IMPACT OF 4D MODELING ON CONSTRUCTION PLANNING PROCESS

Master of Science Thesis in the Design and Construction project management

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CHALMERS UNIVERSITY OF TECHNOLOGY
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ABSTRACT

Increasingly, construction planning is playing an important role within the development of construction industry. However, outlining an appropriate construction plan constitutes one of the most complicated challenges for construction project team. A wide range of planning methodologies have been researched and implemented but they are not qualified enough to satisfy the desire of construction parties and improve the construction performance. There is still an enormous disparity between execution and plan. Therefore, an efficient and effective planning method is intensively needed to enhance the project performance and to minimize the risk of cost overrunning and delays.

This thesis aims to study different aspects of 4D technology and to find out its impact on the construction planning process, and how to benefit most from this technology. A thorough literature review was conducted and different case studies were analyzed to determine the benefits and limitations of 4D modeling on the construction planning process.

The study concluded 4D modeling as a promising tool for construction planning. The most significant benefits of 4D modeling determined are better visualization of construction work, better communication among project teams and increased planning efficiency. Additionally, 4D modeling supports planners in achieving detailed and accurate work plans, planning of temporary structure, quantity takeoffs and managing site logistics. Despite of few shortcomings, it is recommended that 4D modeling should be widely introduced into construction industry.

Key words: *4D modeling, 4D planning, 4D BIM, construction planning, planning methods.*

Contents

Preface

This master's thesis has been carried out from January 2012 to May 2012. The study was conducted at Chalmers University of Technology, the division of Construction Management under the supervision of Christian Koch and Mikael Johansson.

We would like to express our sincere gratitude to our supervisors and Göran Lindahl for their professional support and valuable inputs which have enabled us to successfully accomplish this thesis. We would also want to thank our opponent - Mahvin Delnavaz for her constructive comments and reflections on the thesis.

Last but not least, we want to show appreciation to our parents and friends as their support and encouragement helped us a lot in conducting this master thesis.

Göteborg, May 2012

Dung Dang & Moiz Tarar

1 Introduction

This chapter firstly presents the background for the study. In order to clarify the context and focus of the study, the problem description is then stated followed by purpose and research questions. Finally, an outline of the report will close this chapter.

1.1 Background

“Plan your work and work your plan.” (Vince Lombardi)

The applicability of this quotation is very high in the construction industry where the ultimate success is significantly influenced by the planning (Dixit, 2007). Attached to the history of construction industry is a great deal of efforts from project teams to deliver construction projects with the best corollary and to satisfy their customers. Nowadays, construction projects are coupled with increased number of project participants, making the requirement of effective planning and better communication more prominent (Wanga, Zhanga, Chaub, & Anson, 2004). Unfortunately, despite the fact that architects, contractors and suppliers are struggling every day to accomplish their projects in time, within budget and closely meet their clients’ needs, not many of them achieve the desired results. According to UK Industry Performance Report (2011), only 45% of the construction projects completed on or within the prescribed time, and the number of projects on budget is recorded at 63%. Additionally, it is believed that construction industry has been growing fragmented. The gaps between different construction actors are becoming larger where each of them works within their own processes and without collaborative knowledge (Kymmell, 2008). Consequently, there is usually inconsistency between construction phases/processes, particularly in execution and planning.

In 1996, the Center for Integrated Facility Engineering (CIFE) at Stanford University officially used the concept of 4D CAD (Wanga, Zhanga, Chaub, & Anson, 2004). Within 4D, Three-Dimensional (3D) graphic model of a project (physical aspect) is intimately connected with its construction schedule (time aspect), thereby, the project is visualized the sequence of construction and according to how it would be during the actual construction processes (McKinney, Kim, Martin, & Howard, 1996). The adaption of 4D modeling provides schedulers, planners and project managers an exceptional tool to solve the problems that might arise during construction phase like; trade flows, work conflicts, material lay down areas and move in and move out of material and labor force before the actual start of construction (Dixit, 2007). In addition to this, 4D modeling also reduces the misunderstandings between various parties involved in construction project. Due to its significant potential benefits in the construction industry, 4D concept has attracted many researchers to develop its potential in the past decade (Wanga, Zhanga, Chaub, & Anson, 2004).

1.2 Problem description

Construction planning is a challenging and essential activity in the execution and management of construction projects (Hendrickson, 2000). According to Chevallier & Russell cited in (Heesom & Mahdjoubi, 2004), effective planning is one of the most significant aspects of a construction project and the success of the project is greatly influenced by it. However, Kelsey cited in (Heesom & Mahdjoubi, 2004) stated that emerging evidence indicates a shortage of skill in the construction planning area, with a decreasing number of experienced planners having the ability or knowledge to effectively plan construction projects. A wide range of planning methodologies have been researched and implemented but they are not qualified enough to satisfy the desire of construction parties. There is still an enormous disparity between execution and plan (Allen & Smallwood, 2008).

The construction plans are usually being generated by a computer based tool as 2D charts or drawings from a long period of time with the absence of spatial features of actual construction (Wanga, Zhanga, Chaub, & Anson, 2004). Activity based critical path method (CPM) is the most used technique to schedule the construction process these days. Construction planners split up a project into a number of small activities and each activity is included in the bar chart and a network which represents the proposed schedule of the project (Jongeling & Olofsson, 2007). The computer based CPM scheduling has helped the construction planner to plan the construction tasks efficiently. However, the major disadvantage of a CPM network is in the development of correct sequencing alternatives. This process usually relies on how delays and priorities are identified which heavily depend upon the experience and instinct of the scheduler/planner (Dixit, 2007). According to Akbas cited in (Jongeling & Olofsson, 2007), another difficulty in the use of CPM scheduling for construction planning is linked to the spatial configuration of project. The spatial configuration of each construction project is unique and constitutes an immense foundation of planning decisions. The CPM schedule fails to provide enough information regarding the spatial configuration and complexities of the project components (Koo & Fischer, 2000). Therefore, the user has to look at 2D drawings and conceptually connect the components of the building with the related activities from the CPM schedule to identify the spatial aspects of a project. Analyzing detailed CPM schedules in combination with 2D drawing might lead to a complex process, which limits the possibility to identify problematic sequences, mistakes and opportunities. Conflicting interpretations of the schedule might be developed by different project members when viewing the 2D drawings and CPM schedule. This in turn might lead to ineffective communication among different project participants (Jongeling & Olofsson, 2007). In parallel to the construction schedules, many construction enterprises build 3D models with the aid of widely used CAD applications for their projects. However, those 3D models cannot display the exact status of a project at a specified time but can only provide static images. The data integration between the schedule information, 3D model and other information is not present. Without the visualization of the construction progress at the construction site as the time elapses, planners must rely much on their experience, imagination and judgment to perceive data from paper based documents and come up with the appropriate method of construction, thus receiving minimum benefit from the computer (Wanga, Zhanga, Chaub, & Anson, 2004).

All such circumstances might affect the performance of the construction projects adversely. The construction industry needs to consider the use of technology to improve working practices and efficiencies in order to make construction more attractive to both investors and potential recruits. Given that planning has a significant impact on the ability of any organization to achieve this, the focus of their attention should be on using technology to improve the construction planning process (Allen & Smallwood, 2008).

1.3 Purpose and Research questions

This thesis is aimed to study different aspects of 4D technology and to find out its impact on the performance of the construction planning, and how to benefit most from this technology to address the most common problems faced in the construction planning process. The following question is addressed in the study:

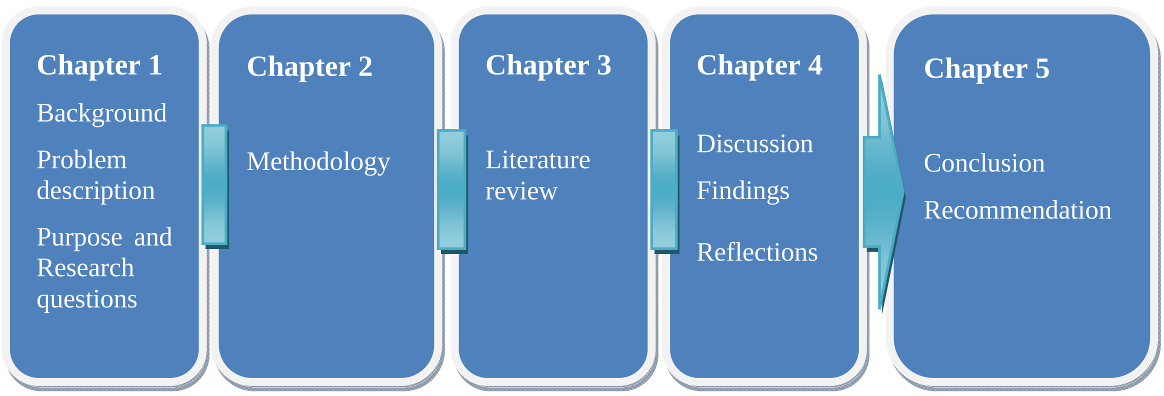
i. What are the impacts of 4D modeling on construction planning process over traditional planning methods?
   a. What are the benefits of 4D modeling?
   b. What are the shortcomings of 4D modeling?

The study will be further enhanced with determining ways to mitigate the shortcomings and enhance the benefits of the 4D modeling by addressing the following subject:

ii. Maximizing the effectiveness of 4D modeling for the planning process.

1.4 Thesis structure

The thesis includes 5 chapters. The remaining chapters are as following. Chapter 2 describes the methods this thesis used to study the problems. Chapter 3 reviews through relevant literature and explains more about construction planning process and 4D modeling together with its implementation in construction planning. Afterwards, in chapter 4 the discussion, the findings and the reflection are presented respectively. The thesis finishes with the conclusion and recommendation in chapter 5.



2 Methodology

2.1 Deductive and inductive theory

Bryman (2004) described two approaches for relating theory to practice which are deductive and inductive. In deductive method, the researchers observe, review and analyze existing theories; derive a hypothesis from it and validate it using empirical analysis. That is, deductive method begins with general ideas and ends with specific results, whereas in inductive method, the researchers perform a series of studies and observations to come up with findings which lead to the formation of a general theory. It means that general ideas are generated from specific results in inductive approach.

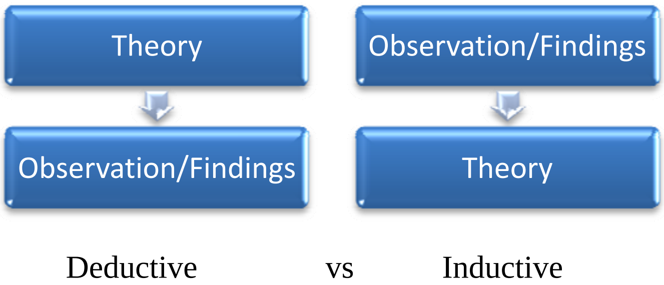


Figure 0-1: Deductive and Inductive approach (Bryman, 2004)

2.2 Adopted Method

The approach used to conduct this thesis is deductive approach. A topic of interest was first selected and the hypothesis was derived for this study, that is: is 4D-modeling beneficial for construction planning process? In order to validate this hypothesis, study was narrowed down to addressing specific research questions. To carry out the study, the quantitative methods for collecting data were mainly used. The quantitative data collection techniques include surveys, experiments, existing statistics and content analyses (Neuman, 2006). Due to the limitation of not having a company to conduct surveys and experiments, the data was mostly collected by content analysis and existing statistics.

Content analysis is a technique to examine written information, content or symbolic material e.g. pictures. The researcher first identifies a body of material to analyze, for example, books, articles, and reports or other such material. Useful relevant data is then extracted, to assist in reaching the findings. Whereas in existing statistics research, the researcher collects data from previously conducted experiments, surveys or reports, then reorganizes or combines the information in new ways to address the research questions and come up with the findings (Neuman, 2006).

A thorough literature review was conducted with a number of articles and books studied and categorized into three levels according to relevancy to the topic. Afterwards, the major portion of data including nine case studies was collected from the most relevant literature. These already performed case studies provided us with broader perspective on the topic as compared to conducting a single case study on our own.

For analysis, a majority of numerical data was extracted from the case studies. The data from different case studies was coinciding and sufficient to address the research questions. This extracted data was then evaluated and interpreted to come up with the findings.

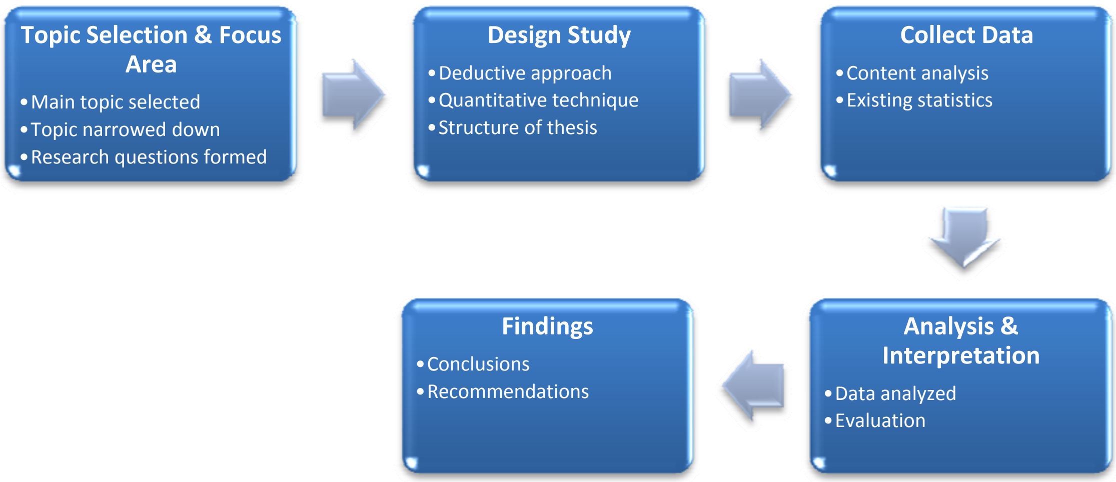


Figure 0-2: Adopted methodology

3 Literature Review

3.1 Construction planning

Increasingly, construction planning is playing an important role within the development of construction industry (Allen & Smallwood, 2008). It involves tracing back from the result and identifying the sequences of events which lead to that result. This is a challenging job for the planner since the final outcomes of construction projects are not possible to observe until they are completed (Hendrickson, 2000). Moreover, the inevitable nature of uncertainties and complexity of construction projects are also put together to create more intricate challenges for project team in accomplish construction planning (Li, Chan, Huang, Guo, Lu, & Skitmore, 2009). Zanen & Hartmann (2010) pointed out that it is important to effectively plan ahead in the early stage of a project; to specify potential errors, prepare possible solutions and to assign work tasks to the right people with the right techniques. Those are what will enhance the percentage of success. However, construction planning is not a process only limited in the period before construction's actual start; it should be considerably taken into account during the project life cycle and would require re-planning if something wrong should happen (Hendrickson, 2000). Not only can an effective and proper plan limit the possibility of problems occurrence, it also lessen the adverse consequences of such problems (Zanen & Hartmann, 2010).

The aim of planning is to generate required activities as well as their interdependence and thereby ensuring that the project will be completed within the best manners of economics, safety and environmental acceptance (Zanen & Hartmann, 2010). Fundamentally, construction planning associates with the identification of essential activities that lead projects to their final outcomes. Planners have to thoroughly analyze the sequences, the implementation and also impacts of such various activities. Afterwards, based on the evaluation and experiences from previous projects, decisions will be made to determine what strategies and performance methods are the most beneficial. In other words, through construction planning, suitable technologies are selected; work tasks are assigned; resources are allocated and project participants as well as the interaction between them are identified (Hendrickson, 2000).

3.1.1 Construction planning aspects by function

As mentioned above, planning is a vital and challenging task in construction project. The process of planning is complex and involves a number of steps which will be elucidated in this part. Figure 3-1 briefly illustrates all the functional steps required during construction planning.

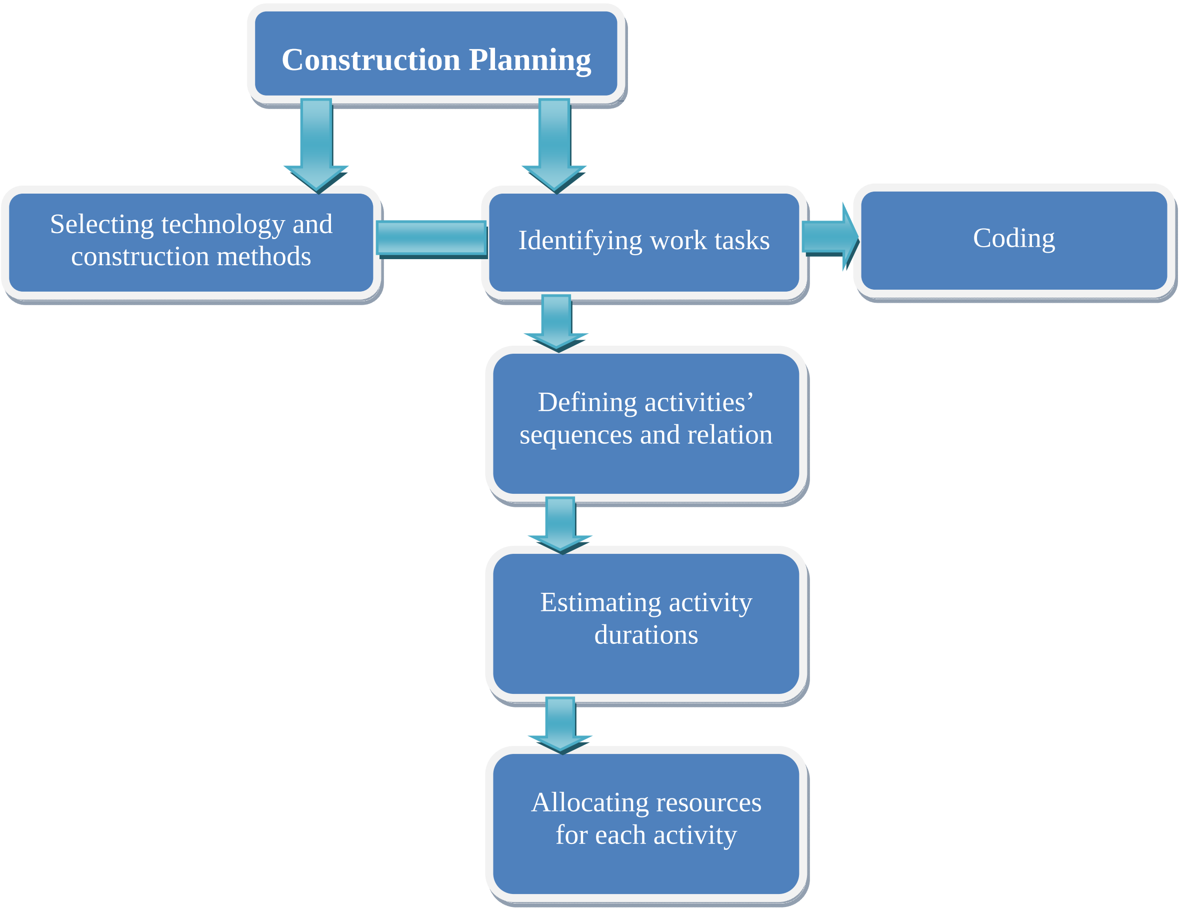


Figure 0-3: Construction planning aspects by function (Hendrickson, 2000)

The two first functional steps are to select technology and construction methods and to identify work tasks which can be conducted concurrently. Since the selection of technology and construction methods can have huge impacts on the project as a whole, Hendrickson (2000) suggested that planners must cautiously consider the level of workers' skills and experience. He also recommended generating a construction plan based on each technology and method in order to assess and compare the benefits of alternative methods for the projects.

Identifying work tasks assist in informing project participants about all the activities required to complete the projects. These work tasks will then be included in the construction schedule and be allocated with the resources. Generally, the designation of work tasks is developed throughout the planning process and is finally finished in a hierarchical framework. Planners need to consider the project with a holistic point of view because neither too detailed nor too simple set of activities is beneficial for the project (Hendrickson, 2000).

Once the work tasks have been defined, planners have to decide how long of this duration is appropriate for the project as well as to put buffer time in case of delay. In most of construction projects, the preferable way of scheduling is to base on planners' own experiences and records of similar activities from previous projects. Absolutely, each project is unique and therefore work tasks cannot be identically the same, and that is when the planners' planning skills are brought into play (Hendrickson, 2000).

Along with scheduling and time estimating, allocating required resources for each work task is also a crucial step in construction planning. Throughout this step, the number of workers (measured by working hour), the proportion of materials, the equipments needed and thereby, the total cost of each activity can be defined (Hendrickson, 2000).

Additionally, since a construction projects involves thousands of activities, using the full description of each task can make the schedule be intricate and difficult to comprehend. Using coding system is the favorable method to replaces such lengthy information with a neat and concise system of numbers. Additionally, this coding system helps improve information flow, ensure the consistency of various components in construction projects and between construction parties (Hendrickson, 2000).

3.1.2 Construction planning methods

Throughout the development of construction industry, there have been a numerous of methods implemented in construction planning such as Gantt chart, critical path method, linear scheduling and last planner. This part of the literature review will summarize such existing methods, their advantages and disadvantages.

3.1.2.1 Gantt chart

Gantt chart is a time schedule developed by Henry L. Gantt, a predecessor who initiated applying "scientific management methods" in the industry. Gantt chart exists as several variants of which form and application depend on scope of the projects

(Nunnally, 2007). An example of a Gantt chart schedule is illustrated in Figure 0-4 below.

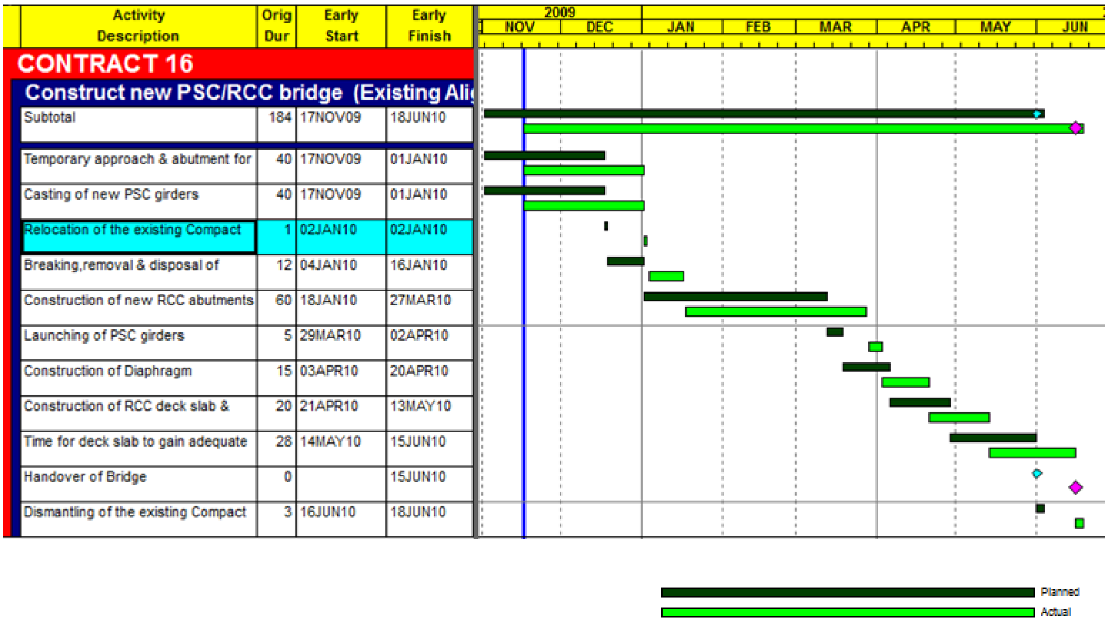


Figure 0-4: Gantt chart schedule example

As can be seen in Figure 0-4, a Gantt chart depicts key activities and their durations recorded according to planned schedule and actual performance. Nowadays, Gantt chart still gains its popularity mostly due to the advantage that it is very easy to formulate and use. However, Gantt chart fails to present the relationship between project activities. From the graph schedule, it is impossible to determine what activities are the most important. That is to say, Gantt chart is not so much valuable in helping project team identify the effects of delay or change of activities on each other (Nunnally, 2007).

3.1.2.2 Critical Path Method (CPM)

During the period from 1957 to 1958, a considerable improvement in planning gave birth to the Critical Path Method (CPM). More advanced than Gantt chart, CPM not only shows activities required for the projects, it as well provides information on the relationship between each work tasks. In general, an appropriate format of CPM requires a good preparation of followings: i) a work breakdown structure containing all necessary work tasks, ii) estimation of activities completion time and iii) specification of the interdependence between activities (Santiago & Magallon, 2009).

Andersson & Christensen (2007) claimed that CPM is unable to cope with resource constraints as regards repetitive activities. Whereas CPM presumes that resources are unlimited for constructing the jobs, this is not true in reality. Consequently, it is impossible to foreseen whether there are shortage in resources or conflicts between work tasks concerning the ultilization of resources. This problem will lead to disruptions in construction processes and thereby delays can be unavoidable. Additionally, in a construction project, same activities can be performed at different locations in construction site and at the same time whereas CPM fails to deal with such type of work tasks.

3.1.2.3 Linear scheduling method/Location-based scheduling

Linear scheduling method (LSM) and also called location-based scheduling (LBS) was firstly formulated in the early 1950s (Andersson & Christensen, 2007). It is mainly applied for construction projects such as multiple housing units, railway, highway and high-rise building. LSM supports planners to avoid creating schedules that can cause conflicts between repetitive activities and to ensure the continuous flow of resources working during the project life cycle (Nunnally, 2007). However, LSM has not achieved much concentration from construction actors. One of the main reasons is that it is very difficult to change the level of detail for information once they have been put in the schedule. Additionally, LSM software also requires a large amount of input information at the initial phase of planning and scheduling (Andersson & Christensen, 2007). Below is an example of LSM:

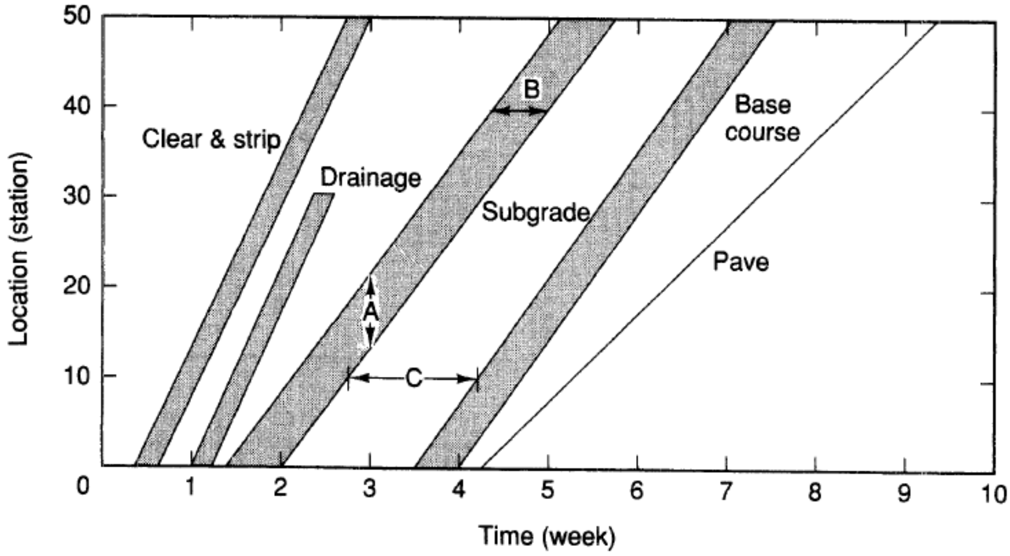


Figure 0-5: Linear scheduling (Nunnally, 2007)

3.2 4D BIM

3.2.1 Introduction to BIM

One of the most promising developments which the architecture, engineering and construction industries have achieved in the past few years is Building Information Modeling (BIM). BIM is used to construct virtual models of a building digitally. These computer generated models contain accurate geometrical data of the building components and other necessary data needed to support the fabrication, construction and procurement activities. BIM also contains several of the functions required to model the lifecycle of a building, providing the platform for new design and construction capabilities. When efficiently utilized, BIM facilitates a more integrated design and construction process which results in high quality of buildings at reduced project duration and lower cost (Eastman, Teicholz, Sacks, & Liston, 2011).

BuildingSMART (2010) defines BIM as follows:

"The building information model (BIM) is a set of information that is structured in such a way that the data can be shared. A BIM is a digital model of a building in which information about a project is stored. It can be 3D, 4D (integrating time) or even 5D (including cost) – right up to 'nD' (a term that covers any other information)."

BIM aims at improving collaboration between stakeholders (see Figure 0-6), reducing the time needed for documentation of the project and producing more predictable project outcomes. BIM has massive potential and versatility as a receptacle for project information (BuildingSMART, 2010).

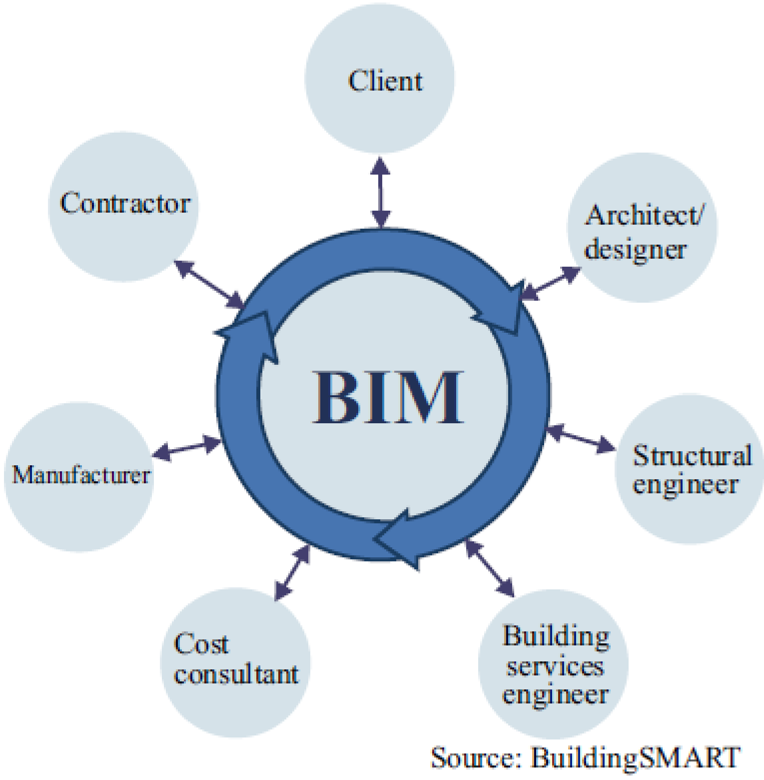


Figure 0-6: Major stakeholders in BIM (BuildingSMART, 2010)

3.2.2 Functions of BIM

A fully functional BIM can be integrated with several functions as shown in Figure 0-7. Different projects can use BIM for a set of desired functions according to the needs and nature of the project. Each of the BIM function can bring much to the share knowledge pool and a lot can be gained from it (BuildingSMART, 2010).

BIM can be used from the starting phase of a project, in the planning approval process and in checking whether the project conforms to the regulations till various design stages of a project. Different BIM software packages can ease the working of architectures, building services engineers and structural engineers and enhance their performance. 3D visualizations are also possible by the applicability of BIM to see the project alive before it is built. BIM allows different checks and function to be performed to improve the design and cost data can also be extracted by the utilization of BIM. In addition to this, a time dimension can also be added to the BIM to assist with scheduling, planning and construction management and after the completion of the project, BIM can be used by the building operator to support the operation and maintenance activities (BuildingSMART, 2010).

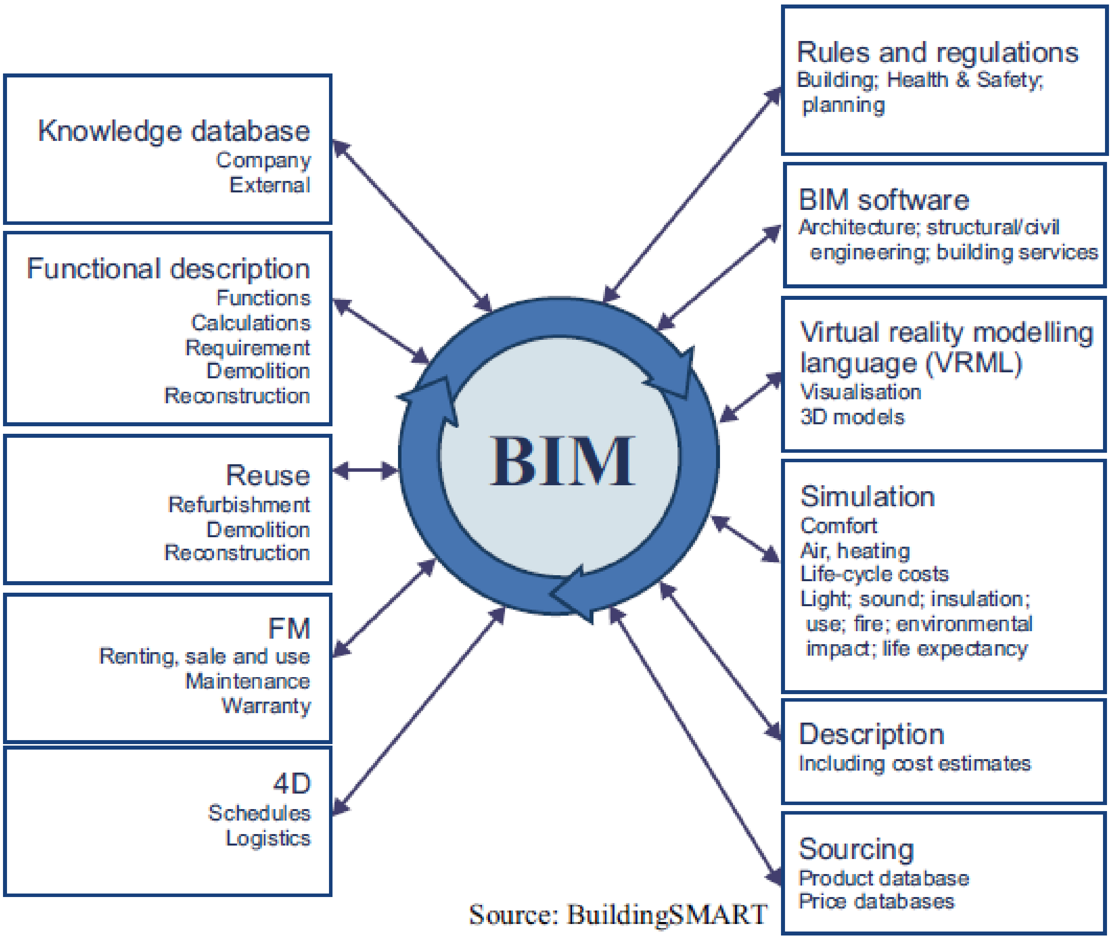


Figure 0-7: Functions of BIM (BuildingSMART, 2010)

3.2.3 Dimensions of BIM

The availability of the information regarding the project and its connectedness characterizes BIM dimensionally, that is, 3D, 4D and 5D, where 3D is three-dimensional space; 4D adds time as a dimension; and 5D includes cost as a dimension (Kymmell, 2008). An illustration of different dimensions of BIM is represented in Figure 0-8 below.

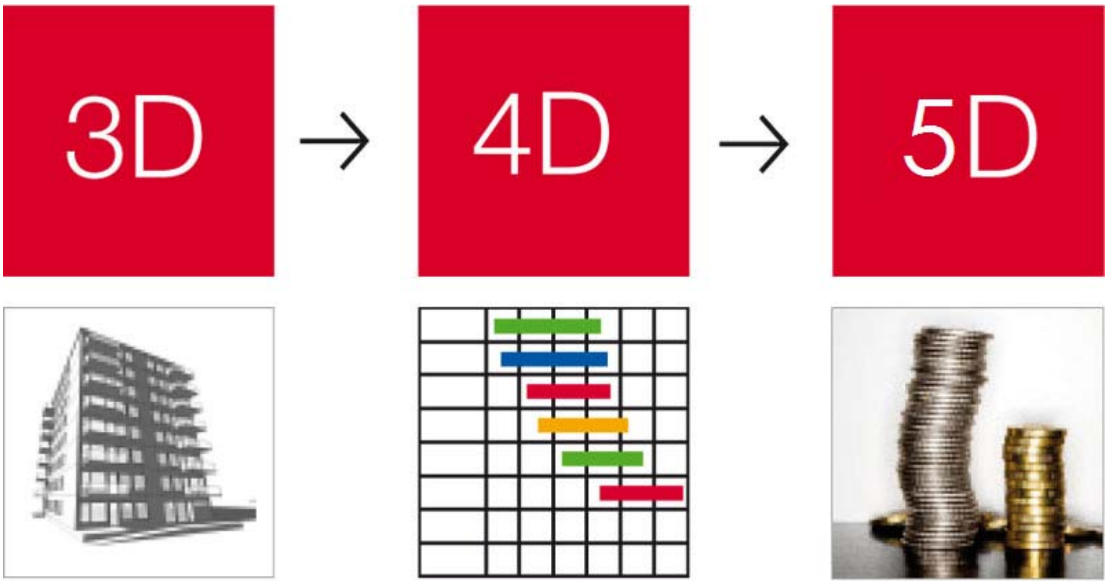


Figure 0-8: Dimensions of BIM

3.2.3.1 3D BIM

3D BIM contains all the spatial relationships, geographic information and geometry e.g., length, width, and height of the building components. By the use of virtual 3D building model, design errors due to inconsistent 2D drawing are identified and eliminated. In addition to this, models from different disciplines can be brought together and compared to check for any conflicts and constructability problems before they are identified on the construction site. By the implementation of 3D building model the coordination among different project participants is enhanced and errors are significantly reduced. This leads to an efficient construction process with reduced cost and minimized likelihood of legal disputes (Eastman, Teicholz, Sacks, & Liston, 2011).

3.2.3.2 4D BIM

4D BIM requires linking construction plan to the 3D model, which makes possible to visualize how the building and site would look like at any point in time by simulation the construction process. 4D tools allow planners to visually communicate and plan activities in the context of time and space (Eastman, Teicholz, Sacks, & Liston, 2011). This makes possible the adoption of alternative approaches to site layout, scheduling and crane placement etc. during the construction phase. The production rate information can also be contained in the model which will permit lines of balance schedule analysis. This allows the efficient configuration of the tasks based on their production rate and location in the project. A significant difference in the efficiency of a project can be made by making improvements in production rates and repetitive tasks (Kymmell, 2008).

3.2.3.3 5D BIM

5D BIM requires project cost to be integrated with the 3D model of the building making it possible to forecast and track the project cost throughout all the phases of construction. It is helpful in the early stages of the project to establish budget areas. With the evolvement of the model, cost estimation can be enhanced with the increased level of model detail and the cost implementations of different design alternatives can be estimated at any stage of design phase. The cost data extracted from the 5D model can also be utilized to measure the financial performance of the project during the actual construction phase (Kymmell, 2008).

3.2.4 4D Planning

Construction planning involves scheduling and sequencing activities in time and space, taking in account resources, procurement, spatial constraints and other concerns in process. Traditionally, bar charts and Critical Path Method (CPM) scheduling are used to plan the construction activities. However, these methods do not consider the spatial configuration related to these activities and neither do they link these activities directly to the building model. Therefore, scheduling is an intensive manual job and it often does not synchronize completely with the design and makes it difficult for the project stakeholders to understand the schedule easily and its effect on the site logistics. To address these shortcomings in the planning process, 4D technology has evolved. Many commercial tools have evolved till now to facilitate the process of creating a 4D model with automatic links to 3D geometry or entities for construction activities (see Figure 0-9). BIM tools have enabled scheduler to create, evaluation, and amend 4D models more efficiently, which has resulted in the implementation of more reliable and effective schedules (Eastman, Teicholz, Sacks, & Liston, 2011).

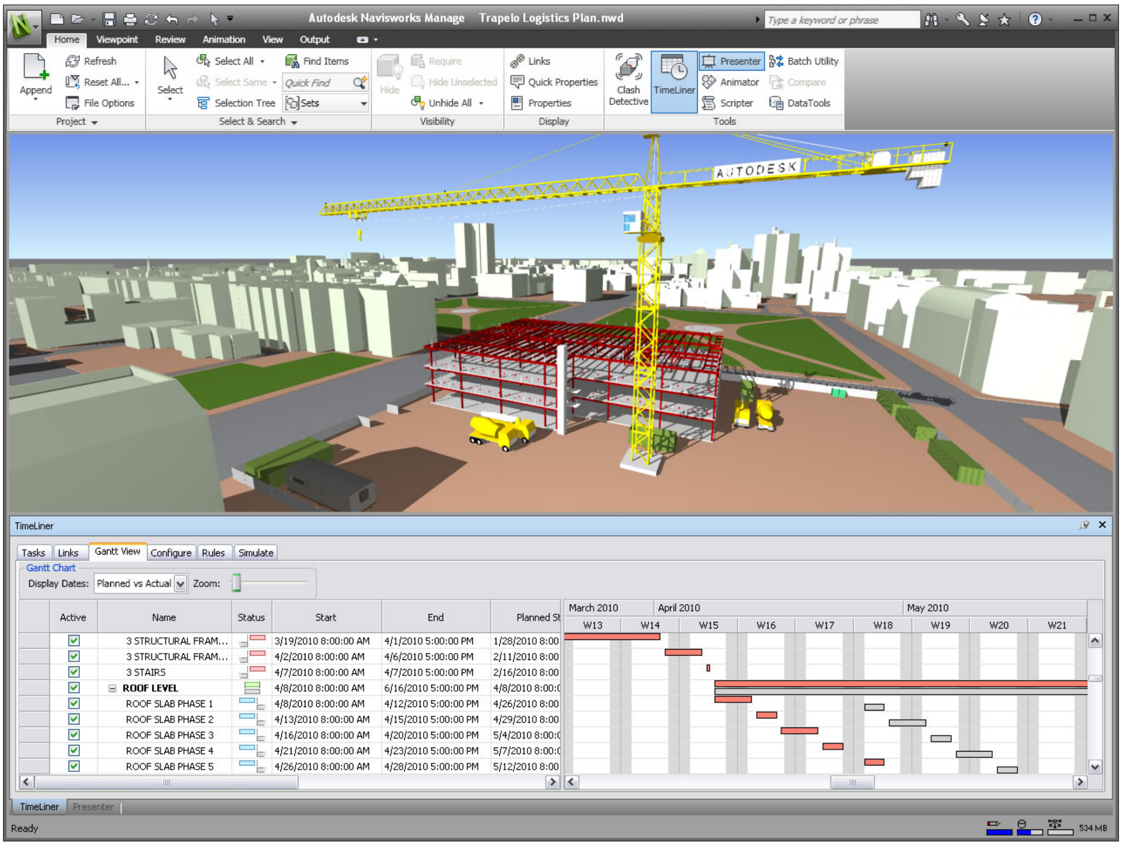


Figure 0-9: Illustration of 4D model

4D modeling allows the simulation and evaluation of the planned construction schedule. Grouping of the objects in the building model should be done according to the construction phases and linked to relevant activities in the construction schedule. For example, if a concrete slab is to be poured in three steps, then the model of the slab should be divided into three sections so that the sequence can be effectively planned and illustrated. In addition, temporary activities and structures like scaffolding and tower cranes should also be included in the building model. The contractor knowledge is very significant when building a 4D model for planning process. If the model is built during the design phase of the building, then the contractor can give his valuable feedback regarding constructability, estimated construction cost and sequencing. 4D simulations for planning process acts as a communication tool for identifying potential bottlenecks and as method to improve collaboration among different project teams (Eastman, Teicholz, Sacks, & Liston, 2011).

3.2.4.1 4D Modeling Processes

Variety of tools and processes for building 4D models are available to the scheduler to choose from listed below.

1. Manual method using 3D or 2D tools

2. Built-in 4D features in a 3D or BIM tool

3. Export 3D/BIM to 4D tool and import schedule

Manual CAD-Based Methods

Colored pencils and drawings, with different colors to represent different sequences to show progress of work with time have been used by construction planners for decades. This process was shifted to CAD drawings by the planners with the advent of CAD. Planners worked with a third party to create rendered animations to visually present the schedule in most of the cases. These animations are very appealing visually and tend to be a very effective marketing tool, but they are an inadequate scheduling and planning tools. The main reason for this is the manual production of the animations with limited options to change, update, and do real time scenario planning. With every change in schedule detail, the planner must create a new set of images or animations to manually resynchronize the 4D image with the schedule. Due to these limitations, the use of these tools is normally restricted to the initial stages of the design when visualizations of the construction process play an important role and is much desired by the clients (Eastman, Teicholz, Sacks, & Liston, 2011).

BIM Tools with 4D Capability

Another way to generate 4D images is through features that automatically filter the objects in the view on the bases of the parameters set. Revit is one such tool which distributes the objects into several phases according to the requirement. The user can then apply filters to view the desired object in a specific phase. This type of 4D functionality is applicable to basis phasing and generation of 4D images at desired requirements but does not provide direct integration with the project schedule. Whereas, Tekla Structures, a BIM tool, provides a built-in scheduling interface enabling multiple links between the physical objects and the activities in the model. A single physical object can be linked to one or several activities and a single activity can be linked with one and several physical objects making the 4D evaluation of construction sequence possible, with emergence and disappearance of temporary facilities. Most of the BIM tools, however, do not have built-in “time” or “date” capabilities, and require specific add-on tools or 4D modules to directly link to schedule data (Eastman, Teicholz, Sacks, & Liston, 2011).

Export 3D/BIM to 4D tool and import schedule

Due to the shortcomings in the manual and CAD/BIM based 4D modeling tools, many new specialized tools emerged for producing 4D model by linking 3D model and schedule from separate platforms. These tools enhance the production of 4D models and give scheduler a lot options for customizing the 4D model. Usually, these tools require a 3D model data imported from a CAD or BIM application and the schedule data imported from planning/scheduling applications like MS Project and Primavera. The scheduler then links the components from the 3D model to the construction activities from the schedule and form a time based 4D model (Eastman, Teicholz, Sacks, & Liston, 2011).

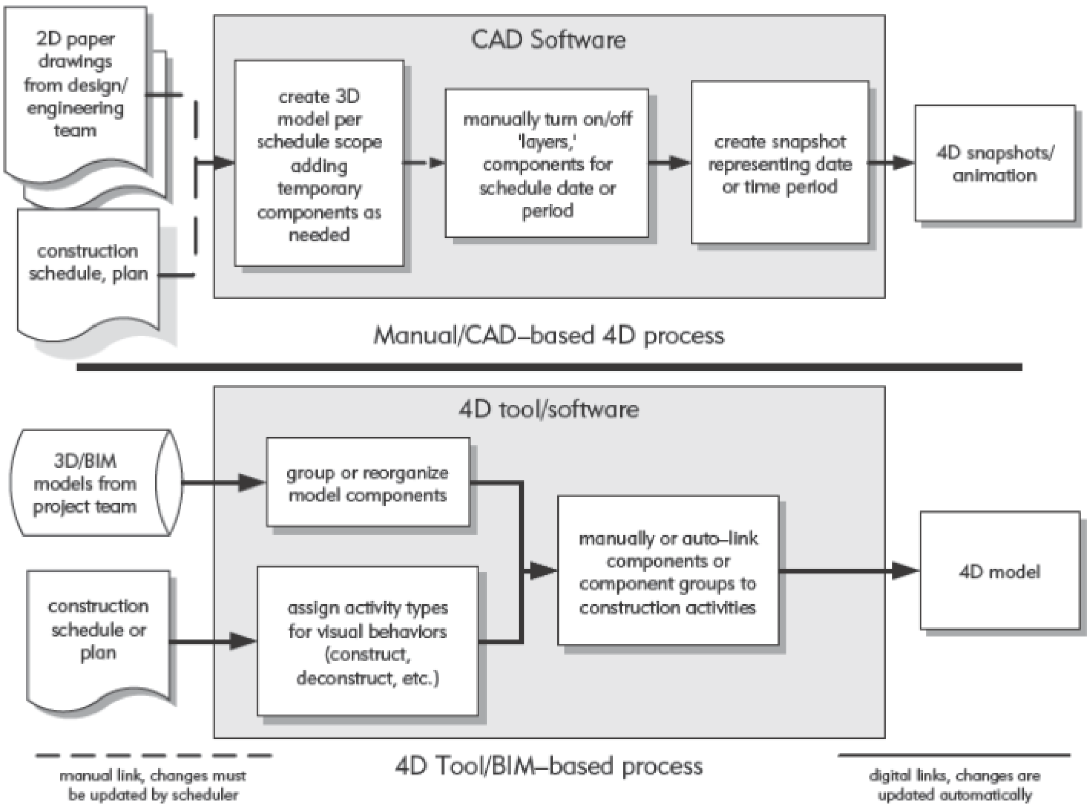


Figure 0-10: Manual and 4D BIM Tools (Eastman, Teicholz, Sacks, & Liston, 2011)

3.2.4.2 4D Planning and Scheduling Issues

The system and mechanism of the planning and scheduling process varies significantly on the planner's tool, but there are several issues that any 4D modeling team or planner should consider while developing a 4D model (Eastman, Teicholz, Sacks, & Liston, 2011).

Model Scope

Model scope plays an important in its design. The model life will be relatively short if it has to be developed for marketing or a design competition. The level of detail of the model directly depends upon the client request. If the model is to be used for the whole duration of the project, then the schedule should contain more detailed activities covering every single important step of the construction process (Eastman, Teicholz, Sacks, & Liston, 2011).

Level of Detail

The level of details of the model is directly affected by the time allocated to build it, size of the model, and the critical items need to be communicated. A highly detailed wall system containing several components to support a rendering for different materials may be used by an architect. Whereas, the contractor may elect to represent this system using a single component because the sequencing of wall sections and floors is more crucial for them. The sequencing of detailed components in some cases may require a more detailed model for installation of each step. To build a single object, the construction tasks may require several activities. Planners in this case can apply multiple activities to a single component. For example, a single wall section can be used to show rebar placement, formwork, concrete pour and wall finishes (Eastman, Teicholz, Sacks, & Liston, 2011).

Reorganization

The scheduler can create custom grouping of the components and can reorganize them to suit the planning process in most of the 4D tools. This is a very important feature for the planner as the way the designer or architect organizes the model is not usually sufficient to relate the components to the activities efficiently. For example, the designer may group similar components like columns or slabs for the ease of applying changes and duplicating. However, these components will be organized into zones of slabs or columns according to the sequence of work by the planner. The ability to reorganize components is very critical for developing an accurate and flexible 4D model (Eastman, Teicholz, Sacks, & Liston, 2011).

Temporary Components

The building model should also contain the temporary structures and activities to form an effective 4D model that represents the realistic construction process. Excavation details, scaffolding, tower cranes and other features that are a part of construction process can be shown in 4D simulation. Integration of scaffolding and tower cranes in 4D model can help the planners to evaluate constructability and safety issues. Scaffolding is also necessary because it influences the spatial constraints for equipment and people (Eastman, Teicholz, Sacks, & Liston, 2011).

Decomposition and Aggregation

During the development of the 4D model, the objects shown as a single component may need to be broken into a number of small portions to show how they will be constructed. For example, a slab needs to be broken down into smaller portions to represent the pouring sequence. This becomes an issue for the planners to breakup specific components, such as slabs or walls, that the designer or architect modeled as a single component. Most of the specialized tools do not provide this functionality, and the planner must perform these split-ups of big components within the 3D tool (Eastman, Teicholz, Sacks, & Liston, 2011).

Schedule Properties

4D models often use early start and early finish dates to simulate the construction process. However, it may be desirable to explore other dates in some situations, such as late start and late finish, to view the effect of alternate schedules on the simulation process of the construction (Eastman, Teicholz, Sacks, & Liston, 2011).

3.3 Case studies

In order to produce more reliable results, a total of 9 case studies covering projects with a variety of scope were selected from the literature. All the case studies involved the implementation of 4D BIM in the construction practices. The case studies were selected keeping in view the different diversity of projects. The projects also varied from small to large scaled projects located in different parts of the world.

3.3.1 Case study 1 (Kymmell, 2008)

This case study involves implementation of virtual design and construction tools (3D/4D) on a large health care project and determining its impact on the performance of the construction process. Virtual design and construction (VDC) tools were used in the project to perform the following functions.

- Mechanical Electrical Plumbing (MEP) coordination
- 3D MEP model for fabrication efforts
- 3D clash detection to identify and resolve conflicts
- Manage the process using the Last Planner System
- Create the 4D models for MEP coordination
- Update the 4D models for coordination.

One critical question addressed in the case study was, what value does the use of VDC tools provide? First of all the project team should clearly identify the return on investment (ROI) for the client for using VDC tools, as the 3D/4D modeling is an investment for the client like any other. Currently, 3D modeling and coordination require more time than traditional drafting in 2D space and overlaying the drawings for coordination on a light table. Additionally, 3D/4D modeling require highly skilled and trained staff to execute the process which are in short supply and expensive to bear. But the experience proved that using VDC tools in a collaborative coordination effort allows a project team to achieve greater value during construction. Within 6 to 9 months, the health care project reported a return on investment of 2 to 3 times the original investment in VDC. Savings occurred through elimination of conflicts among different systems, greater prefabrication, reduction in change orders, and an increase productivity of work with the elimination of work space conflicts. The return on investment therefore accrued from the time design completed to the time all the activities for the MEP systems completed.

After the implementation of the VDC tools for modeling and coordination, the health care project team estimated that on a $94.5 million contract the client saved approximately $1.2 million. Some of the significant benefits achieved in the project are as follows:

Increased field productivity

The HVAC subcontractor achieved 20 to 33% increase in field productivity due to prefabrication of systems which was possible by the use of VDC tools for MEP coordination.

Zero field conflicts among systems modeled and coordinated using VDC tools

There were zero field conflicts on the health care project among systems that were coordinated and modeled using VDC tools. The superintendents' estimated that normally there would be about 100 to 200 conflicts that get resolved on the field on a similar project without the implementation of VDC tools.

Only 43 hours of rework out of 25,000 hours worked.

There was only 43 hours of rework out of 25,000 hours worked. Although there is no comparable data available to evaluate this result, but the project team believes that this a phenomenal result as compared to projects where the coordination is done on a 2D level.

Only six RFIs related to field conflicts.

There were only six request for information (RFI) issued regarding the field conflicts. These RFIs were for the conflicts between systems what were not included in the modeling process. The project team estimated that this is about 5 to 10% of what the number of RFIs get raised on a comparable project using 2D systems for coordination.

Increased planning reliability on the project

The planning reliability was tracked in the project using the percent plan complete (PPC) metric, which is the percentage ration of the tasks actually completed to the tasks that were planned to complete. The PPC chart for the heath care project is shown in Figure 0-11. The cumulative PPC for the project was about 83%. The average PPC on a well-managed project is estimated to be about 60% by the Lean Construction Institution. On these bases, the planning reliability of the health care project was much higher than the comparable projects.

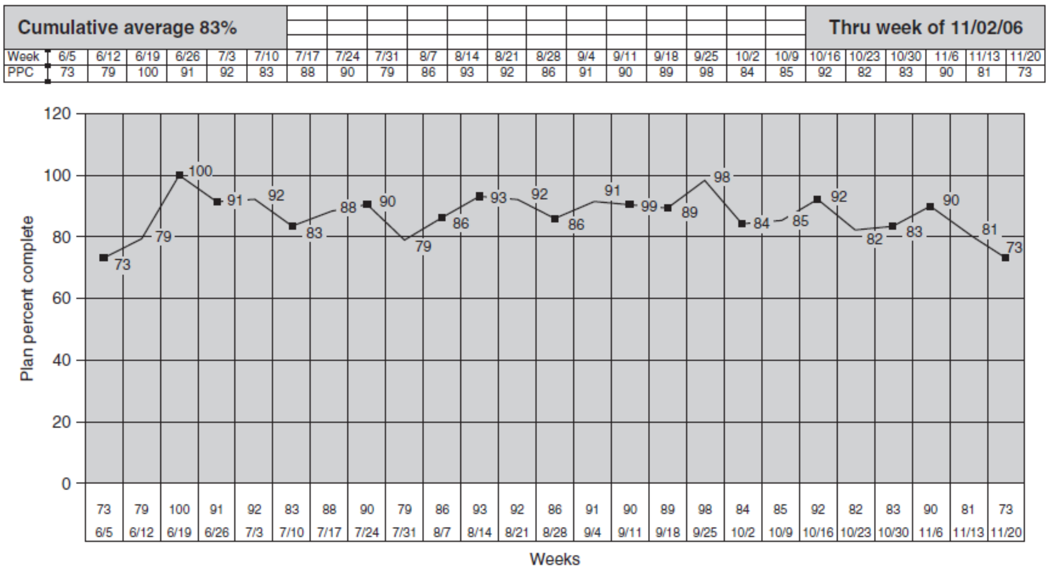


Figure 0-11: Percent plan complete over project duration

3.3.2 Case study 2 (Kymmell, 2008)

This case study is about a contractor developing virtual design and construction (VDC) tools and integrating them into their standard processes. The VDC program focused on 3D quality control, 4D scheduling, and 5D cost estimation. The contractor's executives were convinced from the start that the VDC process will be beneficial for them, so not much effort was paid on return on investment (ROI) studies. Rather their focus was to design and develop standards, processes, and infrastructure for the effective delivery of new approach and to validate results to gain confidence in the new BIM tools. Quite early in the program phase, two points became obvious.

- A quantity estimated by constructing a model is much more reliable than one estimated from traditional methods and 2D documents and drawings.
- The time spent in creating a model replaces the time spent in taking off quantities from 2D documents and drawings. With proper standards, processes and training, creating a model is as fast as extracting data from the 2D documents and drawings. That is, the time spent is evaluating the 2D documents equals the time in creating a 3D model which will help us visualize the 2D documents more efficiently and precisely. Thus the 3D model can further be used for scheduling and coordination by transforming it into a 4D model.

Because of the adoption of the BIM based processes by the contractor in the early stages of its development, there were several challenges faced. But the contractor never looked backed and adopted BIM based processes as their standard way of doing business in many areas.

3.3.3 Case study 3 (Eastman, Teicholz, Sacks, & Liston, 2011)

This case study covers construction of the bridge in the city of Helsinki, Finland. The construction of the bridge started in the fall of 2008 and was scheduled to complete by late 2010. Because the design of bridge incorporated heavy steel work and there was a need for accuracy, the designer recommended the use of modeling for the project. The client decided to adopt modeling not just for the steel parts, but all other construction works, including time and management dimensions. The initial model of the bridge was prepared by the designers, but the contractor used the same model and added to it and edited it to use it for the construction process. Following are the different ways in which the model was used for construction management.

- Visualization
- Design and Planning of Temporary Structures
- Clash Detection
- 4D Construction Planning
- Fabrication and Installation of Structural Steel Components
- Rebar Detailing, Fabrication, and Installation
- Laser Scanning

The model was used very productively for work and activity sequencing, and for viewing the work. The 3D model helped different parties involved in the project to better understand the details and concept of the design, enabling a common understanding and mental picture to evolve far more quickly than with traditional 2D drawings and documents. Through modeling the temporary structures including scaffolding, formwork, tower cranes and other temporary structures, a better understanding of the construction process and structures was developed. This enabled identification of various conflicts, and effective planning of temporary works along with the implementation of 4D planning.

The 4D model enabled the team to develop more accurate and detailed work plan then they would have achieved with the traditional methods. It provided actual spatial information and gave precise quantities for material needed at required time. This helped to reduce the need for excess material buffers. Since the association of the objects in the model to the activities was done manually within the software tool for 4D modeling, the initial setup was quite time consuming. During the execution of the project, the project team decided to reverse the overall sequence of bridge deck construction due to several engineering problems with the piles of central pier. However, the 4D model was not updated because of the time required for redefining the logical relations between the tasks. The update process was considered to be more costly than the benefit it would have achieved. The schedule uncertainty was referred as an additional reason for not spending time in the updating process of the 4D model.

The implementation of modeling process provided many benefits for the parties involved in the construction of bridge project. Intensive use of BIM enabled better construction management and saved money and time according to all the project participants. Some of the key lessons learned during the execution of the project are as follows.

- Plan using BIM right from the start of the project by setting objectives, conducting trainings, and creating an environment for learning and improvement.
- Use model to complement construction management techniques.
- Fast information exchanges can be achieved by model synchronization feature.
- Use 4D scheduling to understand and assess whether the scheduling is realistic or not.
- 4D planning gives a better understanding of the period over which temporary structures are required.
- Using laser scanning and importing the data into the model to check the locations and work quality is very effective.
- All project participants should upgrade their project tool simultaneously, so that the compatibility issues due to different versions can be avoided.

3.3.4 Case study 4 (Eastman, Teicholz, Sacks, & Liston, 2011)

This case study involves the study of implementation of BIM tools on a large scaled complex project. The owner integrated the BIM process in their project after the design using 2D tools had already started. The BIM tools were used to support the design, clash detection, quantities takeoff, coordination of work and 4D planning. The design team consisted of architect team, the structural engineer team, the mechanical and electrical engineer (M&E) team, and the quantity surveyor team. Initially the four teams which comprised the design team used 2D drawing to communicate between themselves, but subsequently they developed a 3D model for communication using the BIM tools.

The clashes were identified manually by the design consultants using the traditional methods of overlaid drawings on light table, which leads to a great deal of clash detection and management to be faced by the contractor. By the implementation of BIM tools, over 2000 errors and clashes were found before the tendering and construction. In this way a substantial cost saving was achieved by adopting modeling compared to the traditional 2D processes. BIM tools were also used to perform advanced construction process modeling to verify and enhance the construction mythology. The building model was integrated with its detailed schedule to form a 4D model. This enabled the visualization of the sequence of construction work and spatial and safety issues were identified prior to construction. The sequence of the construction activities was thoroughly checked to make sure that the schedule is authentic and to enhance the construction process. This resulted in cost and time savings on site because of effective planning.

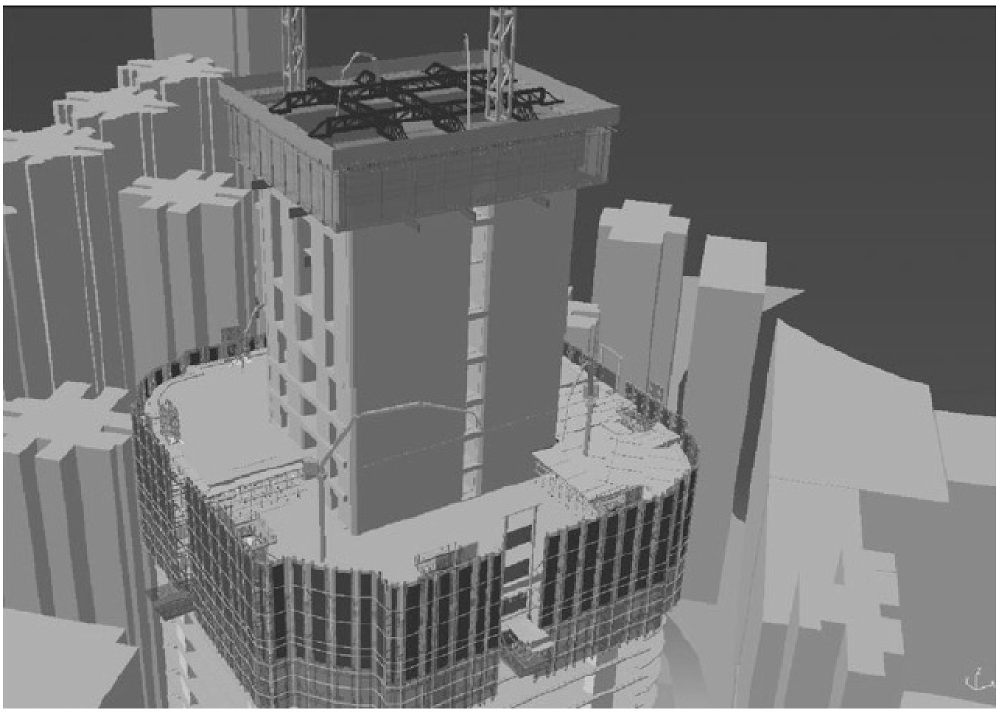


Figure 0-12: Visualization of the construction process

In this project, transformation from 2D to 3D and 4D was one of the main challenges faced by the project team. As the project was still underway when the case study was written so it is not possible to quantify all the problems and benefits associated with implementation of BIM tools. Though its implementation resulted in significant reduction of design errors and clashes and assured a fast, safe and efficient schedule.

3.3.5 Case study 5 (Dawood & Sikka, 2008)

In this project, 6 groups including participants from 11 years old to over 22 years old were divided into three 2D-group and three 4D-group and were asked to assemble a Lego house (see Figure 0-13). Afterwards, the performance of them was compared to find out the effectiveness of 4D model.

Figure 0-13: Lego house model

2D groups used a construction schedule and 2D CAD drawings of the house model including plans, elevations and section to assemble the house. They have to imagine the construction sequence in their mind by linking the set of activities listed in the bar charts and the 2D drawings. Whereas, 4D groups used 4D model and have the visual construction sequence to base their works on. Each group had been given fifteen minutes to investigate and discuss the drawings, bar charts or 4D simulations before those inputs were taken away; and then one hour and forty-five minutes to construct the model. They could ask to access the information during construction period.

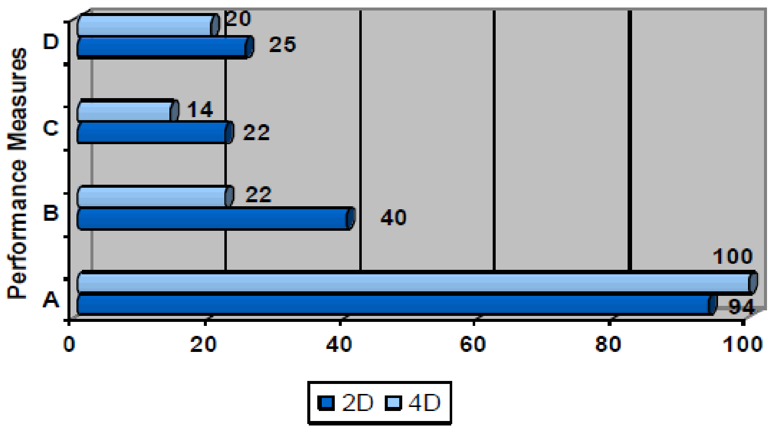
The performance of both the groups was measured through the following four indicators:

- Percentage of model completed (%)

- Number of times information accessed during the session of two hrs
- Total time spent on understanding building information (Minutes)
- Number of times Lego pieces were reconstructed

The results for one of the 6 groups, that is industry professionals group, are portrayed in Figure 0-14 as they are most relevant to the topic. After successfully conducting the experiment following were the results obtained:

- 4D group was able to achieve 100% of model completion as compared to 80% of model completion by the 2D group within the allocated time of 2 hours.
- 4D group requested access to 4D model 22 times during the 2 hours of execution as compared to 40 times request made by the 2D group to access the drawings.
- 4D group spent 14 minutes in extracting information from the 4D model as compared to 22 minutes spent in extracting information from the drawings by the 2D group.
- 4D group reconstructed the Lego pieces 20 times as compared to the 25 times reconstruction by the 2D group.



Where, A= Percentage of model completed (%), B = Number of times information accessed during the session of two hrs, C = Total time spent on understanding building information (Minutes) and D = Number of times Lego pieces were reconstructed

Figure 0-14: Results for the industry professionals group

3.3.6 Case study 6 (Jianping, Yang, Zhenzong, & Ming, 2008)

This case study involves the construction of large scale and complex project of the National Stadium for Beijing Olympic 2008. The project started to construct in December 2003 and completed in June 2008 which since then became a new landmark of Beijing and of China in general. 4D planning was mainly implemented in two following processes which involved intricate structural designs: i) construction of concrete grandstand structure and ii) installation of the steel-structure.

In order to generate 4D models for running simulation, 3D models of those two structures were built up from 2D drawings and work schedules were prepared by Microsoft project software. Afterwards, each component of the 3D modeling was aligned with a specific activity identified in work break down structure and work schedule. These processes of alignment were then executed in 4D simulation software which provided managers, contractors and workers with a visualization of work tasks. Figure 3-13 illustrates several snapshots of the 4D simulation.

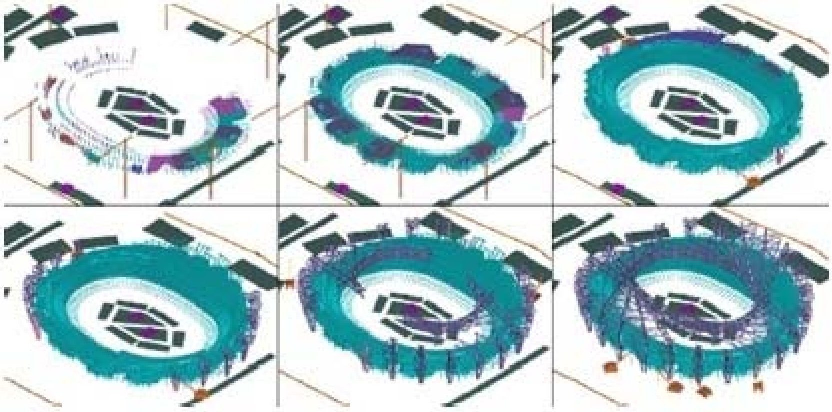


Figure 0-15: Snapshots of the 4D simulation

At the end of this case study, the application of 4D modeling in this project has been pointed out as a beneficial tool. It helped shorten the installation duration by 16% and also assisted managers in allocating resources, reducing consumption and increasing productivity. The underground reasons for such profits of 4D modeling are that: i) it visualized construction process, clearly showed the relationship among components and their construction sequence and ii) it acted as a support tool to spot conflicts and allow prior adjustments.

3.3.7 Case study 7 (Dawood & Sikka, 2004)

With the intention of measuring the performance of 4D planning in construction industry, 3 concurrent projects in London were selected. Those three projects were in process of construction at the time of research and their total construction value was £230 million. Two out of three projects' performance were measured by hit rate analysis and will be considered for analysis. Project A was a 700,000 square feet office and retail development and project B was developed because of the demand for residential, office and retail spaces in London city.

Hit rate percentage is important and useful when measuring the reliability, efficiency and effectiveness of construction performance. It is the percentage of activities that commence and complete on time – activities which have zero variance between planned and actual start and finish date. Hit rate percentages can be calculated by using following formula:

$$\text{Hit Rate Percentage (\%)} = \frac{\text{Total Number of activities having zero start and finish variances}}{\text{total number of activities in a package}}\ x\ 100$$

The hit rate percentage was recorded as 48% for the project A. And 26% of activities out of 30% of activities which started and ended late completed within the planned duration, that is, their durations were correctly estimated. The results of hit rate analysis conducted on project A are shown below.

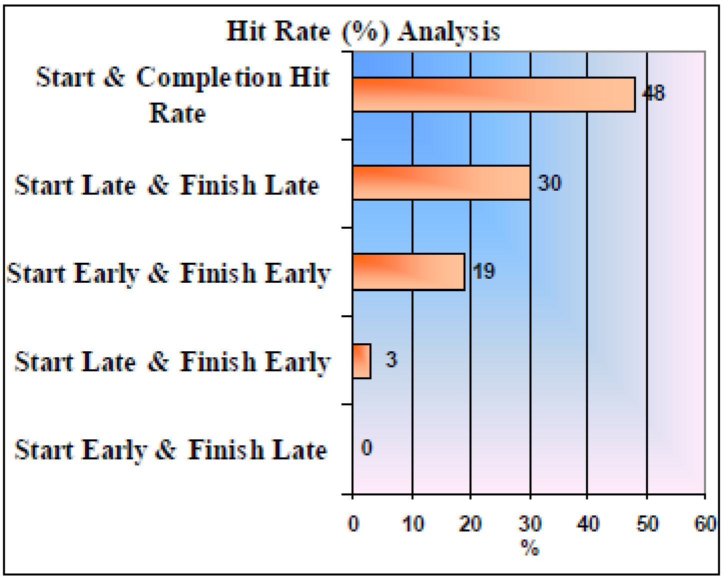


Figure 0-16: Hit Rate (%) Analysis for Project A

For project B, the hit rate was 65% and 24% out of 30% activities which started and ended late completed within planned duration. The hit rate analysis percentages for project B are shown below.

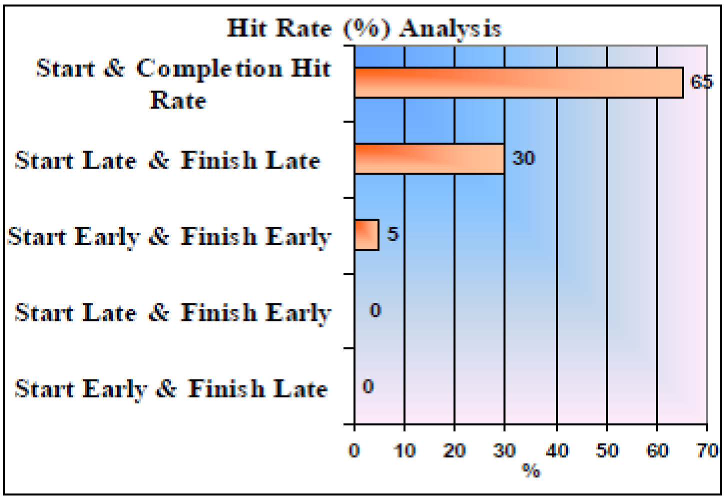


Figure 0-17: Hit Rate (%) Analysis for Project B

Initial outcomes of the hit rate percentages indicated that the use of 4D planning on a construction project can assist in enhancing the efficiency of planning.

Furthermore, the evaluation of information gathered through interviews revealed several benefits of utilizing 4D planning which are as follow.

- Risk reduction in a program
- Detecting planning clashes
- Improves visualization
- Assist in reducing overall project duration
- Enhanced client satisfaction
- Assists in reducing the amount of rework required to be done
- Helps in reducing the design time

3.3.8 Case study 8 (Mahalingam, Kashyap, & Mahajan, 2010)

This case study mainly focused on the following points:

- Where and when in construction projects 4D planning can be most advantageous.
- Improve construction actors' perception of how to effectively use 4D technology.

Firstly, the implementation of 3D and 4D models in three major construction phases were analyzed. These three phases were planning, design and construction phase. Secondly, the impacts of 4D modeling on two types of construction project -

infrastructure and commercial projects - were analyzed discretely. Finally, the case studied the benefits of 4D technology for three groups of users which are top managers/executives, construction professionals/project managers/site managers and workers.

This case study was conducted in India with the selection of four projects – two infrastructure and two commercial projects. In order to concrete the validity and reliability of the results, these chosen projects were in large scale, complex and implemented international construction technologies as well as materials. The first task of the case study was to generate detailed 4D modeling for each of those four projects. Later on, a survey was created with the participation of 63 interviewees. Each individual participated in the survey was asked to evaluate the applicability of 4D following the scale from 1 to 5.

The first infrastructure 4D model was made for the construction of cargo berth in a typical port and the second model was of a breakwater. One of the two commercial 4D modeling was developed for the project of a three-floor academic building with the total area of $1600m^2$. Another commercial model was of an office building in a series of 6 buildings constructed on a large office campus.

Benefits from using 4D modeling in this case study can be summarized as following:

- 4D modeling is most profitable in the project planning and construction phase.
  - In planning phase, it plays an important and effective role in communication between planners and clients.
  - In construction phase, it helps projects stakeholders detect problems and keep track of construction progress.
- Top managers and workers are those can get the most benefits from the implementation of 4D modeling whereas construction professionals greatly appreciate its ability to support them during construction phase.
- Table 0-1 describes the areas of usefulness of 4D modeling

Table 0-1: Usefulness of 4D modeling

Parameter	Mean value (max=5)	95% confidence interval for mean
Usefulness of 4D for clients to visualize, understand and commit on the construction process	4.74	4.54-4.94
Usefulness of 4D for visualizing for construction review	4.26	4.06-4.46
Usefulness of 4D in project review meetings	4.31	4.11-4.52

When it related to how 4D CAD is useful for client to visualize and completely understand the construction process performed by contractors, the mean value was 4.74 out of 5 – maximum value. This mean value was the average of the 63 numbers given by survey individuals. This amount expressed a strong agreement on the benefits of 4D. The same situation happened when measuring the usefulness of 4D for visualizing for construction review and in project review meetings (4.26 and 4.31 respectively). Additionally, the high value of 95% confidence for mean (for example, 4.54-4.94) gave the insurance that the results are reliable.

However, finding from the survey also indicated that although project participants endorsed the usefulness of 4D CAD, they were in a dither about using it as a separate management tool. There is a need of an integrated project planning tool that can make the most of 4D simulations' advantages and integrate these results with existing project management processes. Interviewees also expressed their concerns over the large amount of required effort to process and develop the data generated from 4D simulations to support strategic decisions.

3.3.9 Case study 9 (Jongeling & Olofsson, 2007)

The case study involves construction of a cultural centre in Luleå, Sweden. This building had two underground garages and contained a library and a concert hall. 4D simulation of the building excluding the roof was generated from an existing 3D model provided by the architect and a Location-based schedule (LBS). This 4D simulation was run in Common Point 4 Dimensional software (CP4D) by importing the 3D model, the construction schedule and linking them with each other. There were some problems when simulating the 4D model, for instance, some activities listed in the schedule cannot be visualized because they were not depicted in the 3D model; or some activities that instead of requiring a presentation of ongoing work flow on a component, they needed ongoing work in a location. To deal with such issue, space objects were formulated in 3D model for every location consisted in the Location-based schedule.

After the simulation of 4D modeling, some problems of construction were detected which otherwise could not be seen from the Location-based schedule such as space and resources conflicts. One example issue was presented in Figure 0-18 which made clear that too many activities were performed at the same time around section I-III. In this case, the implementation of 4D modeling provided contractors a visual tool to identify problems prior to construction and thereby reducing the extra amount of money and human efforts on the work of reconstruction.

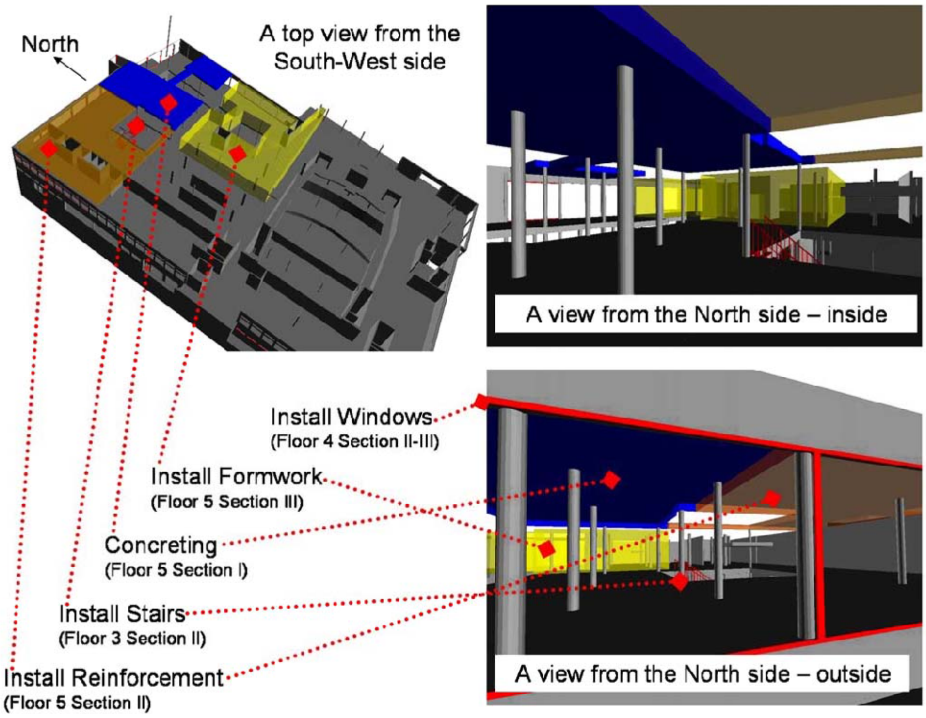


Figure 0-18: Three different screen captures of the same scheduled construction tasks at the beginning of week 7 2006.

4 Analysis and Discussion

This chapter covers the analysis of the case studies and literature review along with reflections and discussion about research questions.

4.1 Impact of 4D modeling on construction planning over traditional planning methods

To determine the impact of 4D modeling, its benefits and shortcomings for the construction planning process are identified by reviewing the case studies and literature. In addition, the advantages of 4D planning over traditional planning methods and the challenges in adopting 4D planning methods are also discovered.

4.1.1 Benefits of 4D modeling

There are six major benefits of 4D modeling for construction planning identified after reviewing the case studies which are analyzed below.

4.1.1.1 Better visualization of construction work

One of the most significant benefits of 4D modeling is that it provides a better visualization of construction work which is not possible to achieve through 2D drawings and documents such as Gantt chart and linear schedule. This enables planners to detect conflicts and clashes in the construction phase during the planning process. As observed in case study 1, there were zero field conflicts by implementing 4D modeling which would have been around 100 to 200 by using traditional planning methods. Also in case study 4, over 2000 errors and clashes were found before the start of construction phase through the adoption of 4D modeling. The indicator value of the usefulness of 4D visualization was also very high in case study 8, that is 4.74 out of 5, which represents that the 4D visualization play a critical role in the construction planning process. In case studies 3, 6 and 9, the implementation of 4D modeling also helped in better visualization of the construction work and enhanced the construction planning process. In addition to detection of conflicts and clashes, the visualization of construction work enabled the planner to incorporate the safety concerns in planning phase of the large complex project in case study 4.

4.1.1.2 More accurate and detailed work plan

4D modeling allows project team to generate precise and comprehensive work plan which would be more difficult to achieve with traditional planning methods. The project team in case study 3 achieved a very detailed and accurate plan by the utilization of 4D modeling. With the use of 4D modeling, the sequence of the activities in the work plan and their impact on each other can be simulated to check the authenticity of the schedule and to enhance the planning process to utilize minimum resources in the construction phase with maximum benefits and in minimum time. This leads to cost and time saving like in the large complex project in case study 4. While Gantt chart is unable to present the relationship and the impact activities have on each other.

By using the traditional methods of planning like Gantt charts and CPM scheduling, it is very easy to miss some activities in the construction plan due to lack of visualization. Whereas, 4D modeling provide a very effective tool to visualize the building project and identify all the possible construction activities leading to an accurate and detailed work plan. 4D modeling also assist the planners in allocating resources, 4D modeling assisted the managers to allocate resources in the National Stadium for Beijing Olympic as mentioned in case study 6, which is not possible with CPM scheduling as it presumes that resources are unlimited for constructing the job.

4.1.1.3 Efficient planning

Efficient construction planning plays an important role in leading the project to its success. By reviewing the case studies it is quite prominent that 4D modeling enables the planners and project teams to achieve a very effective and efficient planning of construction works. As observed in case study 1, the field productivity was increased by 20 to 33% and also the amount of rework reduced significantly. There was only 43 hours of rework out of 25,000 working hours which is not possible to manage if traditional 2D planning methods were employed. Similarly, in case study 5, 4D group restructured the Lego pieces only 20 times in comparison to 25 times by 2D group which used 2D drawings and bar chart schedule. The rework was also reduced for the cultural center project in case study 9 by the implementation of 4D planning and hence, there were human effort and cost savings. In Beijing Stadium project, the installation duration was shortened by 16% and in case study 5 as well, the 4D group managed to achieve 100% project completion as compared to 80% completion by the 2D group within prescribed time implying that productivity has increased due to the implementation of 4D planning.

Furthermore, the reliability of planning was significantly enhanced by adopting 4D modeling as compare to planning by traditional methods. This reliability degree was evaluated by using the percent plan complete (PPC) metric for the large health care project as described in case study 1. This project achieved a cumulative PPC of 83%, which is 23% higher than the average PPC on well managed project, indicating a much more reliable planning than the planning done on comparable projects by utilizing traditional 2D methods.

Another important aspect regarding measuring 4D's performance discussed in the case studies was the hit rate percentage of a project – the percentage of activities that start and complete on time. In case study 7, hit rate percentages for both project A and B were high (48% and 65% respectively) indicating that the use of 4D modeling can enhance the efficiency of planning process.

4.1.1.4 Better communication

4D model can be used as an effective communication tool between different project stakeholders. Case study 8 confirmed that 4D modeling played an important role in communication between client and planners during the planning phase. 2D documents can lead to misunderstanding between parties involved because they do not provide a whole picture of the project, but as described in case study 3, with 4D modeling, construction actors can comprehensively understand the project's details much faster; thereby a good communication process can be established. Additionally, 4D modeling assisted the communication process in the project review meetings during the construction phase. In case study 7, the implementation of 4D modeling for planning enhanced communication leading to more satisfied client.

4.1.1.5 Planning of temporary structures and works

Temporary works and structures play an important role in the execution of projects supporting the main construction process. Traditional 2D planning methods like CPM scheduling and Gantt charts usually do not consider temporary works and structures during the planning process which might result in difficulties at site during execution. However, 4D planning enables the planner to plan the temporary works and structures as well by incorporating them into the model. As observed in case study 3, the modeling of temporary structures including formwork, scaffolding and tower cranes enabled a better understanding of construction process and structures leading to a more effective planning.

4.1.1.6 Accurate quantities takeoff

4D modeling enables the planner to measure quantities more accurately and efficiently, which enables a more effective planning process. In case study 2, the project team realized that the time required to take off quantities from 2D documents can be almost equal to the time and effort required to build a model. And once a building model is created, the quantities estimated from it are much more reliable than the quantities estimated from 2D documents. The 4D model also permits the planner to determine the quantities of material required at any specific time of the project, which results in more precise planning. This helped the project team in case study 3 to reduce the need for excess material buffers.

4.1.1.7 Site Logistics

Another positive impact of 4D modeling was observed to be on logistics of the project. 4D modeling enables the planner to manage and plan the storage areas and its access more efficiently with the aid of better visualization of the construction site (Eastman, Teicholz, Sacks, & Liston, 2011). The material flows within the site can also be planned productively by the implementation of 4D modeling.

4.1.2 Shortcomings of 4D modeling

Although a major portion of 4D modeling impact on construction planning is observed to be positive, there are few weaknesses as well which comes with adaption of 4D modeling instead of traditional planning methods. Above all, development of 4D model from 2D documents is a timely and challenging task. It also requires highly skilled and trained staff to execute the process which is in short supply and expensive to bear. The major challenge faced by the project team of large complex project in case study 4 was the transformation from 2D to 4D model. This exertion do not come to an end after the completion of the model, even for editing the model or updating it with changes as the project progresses requires a great amount of effort and resources.

As seen in case study 3, the change of construction sequence of bridge due to several engineering problems did not lead to updating of the 4D model, as this process was considered more time consuming and costly by the project team than the benefit it would have achieved. Whereas, it is much easier and convenient to develop revised plans or to update the current plan in case of uncertainties if traditional planning methods are applied.

Other problems that impede the adoption of 4D modeling were discussed in case study 8. Despite the fact that 4D modeling constitutes a helpful support tool, transforming the results from 4D simulation to strategic information is a laborious task. Analysis from the case study also indicate a number of planners and managers who are not willing to use 4D modeling separately without software or program to integrate it into existing management tools. Such integration will then facilitate the automation of analysis process for hastening the decision making process.

4.2 Maximizing the efficiency of 4D planning

4D modeling is a productive tool for planning process, but it needs to be more adaptable to be recognized as one of the leading planning methods. As observed in most of the case studies reviewed, a major challenge faced by the project team was development of the 4D model. To address this issue, it is advisable to adopt the model as early as possible in the project. The model can be initiated from the concept phase of design. The architects must consider the scope of the model while its development that the model life of the project is long as it will be used till end of the project for design and 4D modeling. So the architects should ensure that necessary details are included in the model.

This model after finalizing the aesthetics of the building can be handed over to the designers for assistance in the design process. The designers can add more structural details into the model like columns, beams and MEP detail. The nature of project should be kept in mind while evolving its model. A complex project requires a more detailed model with every minute detail included. Whereas, adding too many details in a simpler project will be a waste of effort, time and resources. Once the design of the building is complete, the same 3D model can be used by the planner to transform into a 4D model. This will save a lot of time and ease the workload as the 3D aspects of the model will be almost complete and the planner will just need to work on developing the sequence and integrating it with the model.

The planner can either use integrated 4D BIM tools or can link the 3D model with the schedule separately using a 4D tool for creating the 4D model. The built-in scheduling interface in integrated 4D BIM tool enables linking of physical objects to the activities within the model. For a complex project with high likelihood of uncertainties, an integrated 4D BIM tool is recommended for the planner as it allows ease in updating the model. However, in a 4D tool with interlinking of 3D model and the schedule separately the updating task of the model becomes hectic and time consuming as the whole procedure needs to be repeated again.

The temporary structures should also be added into the model for enhanced spatial configuration and to evaluate the constructability and safety issues to maximize the efficiency of the planning. To ensure that the 4D modeling process executes smoothly, different project teams involved in the project should use inter compatible software tools. Like the 4D tools usually require the 3D model to be imported separately from some other 3D modeling software tool. So the 3D model should be developed in a software tool which is supported by the 4D tool being utilized on the project. This also implies for the schedule if it is being developed in a separate platform and then imported into the 4D tool afterwards.

The reliability of 4D planning can be improved by involving as many project participants as possible in planning phase. The planning process can learn from Integrated Concurrent Engineering (ICE) design process where all the design teams work together at the same time and same place. ICE enables multiple, simultaneous information flows with short lead time and high level of service (Chachere, Kunz, & Levitt, 2009). With the contribution of different project teams working together in the planning process, the 4D model can be developed which acts as an effective communication framework to generate a more reliable and efficient construction plan.

Furthermore, for enhancing 4D planning, another vital requisite is to employ high skilled and experienced staff. The reason is that without knowledge of 4D modeling, it is impossible to build it up properly or it would be time and cost consuming. That is to say, planner should be the one who has enough knowledge and ability to carry on the work. Therefore, top managers of a construction project implementing 4D planning are recommended to employ potential planners and systematically educate 4D technology to them. Training programs should be organized regularly to ensure that the knowledge instructed to planners is continuous and up to date. This solution can benefit both the project and the company in long-term advantages.

5 Conclusion and recommendation

Based on the preceding chapters, this chapter encloses the most important conclusions of the thesis. Moreover, suggestions for further research on this topic will be proposed.

5.1 4D modeling for construction planning

The study brought up 4D modeling as a promising tool for construction planning. There are many positive impacts of 4D modeling discovered which are not possible to achieve through traditional planning methods being used. The most significant benefits of 4D modeling are found out to be better visualization of construction work, better communication among project teams and increased planning efficiency. In addition, 4D modeling assists in achieving detailed and accurate work plans, planning of temporary structures, quantity takeoffs and managing site logistics.

With the help of better visualization and communication, the planners, project team and client can achieve a better and common understanding of the project scope and objectives, which can improve the construction planning and execution process significantly leading to the project success. Implementing 4D modeling allows planners to detect the problems prior to construction phase which lead to reduction in the amount of rework and clashes. Therefore, a more reliable and detailed work plan can be obtained which assists the project to complete within prescribed time and budget.

Researches and practical case studies also indicated few shortcomings of 4D modeling. The main problem lied in the complexity of the model and how to make the adoption of it more convenient. However, these impediment can be solved be providing appropriate training to help participants in 4D planning perceive better understanding of it and to take most use out of it. Development of new 4D tools is also simplifying the adoption of 4D modeling process and making it more convenient for the project team to learn and develop in 4D technology.

All things considered, it is recommended that 4D modeling should be widely introduced into construction industry. Implementing 4D technology could be propitious development for construction firms and can help mitigating the most common problems faced in the construction projects with enhanced planning efficiency.

5.2 Recommendations for further research

After conducting the studies it is prominent that 4D modeling is beneficial for the construction planning process. A good topic to study further can be how much beneficial is 4D modeling for the construction planning, that is, if it is highly effective or not? And if it is highly effective then why it is not yet widely accepted within the construction industry? These subjects, however, were not covered in the initial purposes of the thesis and hence, be suggested as topics of research for future studies. In future research, the validity and reliability of the study should be increased by conducting practical interviews or surveys with construction project stakeholders. Furthermore, applying 4D modeling on runtime projects of a construction firm could be of great help for collecting actual data and information and determining the effectiveness of 4D modeling. Not only such experience will reinforce the statement of findings and discussion, it will develop a broader and holistic perception of 4D planning in construction projects as well.

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