentage.

In this phase, the contractor encountered very few errors and conflicts. Only three design errors and conflicts were recorded while no “time-space conflicts” and “design-onsite conflicts” were found in the project meeting reports during the observed period. The details of design errors and conflicts are described in Table 8. These results indicate that the project has is relatively unproblematic in relation to rework efficiency.

Table 8: Design errors and conflicts in the construction phase

Report	Code	Description
15	13.13.2	Conflicts between designs between distinct contractors regarding foundation
16	13.15.3	Investigating an alternative where bricks are used to build drainage system underground
20	4.18.2	Missing designs for data communication system in the building

Schedule performance is described in Figure 1. In order to draw the graph and calculate Schedule Performance Index (SPI), the analysis was based on the assumption of 25/75. This assumption allows us to assign immediately 25% work completed right after an activity starts and assign the remaining 75% only when the activity finishes. During the activity’s duration, the 25% work completed is divided by the number of the activity’s working days until its completion. This assumption eases the calculation of work completed percentage because we do not need to know exactly how many percentages of measured activities are completed every day. According to the figure, the Budgeted Cost for Work Performed lies above the Budgeted Cost for Work Schedule, so the Schedule Performance Index >1and thus the project progress is considered ahead of the project schedule.

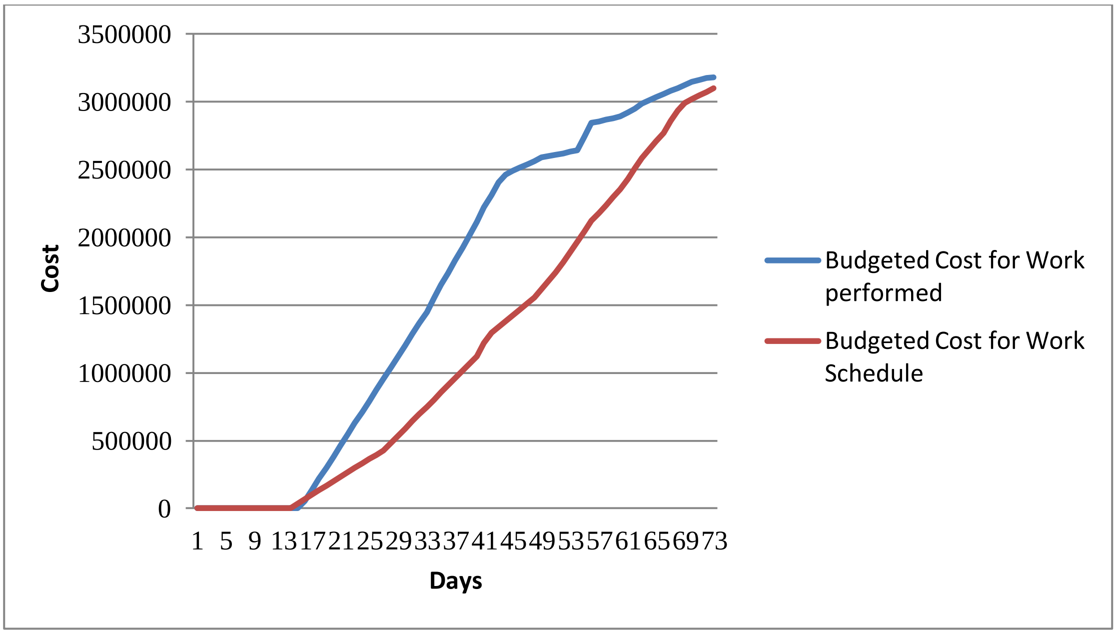

Figure 1: Schedule Performance

The hit rate percentage was measured from 9th November 2011 to 17th February 2012. Eighteen activities were conducted. The summary of hit rate percentage is listed in Table 9. Negative numbers means the number of days delayed and positive numbers means the number of days ahead.

Table 9: Hit Rate Percentage of the observed activities

Activity code	Range start (days[3])	Range end (days)	Total hit/number of activities
1.1	-4	-3	0/1
1.2.1	0	12	0/2
1.2.2	4	-5	0/3
1.2.3	8	11	0/4
1.2.4	10	8	0/5
1.2.5	12	7	0/6
1.2.6	17	Not recorded	0/7
1.2.7	Not recorded	19	0/8
1.2.8	1	Not recorded	0/9
1.2.9	Not recorded	26	0/10
1.3.1	5	-3	0/11
1.3.2	9	Not finished yet[4]	0/12
1.3.3	28	Not finished yet	0/13
1.3.4	-3	7	0/14
1.3.5	27	33	0/15
1.3.7	27	Not finished yet	0/16
1.4.1	4	Not finished yet	0/17
1.4.2	21	24	0/18

[3] 1 working week = 5 working days

[4] Not finished yet: uncompleted within the period from 9th November 2011 to 17th February 2012

According to the table, the overall hit rate percentage is 0%, indicating that none of the listed activities were started and finished according to the initial plan. The percentage of hitting the planned starting day is 6.25% and the percentage of hitting the planned end day is 0%. These results represent very low plan reliability.

5.2 DISCUSSION

This section attempts to interpret the performance of 4D CAD based upon the findings and to evaluate the reliability of the proposed framework. As mentioned in chapter 3, the discussion addresses three aspects of the framework i) the content of the framework, ii) the use of the framework and iii) the practicality of the framework. The results are seen in light of discussions and interviews with employees of the company that used the 4D framework as well as results from studies reported in the literature.

5.2.1 THE CONTENT OF THE FRAMEWORK

The content of the framework was presented and discussed with the Virtual Reality Team in the company who are 4D specialists. Through 3 main presentations and weekly discussions, the specialists showed their confusion between 3D and 4D benefits. They argued that such benefits as "virtually presenting models, construction methods, or complex geometry to multifarious stakeholders and creating a communal medium for join discussion" belonged to 3D models and hence should not be listed when we measure the performance of 4D models. The specialists' argument makes sense, however, only if the research question is to find out when 4D models should be used instead of 3D models. The objective of this thesis, on the other hand, is to develop a quantitative methodology which is able to connect all 4D benefits with their corresponding KPIs. Therefore, because 3D is a part of 4D, the benefits brought by 3D should also be included in the presented framework.

The specialists also raised their concern about the measure Hit Rate Percentage. They were not surprised to see that Hit Rate Percentage is 0%. Since the industry is full of uncertainty, it is almost impossible to hit the planned date exactly. As a result, the outcome attained from Hit Rate Percentage is not relevant. Being aware of this situation, Dawood (2010) suggested a modified calculation of hit rate percentage to "represent the level of confidence and detail of planning done in the schedule". He added the percentage of activities that start early and finish early into the original calculation. According to the new calculating method, the hit rate percentage presented in the case study will increase to 33% after modification. Still, the percentage is lower than the industry average, 55% (Dawood, 2010). Another modification is calculating with day variations. Table 10 shows the hit rate percentage of these 18 activities if they are allowed to be late or ahead a number of days. According to this second method, the Hit Rate Percentage of starting dates and finishing dates reaches 50% only if 8- working days[3] variation is allowed

[3] 1 week = 5 working days

Table 10: Hit rate percentage with day variations

Day variation (+-)	Starting hit rate	Ending hit rate
1	2/16 = 12.5%	0/12
3	3/16 = 18.8%	2/12 =16.6%
4	6/16 = 37.5%	2/12
5	7/16 = 43.8%	3/12 = 25%
7	7/16 = 43.8%	5/12 = 33.3%
8	8/16 = 50%	6/12 = 50%
11	10/16 = 62.5%	7/12 = 58.3%

Because the original form of Hit Rate Percentage has no tolerance for day variation, the measure is criticized as inflexible. Since the concept of Lean has become popular in the construction industry, more construction organizations have opted to use Percentage of Plan Completed proposed by Ballard and Howell (1998) based on the Lean concept. The measure is considered more flexible as it does not require the task to hit start dates or end dates precisely. An activity will be counted if it is completed in an assigned period. If an activity is estimated as not possible to complete in an assigned period, it will not be allocated in to that period's plan. Due to this, Percentage of Plan Completed can only evaluate a plan's reliability and cannot reflect a delayed situation. After understanding the advantages and disadvantages of each measure, a project manager can choose between the Hit Rate Percentage and the Percentage of Plan Completed depending on the purposes of measurement.

5.2.2 THE USE OF THE FRAMEWORK

This section discusses the question whether the data collected by using the framework reflect the actual situations in the case study. In order to answer this question, the collected data from both design and construction phases are reviewed below.

In the design phase, the performance of 4D CAD regarding "Virtually presenting models, construction methods, or complex geometry to multifarious stakeholders and creating a communal medium for joint discussion", "Improving the reliability of design alternatives" and "Better planning site layout and working spaces" are reflected by the number of design errors and conflicts as well as the number of time-space conflicts. The findings show that 4D helps identify errors and conflicts in early phases, especially in connection with visualization. A total of 17 design errors and conflicts were initially found in the collision tests and all of them had been fixed before the construction phase started. This result from the framework agrees with the study by Dawood (2010), which concludes that 4D CAD facilitates the discussion among stakeholders by presenting clearly the designs in multi-dimensions and help reduce rework.

Not only assisting to identify errors and conflicts, 4D CAD also helped suggest reliable design alternatives and better planning for the site layout and working space. The second collision test highlights a reduction of design errors and conflicts. In fact, the involved sub-contractors were quickly able to provide design alternatives within 2 weeks after the first test. After the second test, the client and project managers were satisfied with the result and approved starting execution of the works on site. These facts again confirm the high usefulness of 4D in terms of finding design alternatives. As to planning for site layout and working space, no time-space errors and conflicts were found in either the design or the construction phase, suggesting no problem in this aspect. The result is reasonable since 4D CAD has been validated to be very helpful in automatically simulating working space (Akinci, Fischer, & Kunz, 2002).

Even though 4D CAD performed very well in managing designs and working spaces, the project meeting minutes reported several cases of missing drawings, missing specifications or wrong design information. These results reflect the current problem of lacking regulations governing the level of detail of 3D and 4D models in the construction industry. As a consequence, each sub-contractor in the case study built its 3D and 4D models corresponding to its own standards, leading to mismatched information or insufficient specifications. The level of design detail in 3D and 4D models has been studied for years but very few concrete agreements have been reached among researchers and construction actors so far. One of the fundamental agreements is that the level of design detail varies with the purposes of 4D implementation (Heesom & Mahdjoubi, 2004). For example, the level of graphical details serving visualization purposes must be high, while serving analysis purposes requires only a low level of graphical details. In spite of such theoretical instructions from scholars, construction actors still have struggled to produce a unanimous and more specific standard for the whole industry.

In the construction phase, all the weekly measures in the design phase were continued. There were two additional measures: Schedule Performance Index and Hit Rate Percentage.

Since most of the design errors and conflicts were identified early, only three design problems were discovered in this phase, see Table 8. The first problem was a design conflict between two main contractors of two neighboring projects regarding their foundations. The two contractors failed to coordinate and communicate with each other in advance. According to an interview with Project Manager, the sub-contractor in charge of foundation work did not use 4D models, so this problem is unrelated to 4D performance. The second problem was to evaluate the feasibility of using bricks for the underground drainage system. This problem shows a limitation of the 4D model because it cannot help answer the main concern that bricks may crack at low temperatures in the winter. The limitation poses a tantalizing challenge to further studies, which requires 4D simulations to consider all surrounding conditions. The third problem was simply due to missing design information.

Both the Schedule Performance Index and Hit Rate Percentage alert serious problems in “Visualizing and analyzing the construction sequences” and “Controlling and monitoring the building process”. Because Hit Rate Percentage was already discussed in section 5.2.1, only Schedule Performance Index is mentioned in this section.

The desirable value of Schedule Performance Index ranges slightly under or above 1 (Howes, 2000). If the actual value falls extremely below 1, the project is much behind the planned schedule and requires immediate managers' attention. If the actual value is well above 1, the result is unreliable and thus triggers further investigation. In his study, Howes gave an example of a bridge construction project where the overall Schedule Performance Index was 1.34. According to Howes' analysis, this result is overoptimistic. The average Schedule Performance Index in the present case study during the observed period is 1.57, which means it took approximately only 65% of the planned duration to complete the assigned work. The result drastically exceeds the desired range.

In order to confirm that the value 1.57 is overoptimistic, the project process needs to be analyzed with another method such as Work Package Methodology presented in Howes' study. However, two obvious contradictory issues are noticed here. On the one hand, all the indicators related to Schedule Performance Index show that the project has been running very far ahead of the planned schedule. The highest value of Schedule Performance Index reaches 2.23 and the value varies from 1.30 to 2.23 in 41 consecutive days over 73 observed days (56% of the period). On the other hand, in a regular interview with the Project Manager at the end of the design phase, he pointed out "the project was delayed about 7 weeks". The contradiction questions whether the Schedule Performance Index failed to reflect the actual situation on site or whether the Project Manager did not follow the project closely. The answer may lie in the schedule tracking process. The contradiction may result from different selections of tracking baseline. It was found that the project schedule has not been made and tracked properly. In the design phase, the framework was able to alert the contractor to the possibility of imprecise planning and the potential of severe delay. Table 7 lists two activities that were postponed three times without knowing the end dates. The project's Gantt chart shows no connection among activities, no critical path, no early start, no early finish, no late start and no late finish (Appendix B). Moreover, the schedule's status has not been updated regularly. The schedule was just simply a to-do list and hence there was no consistent baseline to compare with tracked situations.

Ideally, a 4D model is a combination between a detailed 3D model and a precise schedule. If the schedule is incorrectly made, a 4D model merely serves the 3D model's functions. This argument explains why the framework exhibits rather high design quality but very low planning reliability. The framework's results regarding planning reliability in this study are considered reasonable and reliable because these results match the current situation in the construction industry, especially in Sweden. According to the conclusion of a report by Sveriges Byggindustrier (2009) after interviewing 160 construction actors and visiting 10 construction sites across Sweden, lacking knowledge of planning is a very common problem in the industry. The methods such as Critical Path Method (CPM) and Program Evaluation Review Technique (PERT) (Hendrickson, 2008) have not been understood completely and thus have not been implemented properly.

5.2.3 THE PRATICALITY OF THE FRAMEWORK

After all, the framework is still a performance measurement initiative. McCunn (1998) claimed that 70% of performance measurement initiatives are failures. This section discusses whether the presented framework has a potential to become a successful performance measurement initiative. This discussion is based on a study by

Bourne *et al.* (2002) which listed seven factors blocking the implementation of a performance measurement initiative. These factors are i) time and effort required, ii) personal consequences of implementing the performance measures, iii) perceived lack of benefit from proceeding with performance measurement, iv) difficulties with data access and the information technology (IT) systems, v) top management commitment, vi) impacts of parent company activities, and vii) problems with applying the measuring process.

The framework regarding 4D performance obviously has no effect on personal consequences. Additionally, the company has acknowledged the significance of 4D models and included 4D method's improvement in their long term strategy. As a result, the remaining impediments from the list abovementioned are i) time and effort required, ii) difficulties with data access and IT systems, and iii) problems with applying the process.

The framework is neither time nor effort consuming. It does not require users much time and effort to record data and put them into available categories. Users only need to be consistent and update the data weekly. Unfortunately, "difficulties with data access and IT systems" and "problems with applying process" are more serious problems. In an interview, the Manager of Virtual Reality Division commented that it would be hard to compare the data collected from the case study because there has been no data documented from previous projects. Moreover, he added that because the 4D method is still new to the company, only a few projects have tried this method. Consequently, applying the framework for measuring 4D performance is very restricted. The solution for these problems consumes time and effort to accumulate data from other real-life case studies or to integrate data from other academic research.

6 CONCLUSIONS

This study managed to establish a framework connecting the business values of 4D with their key performance indicators. The framework also listed those business values and their corresponding groups of indicators in both design and construction phases. The key performance indicators were categorized into two types: weekly measurement and specific measurement. The weekly measurement involves all project activities and is updated weekly while the specific measurement is used to track specific activities separately. The framework is perceived to be able to quantify the benefits brought by 4D models. However, evidence obtained from the case study is insufficient in order to conclude whether or not the framework is a reliable measuring tool. The insufficiency is due to three main limitations. First, because of time limitation of the thesis, it was possible to collect only data during the design phase and the beginning of the construction phase.. Second, the framework only shows quantified values captured by the indicators but these values' meaning could not be fully interpreted because of lacking documented data to compare with. For example, the finding showed 17 design errors and conflicts but there has been no previous documented number of design errors and conflicts or standardized number design errors and conflicts to compare with. Therefore, it is uncertain if 4D models can help reduce the number of errors and conflicts in comparison with other methods. Last but not least, in the case study, the project's planners did not make a proper schedule, thus disabling the 4D function of analyzing and tracking activities' sequences. One of the most serious mistakes of the planners is not connecting activities together when creating the schedule. Without the connections, 4D models fail to track the project's progress and thus they are unable to help the planners to enhance the schedule's accuracy. Because of three described limitations, it is necessary to test the framework more in other case studies.

APPENDIX A

The errors and conflicts were extracted from two collision tests dated on 8th and 22nd November 2011

Position		Number of Conflicts (8.11)
Plan	Hus	
0	L	10
0	P	0
1	L	1
1	P	0
2	L	0
2	P	0
3	L	0
3	P	0
4	L	0
4	P	0
5	L	0
5	P	0
6	L	0
6	P	0
7	L	0
7	P	0
8	L	0
8	P	0
9	L	0
9	P	0
10	P	0
11	P	0

Position		Number of
Plan	Hus	Conflicts (22.11)
0	L	0
0	P	5
1	L	0
1	P	0
2	L	0
2	P	0
3	L	0
3	P	1
4	L	0
4	P	0
5	L	0
5	P	0
6	L	0
6	P	0
7	L	0
7	P	0
8	L	0
8	P	0
9	L	0
9	P	0
10	P	0
11	P	0

APPENDIX B

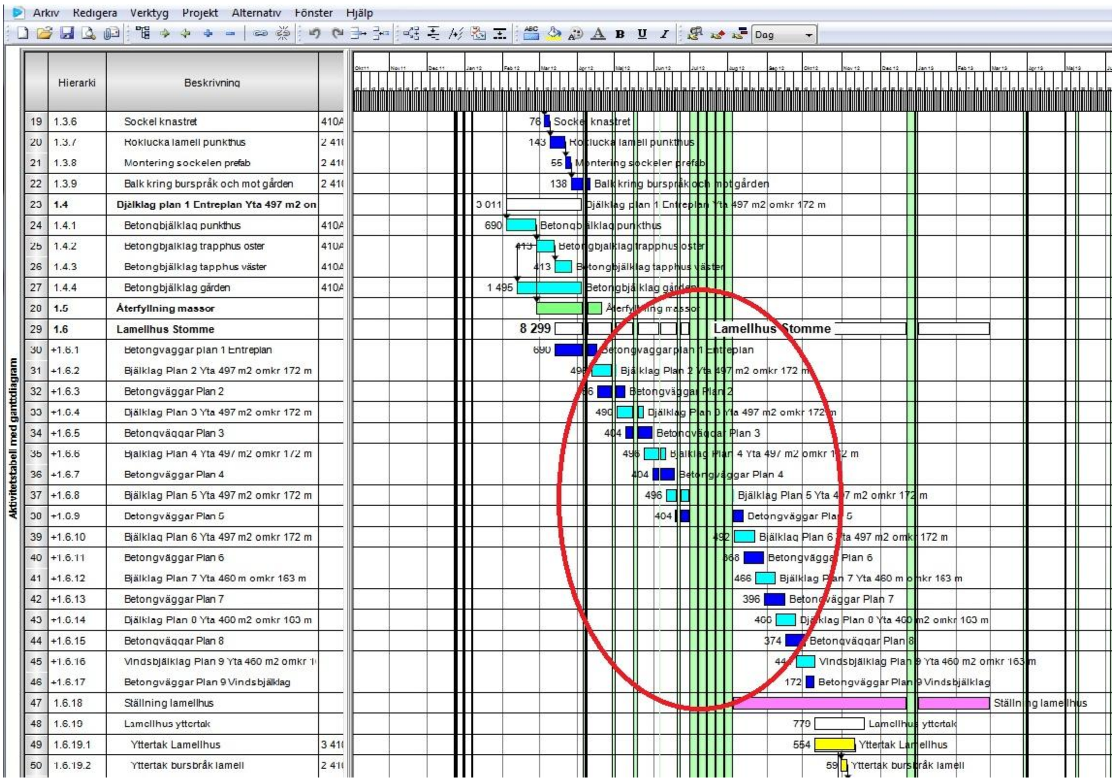

Figure 2: No connection among the planned activities

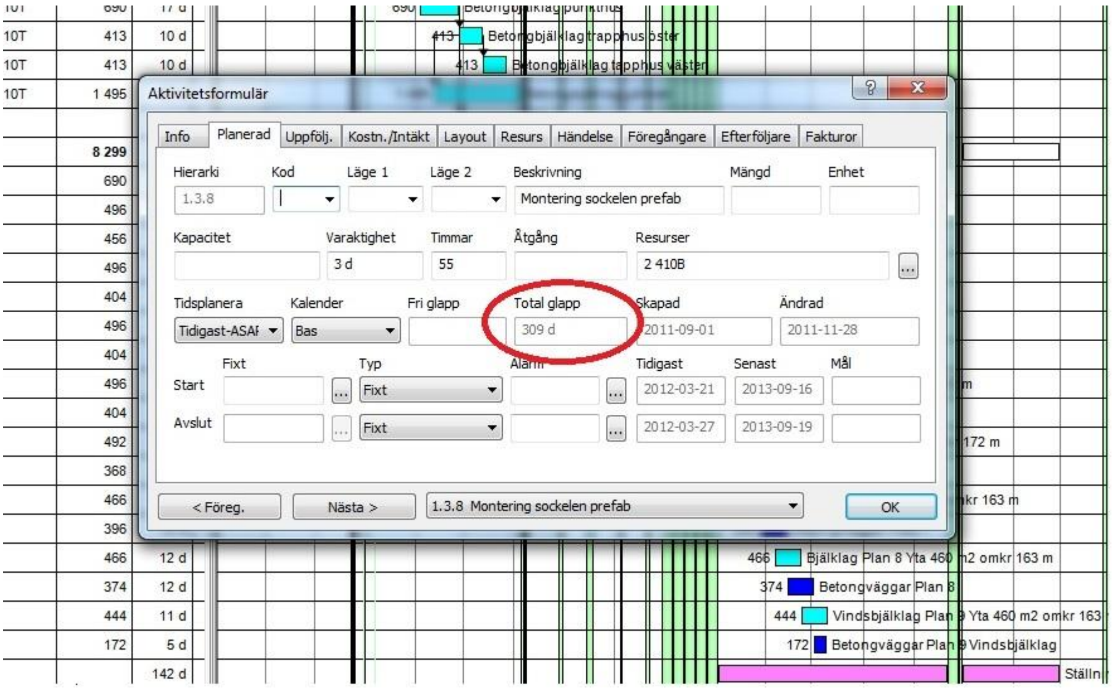

Figure 3: Wrong late start and wrong late finish cause 309 working days in total float

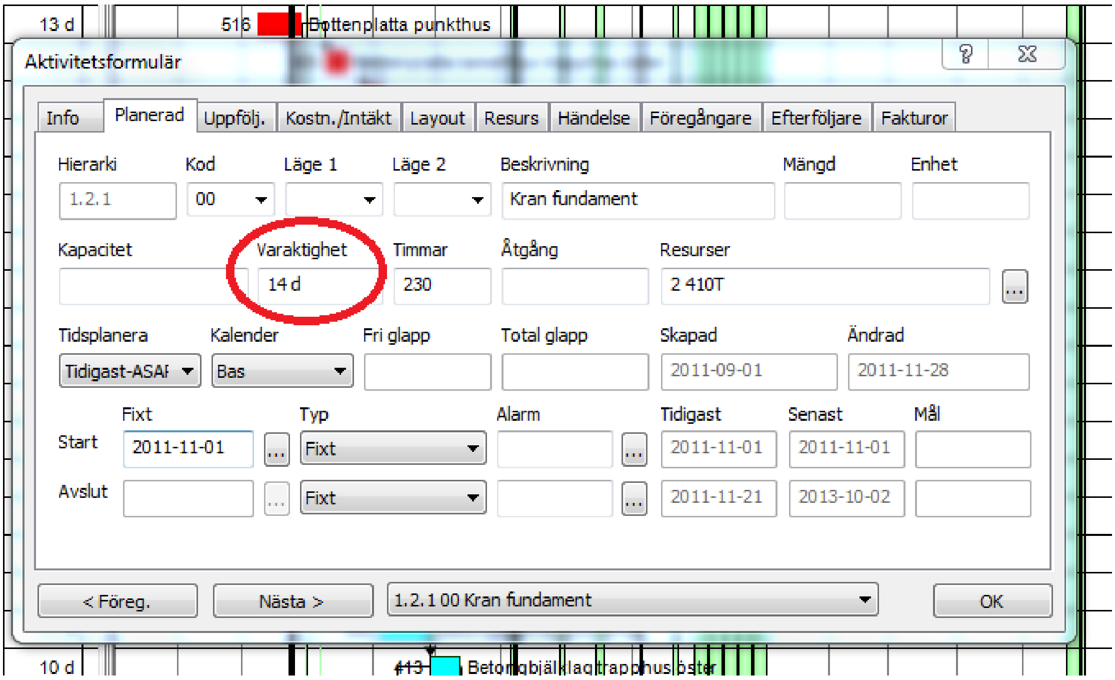

Figure 4: An example of overestimated durations. Activity 1.2.1 was planned to be executed in 14 days but in fact it was completed within 2 days.

7 REFERENCES

Akinci, B., Fischer, M., & Kunz, J. (2002). Automated generation of Work Spaces Required by Construction Activities. Journal of Construction Engineering and Management, 128 (4), 306-315.

Allen, C., & Smallwood, J. (2008). Improving construction planning through 4D planning. Journal of Engineering, Design and Technology, 6 (1), 7-20.

Ballard, G., & Howell, G. (1998). Shielding Production: Essential Step in Production Control. Journal of Construction Engineering and Management, 124 (1), 11-17.

Bassioni, A., Price, A., & Hassan, T. (2004). Performance measurement in construction. Journal of Management in Engineering, 20 (2), 42-50.

Beatham, S., Anumba, C., Thorpe, T., & Hedges, I. (2004). KPIs: a critical appraisal of their use in construction. Benchmarking: An International Journal, 11 (1), 93-117.

Bourne, M., Neely, A., Platts, K., & Mills, J. (2002). The Success and Failure of Performance Measurement Initiatives: Perceptions of Participating Managers. International Journal of Operation & Production Management, 22 (11), 1288-1310.

Chan, A., & Chan, A. (2004). Key performance indicators for measuring construction success. Benchmarking: An International Journal, 11 (2), 203-221.

Chan, A., Scott, D., & Lam, E. (2002). Framework of success criteria for design/build projects. Journal of Management in Engineering, 18 (3), 120-128.

Cox, R. F., Issa, R. R., & Ahrens, D. (2003). Management's Perception of Key Performance Indicators. Journal of Construction Engineering and Management, 129 (2), 142-152.

Crawford, P., & Vogl, B. (2006). Measuring productivity in the construction industry. Building Research and Information, 34 (3), 208-219.

Dawood, N. (2010). Development of 4D-based performance indicators in construction industry. Engineering Construction and Architectural Management, 17 (2), 210-230.

Dawood, N., & Sikka, S. (2008). Measuring the effectiveness of 4D planning as a valuable communication tool. ITcon , 13, 620-635.

Edkins, A., & Winch, G. (1999). The performance of the UK construction industry: An international perspective. London: The Barlett School of Graduate Studies, University College London.

Gambatese, J., Dunston, P., & Pocock, J. (2007). The Way Forward: Recommendation for Future Constructability Research and Practice. ASCE Constructability and Construction Research Council.

Gao, J., Fischer, M., Tollefsen, T., & Haugen, T. (2005). Experience with 3D and 4D CAD on Building Cosntruction Porjects: Benefits for Project Success and Controllable Implementation Factors. 22nd Conference on Information (pp. 225-234). Dresden: Institute for Construction.

Hartmann, T., Gao, J., & Fischer, M. (2008). Areas of Application for 3D and 4D Models on Construction Projects. Journal of Construction Engineering and Management, 134 (10), 776-785.

Heesom, D., & Mahdjoubi, L. (2004). Trends of 4D CAD applications for construction planning. Construction Management and Economics, 22 (2), 171-182.

Hendrickson,C.(2008). *Project Management for Construction.* Pittsburgh: Carnegie Mellon Univeristy.

Hijazi, W., Alkass, S., & Zayed, T. (2009). Constructability Assessment Using BIM/4D CAD Simulation Modeling. AACE International.

Howes, R. (2000). Improving the performance of Earned Value Analysis as a construction project management tool. Engineering, Construction and Architectural Management, 7 (4), 399-411.

Kaplan, R. S., & Norton, D. P. (1992). Balanced Scorecard-measures that drive performance. Harvard Business Review, 70 (1), 71-79.

Li, H., Irani, Z., & Love, P. (2000). The IT performance evaluation in the construction industry. Proceedings of the 33rd Hawaii International Conference on System Science.

Mahalingam, A., Kashyap, R., & Mahajan, C. (2010). An evaluation of the applicability of 4D CAD on construction projects. Automation in Construction, 19 (2), 148-159.

McCunn, P. (1998). The Balanced Scorecard...the eleventh commandment. Management Accounting: Magazine for Chartered Management Accountants, 76 (11), 34-36.

Riley, D., & Sanvido, V. (1997). Space Planning for Mechanical, Electrical, Plumbing and Fire Protection Trades in Multi-story Building Construction. Construction Congress V: Managing Engineered Construction in Expanding Global Markets (pp. 102-109). New York: ASCE.

Robert, F., Raja, R., & Dar, A. (2002). Management's perception of key performance indicators for construction. Journal of Construction Engineering & Management, 129 (2), 142-151.

Roupe, M., & Johansson, M. (2009). Visual quality of the ground in 3D models: Using color-coded images to blend aerial photos with tile detail-textures. The 6th International Conference on Computer graphics, virtual Reality, Visualization and Interaction in Africa (pp. 73-79). New York: AFRIGRAPH '09.

Songer, A. D., Diekmann, J. E., & Karet, D. (2001). Animation-based construction schedule review. Construction Innovation: Information, Process, Management, 1 (3), 181-190.

Sveriges Byggindustrier. (2009). Planering i byggproduktion. Malmo: Prolog Bygglogistik AB.

Thamhain, H. (1998). Integrating Project Management Tools with the Project Team. 29th Annual Project Management Institute Seminars and Symposium. Long Beach.

Vargas, R. V. (2003). Earned Value Analysis in the Control of Projects: Success or Failure? AACE International Transactions (pp. 1-4). AACE International.

Webb, R. M., Smallwood, J., & Haupt, T. C. (2004). The potential of 4D CAD as a tool for construction management. Journal of Construction Research, 5 (1), 43-60.

Woksepp, S., Jongeling, R., & Olofsson, T. (2005). Applying virtual reality and 4D CAD models in the scheduling process of a large pelletizing plant. Proceedings of CONVR 2005 : 5th International Conference on Construction Applications of Virtual Reality, (pp. 352-360). Durham.

Yerrapathruni, S., Messner, J. I., Baratta, A. J., & Horman, M. J. (2003). Using 4D CAD and Immersive Virtual Environments to Improve Construction Planning. Conference on Construction Applications of Virtual, (pp. 179-192). Blacksburg.